The cognitive dynamics of socio-technological thinking in the early phases of expert designers' design processes

Maria, M.C. (Grietjie) Haupt

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by

Maria, M.C. (Grietjie) Haupt

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SUPERVISOR: Prof Ronél Ferreira
(University of Pretoria)

CO-SUPERVISOR: Prof Marc de Vries
(Technical University of Delft, The Netherlands)

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I dedicate this work to all the people in my life that made this journey possible: my husband, who held my hand all the way, my children who never tired from encouraging me, my friends who did not disappear but supported me, and supervisors who understood the art of academic nurturing so well.

I thank all my colleagues involved in this process in some way or another, local and international, for years of intellectual stimulation and sharing.

I thank God for protection, guidance and universal energy.

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The descriptive purpose of this study was to explore and describe the manner in which expert designers transform and represent knowledge in the early phases of the design process. This was done by investigating the interaction between stored knowledge and direct perception in the early phases of the design process. The methodological purpose of the study was to explore innovative ways of extending current interactive design cognition theory on research methodology in design contexts, against the underlying context of conventional protocol studies. Theoretically, the study conceptualised extended design cognition theory. In this manner, the study adds to available literature on one sided computational theory and biased ecological approaches. The practical value lies in documenting ways of mirroring expert design behaviour in learning environments and problem solving spaces in higher education design curricula. The study furthermore may inform the design profession concerning expert practices that can improve the quality of design solutions through the consideration of expert design reasoning. Finally, the study provides methodological knowledge on the potential value of employing protocol studies within the context of creative problem solving by studying both verbal and visual representations.

The conceptual framework of the study integrates a computational approach with embodiment-related principles. I followed a mixed methods approach and employed a case study design applying critical realist principles. I purposefully selected expert designers from three different design domains, with four of them working in pairs and three others as a team. Data collection consisted of three separately video recorded protocol studies (one architectural, one mechanical engineering and one industrial design task), during which verbal protocols and free hand conceptual sketches were produced. Observation and a field journal also formed part of the data collection and documentation strategies. Data analysis was guided by constructs derived from theory embedded in my conceptual framework.

Five themes emerged subsequent to qualitative data analysis. The first theme revolved around the hierarchical order in which expert designers tended to think about various things. They considered abstract design aspects which they then linked with functional intentions as required by the client, or that they reversed and formulated into their own preferred functional ideas. They incrementally concretised their abstract aspectual and functional thoughts by connecting them with physical elements. Once expert designers had exhausted their aspectual and functional intentions, they moved onto considering implementation intentions, which involved practical plans to satisfy their intentions. The second theme which emerged relates to the dominant role that the personalisation of intentions played in the design processes. Intentions served as internal cognitive mechanisms and their functions in the various cognitive phases of the design process. Participants' awareness of intentions and their

subsequent alignment of decisions, activities and objects, played a dominant role. When they disagreed with intentions articulated by the client, they formulated their own preferred intentions, whereby they reversed the direction of transformation. The third emerging theme centred on the incremental development of artefacts. This was made possible by the dual nature of the participants' design sketches. The internal nature of sketches allowed the participants to instantiate mental states (e.g. intentions). The fourth theme relates to the multi-directional nature of participants' thinking. Participants transformed their ideas by integrating new perceived information. Existing internal knowledge resulted in their sketches connecting their internal and external worlds. Finally, the fifth theme that emerged concerns participants' transformations, constructing and manipulating models. In this regard a close connection between participants' involvement in their sketches, making and propagating commitments, visualisation knowledge, lateral and vertical transformations, and subsequent prolonged duration of attention spans was evident.

Quantitative analysis of the data on task environments and problem solving space of expert designers indicate the participants' distinct and overlapping cognitive phases. During these overlaps 'leaky phases' created cognitive links between the experts' problem structuring and problem solving activities as they clarified the various intentions at hand. Secondly, the tendency of experts to extensively use external resources came to the fore. External resources played an important role in influencing the participants' conduct controlling attitudes, as seen in the decisions they took and commitments they made. Thirdly, the synergetic interaction between the participants' internal and external processes and use of resources was evident. This tendency of expert design behaviour emphasised the complex relations between the various intentions which were held together by their ability to synergistically align their ideas with their intentions in a Gestalt manner.

Based on the findings I obtained, I conceptualised 'intention-permeation' by defining this construct as the penetration of objectively, subjectively or opportunistically selected intentions and their alignment with designers' subsequent behaviour. I propose 'intention-permeation' as one possibility of accounting for the way expert designers build conceptual and practical bridges between their inner and outer worlds when they solve complex real world design problems.

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List of Keywords

- Cognitive dynamics
- Designing
- Embodiment
- Expert designers
- Information processing
- Protocol studies
- Representation
- Socio-technological knowledge

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List of Acronyms

- TE: Technology Education
- CTM: Computational Theories of Mind
- DoBE: Department of Basic Education
- CAPS: Curriculum Assessment Policy Statement
- IPS: Information Processing System
- IP: Information Processing
- PBL: Problem-based-learning
- DPS: Design problem solving space
- LTM: Long term memory
- TAPS: Think-aloud-protocol-study

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CHAPTER ONE

Introduction:
Setting the Stage

OVERVIEW

INITIAL RESEARCH PROBLEM:
Novice design and **technology education programmes do not necessarily lead** to complex higher order design activities

INITIAL RESEARCH QUESTION:
How can the development of **novice design programmes** be supported by mirroring the cognitive activities of expert designers?

REFINED WORKING ASSUMPTION:
Effective support of novice designers will require a theory of design cognition based on expert design behaviour

CHAPTER ONE

REFINED RESEARCH QUESTION:
How might current theories on expert design cognition involving representations in the early phases of the design process contribute to the development of novice designers?

INITIAL SUBQUESTIONS

1.
What is the current status concerning learning and teaching support of novices in design and technology education?

2.
What are the current approaches in researching representation in the design process?

3.
Which current theories to design problem solving exist?

4.
How may innovative methods study design cognition?

1.1 INTRODUCTION AND RATIONALE

This study is nested in the general need in society for excellence in designs that could contribute to the quality of peoples' lives, and conceivably direct the way people live by using the artifacts designers conceptualise. More specifically, this study aimed to gain insight into the design process practised by expert designers, with the subsequent aim of informing design education from an expertise perspective. If design educators are knowledgeable of typical expert design behaviour, they may develop design education programmes that are based on both philosophical theory of design cognition and the theory related to designers' typical problem solving behaviour. Reflecting on the generic characteristics of design problem solving and expert design cognition (reasoning), and exploring ways to extend existing design theory may in turn assist educators to position their individual design disciplines among other disciplines (De Vries, 2005). Reflecting on the knowledge and sources that expert designers typically use in the design process may thus assist educators to design meaningful curricula and in turn contribute to practitioners improving their own design skills.

The history of design cognition suggests that the Computational Theories of Mind approach on its own became unpopular (Cross, 2007b) because it does not account for thinking in realistic situations (Bickhard, 2008; Cross, 2007b; A. Gomila, 2008). However, the legacy of Symbol Systems Theory (Simon, 1996) continues to contribute to researchers' understanding of design reasoning and problem solving because of its inherent systematicy. The foreseen contribution of this study rests on the innovative way in which I attempted to integrate adaptations of a conventional computational approach to symbol systems in design cognition theory and research, with elements of a current constructivist approach, namely embodiment.

1.1.1 TECHNOLOGY EDUCATION IN THE SOUTH AFRICAN CONTEXT

The development of education curricula about design in general, and about technology specifically, should ideally be supported by educational research (De Vries, 2005). However, due to design education in general, and Technology Education[1] specifically, being a relatively new development in the context of South Africa's history of secondary and tertiary education, this is not always the case (Reddy, Ankiewicz, de Swardt & Gross, 2003). University programmes for fields such as fashion design, interior design and industrial design have only been introduced at some universities as recent as 2005 through integration of former technikon design departments and universities (Johannesburg, 2010). In addition, a new school subject in the

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[1] Different countries have different names for the learning area at issue. In the *United Kingdom* it is called *Design and TE*, while some European countries call it *Technology and Design Education.* At the Faculty of Education at the *University of Pretoria* it is called *Design and TE* in order to emphasise the centrality of designing in solving technological problems. When I refer to the learning area implemented in South African schools, I will use the term *TE* (TE), as it is formalised in the South African Curriculum and Assessment Policy Statement (CAPS). The CAPS document replaced the previous National Curriculum Statement (NSC).

General Education Band, namely TE, which supposedly forms the foundation for design related professional training, was introduced in 1998. The result is a limited generic philosophical cognitive basis for developing training programmes based on empirical research in South Africa. Although international research in the fields of architecture, engineering and information science cognition has contributed to local understanding of design cognition for the past twenty years, some design fields such as industrial design, fashion design, and interior design are still in need of contextualising a generic understanding of cognitive behaviour in their respective fields of professional education. In cases where conceptualisation of 'designing' in the lower levels of (design and) technology education is not based on continual sound philosophical and theoretical foundations, De Vries (2005, p.128) states that

> *... intuitive concepts and attitudes with respect to technology may already have become fixed to such an extent that it is very difficult to modify them at that late stage. Therefore it is necessary that lower levels of education also include proper conceptualisation of technology in the learners' minds.*

The South African Department of Basic Education suggests that technology educators both at secondary and tertiary levels can achieve proper conceptualisation by, *inter alia,* giving learners opportunities to develop and apply specific skills to solve technological problems. In order to solve technological problems, learners should understand the concepts and knowledge used in TE. They should also learn how to use knowledge responsibly and intentionally while appreciating the interaction between people's values and attitudes, technology, society and the environment. The CAPS (Grades R-9 [Schools]) defines Technology as

> *The use of knowledge, skills and resources to meet people's needs and wants by developing practical solutions to problems, taking social and environmental factors into consideration* (SADoBE, 2002).

Much emphasis is placed on the significance of the design process in Technology Education, which is seen as the backbone outcome for the Technology Education curriculum (refer to Appendix F) (SADoBE, 2002). For example, learning outcomes require of learners to engage in investigating, designing, making, evaluating, and communicating solutions during technological activities. The general teaching and learning approach of Technology Education is required to be practical and solution-oriented (refer to Appendix F for an overview of all learning outcomes of Technology Education). The aim is to develop technological knowledge and skills, where the design process is used as an integrating learning outcome, to structure projects that develop the learner's skills, knowledge, values and attitudes in a holistic way. This objective supports the Department of Basic Education's (formerly the Department of Education) view of teaching and learning of the design process as being a creative and interactive approach used to develop solutions to identified problems or human needs.

As mentioned earlier, the Technology Education learning area in South Africa did not exist on school level prior to 1998 when it was introduced in the national education programme as part

of a complete overhaul of the entire national education approach to teaching and learning. The challenges embedded in this relatively new learning area, however, are manifold. Although policy documents supporting the National Curriculum Statement, including the *Teachers' Guide for Developing Learning Programmes* (Department of Education, 2004), provide valuable practical support to developing contextualised learning programmes, they seem to focus on the ill-structured nature of design problems and the impact this may have on designing and implementing learning activities that centre around problems. Although the National Curriculum Statement seemingly emphasises a problem-based-learning (PBL) approach for Technology Education, very few text books and existing learning programmes designed by teachers comply with either the problems of PBL (Rauscher, 2011) or centre around ill-structured problems (Haupt, 2011).

1.1.2 TRAINING OF EDUCATORS IN TE

One of the challenges to tertiary institutions offering design and TE courses is thus to find appropriate and contextually satisfactory data that could inform courses on philosophical, theoretical, and practical ways to enhance and promote excellence in teaching and attain the knowledge and skills of designing (Economou & Joubert, 2009). Such courses need to be sustainable in an educational environment where change and improvement is not only necessary but inevitable (Motshekga, 2010). However, both current teaching practice (Haupt, 2011; Reitsma, 2009) and existing learning support material (Rauscher, 2011) seemingly indicate the need for informed and theoretically based engagement in the cognitive challenges related to the design process (Dym, Agogino, Eris, Frey & Leifer, 2005; Eastman, 2001; Haupt, 2011; Reddy et al., 2003). Another challenge regarding successful delivery of quality TE teaching can be linked to the relative newness of this learning area (Reddy et al., 2003). A pervasive and general lack of insight in design activity (Reddy et al., 2003) as a conscious and complex process of solving ill-structured problems (Simon, 1996) is often evident amongst first year TE students enrolling for design and technology education modules at a tertiary level (Haupt, 2011).

In my search for theoretically based design and Technology Education learning programmes, I found both scientific and non-scientific literature to indicate limited academic focus on design cognition, philosophical foundations, as well as theoretical and practical design experience (Van Niekerk, Ankiewicz & De Swardt, 2008). Furthermore, insufficient consideration is generally given to the value of professional practice to provide models to tertiary as well as secondary design education (Lloyd & Scott, 1994). In light of the emphasis by the former Department of Education (SADoBE, 2002) on the design process as structuring element for designing Technology Education curricula as well as the importance of integrating contextualised socio-technological knowledge, it seems important for design and Technology Education lecturers at

tertiary level to familiarise themselves with the complex cognitive activities involved in professional design practice.

Existing literature on design and Technology Education does not regularly report on the endeavours of educators applying design education models that were taken from professional design expert behaviour, nor does it report on research relating to the possibilities of applying such models. Literature in the field of design and Technology Education tends to rather focus on novice design behaviour (Black, 1998; Davies, 2000; Hill, 1997; Petrina, Feng & Kim, 2008). In my view, both researchers and practitioners may not sufficiently learn from such novice design research regarding the higher order design cognition that should be aimed for in tertiary education (Cross, 1999, 2004). This viewpoint is supported by comparative studies reporting on the limited value that studying novice design behaviour for domain specific design disciplines holds (Cross, 2004; Popovic, 2004). One way of meeting the challenge of best design education practices therefore seems to be focusing on expert design behaviour rather than novice design behaviour (Cross, 2004; Eastman, 2001; Ericsson, 2006; Popovic, 2004).

It thus seems necessary to examine professional models of design cognition that may inform researchers and practitioners in developing appropriate learning and teaching programmes for novice designers on philosophical, theoretical and practical levels. In an attempt to establish how expert design practice may improve the development of such programmes, I undertook this study. For the purpose of my research, I assumed that local tertiary institutions mainly rely on research in Technology Education for guidance. I further assumed that teachers in schools mostly rely on information and guidance from Department of Basic Education officials of whom few seem to have been formally trained in designing. I further presumed a possible connection between the intention of the Curriculum Assessment Policy Statement and expert design practice. Therefore I decided to investigate the mechanisms of adaptive behaviour (Gibbs, 2005) by considering the role of intention as a driving force in what expert designers pay attention to, which information they access, and their processes of making commitments and transforming their ideas (Simon, 1973). I aimed to gain insight in this area by exploring the way in which experts represent socio-technological knowledge in the early phases of the design process. I assumed that by studying their representations, I would be able to learn how the ill-structured nature of design task environments could allow expert designers to interact with the physical environment and subsequently influence their design behaviour in the design problems space (Goel & Pirolli, 1992; Simon, 1973).

Although education in design has well-established practices that are assumed to facilitate the progression from novice to expert level, an understanding of possible ways of facilitating this where students move from one to the other seems to be superficial (Cross, 2004). In an attempt

to find ways of modelling a set of generic design reasoning skills that could be included in a curriculum for design education in general, and for teacher training in the field of Technology Education in particular, I set out to investigate the cognitive dynamics involved in the reasoning processes of expert designers in the early phases of the design process. My initial premise was that socio-technological propositions emerging during the early phases of the design process could contribute to revealing patterns and trends of intentions. Finding such trends and emergences could potentially indicate the dynamic processes involved when designers relate (through direct perception, memory retrieval and questioning), access and use knowledge to structure and solve their design problems.

Based on the said need for designing Technology Education curricula on tertiary level, the purpose of this study is twofold. First, the study aimed to explore and describe the manner in which expert designers transform and represent knowledge in the early phases of the design process by relying on stored knowledge and direct perception. In an attempt to clarify this, I integrated a computational lens, in particular information processing[2] (rooted in post-positivist philosophy) on design problem solving with elements of embodiment[3] from the ecological approach (rooted in constructivist philosophy). In integrating elements of these two approaches, I attempted to encompass a model that may be applied across design tasks. In this way I aimed to provide examples of individual acts of designing computational accounts of moment-to-moment information processing. At the same time I assumed that designers' intentions will necessitate them to access and use external information afforded by primary physical objects and elements that they perceive and act on.

The second purpose of this study relates to exploring how the combination of different theories in a methodologically innovative manner may contribute to existing theory on research methodology in design contexts, against the underlying context of conventional protocol studies. In this study, I relied on descriptive knowledge of computational processes and embodiment-related actions to explain how different approaches may be combined in one study of design behaviour. I relate embodiment-related actions of designers to characteristics of ill-structured design task environments and the properties of multiple symbol systems. In doing so, I attempted to identify typical associations between information processing, embodiment and knowledge. In the next section I explain my rationale for focusing on these constructs.

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[2] Information Processing theories are embedded in conventional computational theories of mind.

[3] Embodiment refers to the ecological constructs 'affordance', 'perception-action', 'intention-attention' and 'specification' 'Affordance' refers to real, discoverable properties of the environment and objects in the environment.
'Perception-action' implies understanding, knowing and knowledge as perceived rather than conceived and as part of the same continuous and cyclical process.
'Intention-attention' aims to answer the question 'how it might be possible for designers to act on their perception'.
'Specification of information' refers to the notion that the information accessed by designers perceiving environmental properties, is specific in nature and might aid designers to structure design problems (Anderson, 2003).

1.1.3   RATIONALE FOR MY CHOICES

The background of the research problem and the resulting purpose of this study determined the conceptual choices that I made.

1.1.3.1   Why 'cognitive dynamics?

The notion of design 'process' refers to mental 'activity' which is influenced by the nature of design problems, potentially including its ill-structured nature, its relative large size and complexity, and its ambiguity. These factors all play a significant role during the early phases of the design process. As such, 'dynamics' alludes to mental flexibility involving implicit negotiation between certainty and uncertainty in order to move from one state to the other, and to adapt to constraints and requirements (Newell & Simon, 1972). This process typically starts with an exploration and decomposition of a problem, followed by intentional identification of the interconnections between the various components of the problem. Next, designers would typically solve sub-problems in isolation. Finally, partial solutions are combined into the overall problem solution. Designing thus essentially seems to involve accessing and analysing information, and transforming it through inter-relational thinking and synthesis (Cross, 2007a; Goel & Pirolli, 1989). Solutions in design and technology contexts imply the design of an artifact that would solve a human problem. Cognitive dynamics of designers therefore includes drawing interrelations between the physical properties of the intended artifact and its potential technical, contextual, social and cultural functions (Kroes, 2002).

The importance of understanding the dynamics involved in the early phases of design processes cannot be underestimated as the quality of solutions is directly linked to the information available to the designer (Goel & Pirolli, 1992). Input information by means of a design brief is usually insufficient, leading to multiple mental strategies from designers to fill the gaps by relying on observation of the physical environment and stored knowledge. This typically aids designers in understanding the scope and requirements of the design problem (Suwa, Gero & Purcell, 1998). However, I believe that the computational view of problem solving as autonomous, logical and embodied (Gibbs, 2005; Goel, 1995) is limiting. Based on information processing models allowing for the use of symbol systems that react on perceptual situations (Ericsson & Simon, 1993), I was able to integrate the ecological construct of embodiment to consider the way in which designers adapt their behaviour (Gibbs, 2005).

1.1.3.2   Why socio-technological knowledge?

The success of design problem solutions are determined by identifying and applying appropriate knowledge of the variety of social, technical and scientific factors embedded in these multi-

disciplinary fields of knowledge. At the same time designers need to consider the impact of the choices they make when developing solutions. The knowledge that designers need to identify and analyse multi-relational design aspects, which I refer to as socio-technological knowledge, has its roots in the epistemology of scientific technology, and implies a particular kind of generic cross-disciplinary knowledge which is required for a general understanding of the technical world (Love, 2002; Ropohl, 1997).

As such, theorists and practitioners generally consider socio-technological knowledge as the rudiments of designing (Mioduser, 1998), mandatory for negotiating design aspects in the early phases of the design process (Liikkanen, 2009). The importance of understanding how designers access and use such knowledge could provide insight into their own understanding of how humans, the world of objects and the context in which they are required to be used operate in an integrated socio-technological system (De Vries, 1996; Mitcham & Holbrook, 2006; Ropohl, 1997). The knowledge involved in these design aspects are founded in multiple cross-disciplinary fields, for example engineering, physics, visual arts, psychology, and sociology (Love, 2002). Embedded in these knowledge fields, designers typically use abstract conceptual knowledge (Goel & Pirolli, 1989) including aesthetics, ergonomics, economics, properties of material, knowledge about structures, machines and systems, and manufacturing methods (De Vries, 2005; Press & Cooper, 2002; Vincenti, 1990). The nature of technology necessitates designers to consider that each choice made and decision taken to solve a problem might, in turn, paradoxically create other problems (Mitcham & Holbrook, 2006).

1.1.3.3   Why expert designers[4]?

For many years, people generally believed that only a small fraction of adults achieve superior performance levels. They ascribed expert behaviour to innate and unique inborn talents that cannot be developed by experience or training (Ericsson, 2003; Prietula & Simon, 1989). This approach has since come under the scrutiny of researchers challenging the innate talent assumption. Resulting from an alternative view of expertise, namely the expert-performance approach (Ericsson, Nandagopal & Roring, 2005), the importance of environmental conditions, appropriate training and deliberate practice are currently emphasised. (Ericsson & Charness, 1999).

The implication of this changed belief seems clear when it comes to educational situations. In order to train novices to achieve some levels of expertise in domain specific fields such as designing, it appears necessary to consider, *inter alia*, what constitutes expert design behaviour. It therefore seems important to take note of the cognitive challenges that expert designers

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[4] Refer to section 1.5.7 for my conceptualisation of expert designers.

typically encounter in order to establish what design educators could strive for in novice design behaviour. Recent research in design education in general, and in TE specifically (Alamäki, 2000; Kimbell, Stables & Green, 1996; Owen-Jackson, 2000; Petrina et al., 2008), reflects on the limited recognition of intellectual complexities and resources demanded in the design process to support good design education (Haupt, 2011; Petrina et al., 2008; Rauscher, 2011).

I believe that by deepening researchers' and educators' understanding of how experts behave when structuring problems and developing design solutions, educational programmes can be developed that will be characterised by deliberate practices of accessing information and transforming knowledge. In this way, it may be possible to contribute to an understanding of how the transition may be facilitated between novice and expert designers in a more efficient way (Bennett, Harper & Hedberg, 2001; Christiaans & Venselaar, 2005; De Vries, 2005; Dorst, 1997; Ericsson, 2003). Thus, examining expert designers' behaviour, as an alternative, may provide different and potentially more apt insights and appreciation of design activity, which could be relied upon when developing models and methods of design education (Cross & Clayburn Cross, 1998).

1.1.3.4   Why early phases of the design process?

The early phases of the design process are widely considered as the stage in the problem solving space where cognitive dynamics are rife (Cross, 2001b; Goeld & Pirolli, 1992; Liikkanen, 2010; Visser, 2004). This phase iteratively connects with a conceptualisation and development of solutions to a design problem. As such, complex and dynamic higher order thinking is quintessential (Goel, 1995).

Designers typically apply critical and creative thinking skills (Liikkanen, 2009; Visser, 2004), constantly seeking appropriate information and applying domain independent and specific knowledge recalled from long term memory (LTM). They are constantly required to adapt their cognitive behaviour to new and non-routine situations (Gero 1999) due to the ill-structured nature of design problems. Shaping their ideas, designers will typically interpret a design brief to ascertain which social, technical and environmental aspects may constrain, limit and challenge them while directly perceiving the physical environment in which the problem is situated (Ferguson, 1992; Goel & Pirolli, 1992; Liikkanen, 2009; Simon, 1996).

1.2   RESEARCH QUESTIONS

This study was directed by three central research questions.

▪   How can applying mixed methodology strategies contribute to the validity of protocol studies in a design context? (Methodological contribution).

- How can a combination of IPS and ecological elements explain dynamic cognitive processes of expert designers in the early phases of the design process? (Theoretical contribution).

- Why is it necessary (or not) to combine computational-related theories with ecological theories in order to understand the dynamics involved in design processes? (Theoretical contribution).

These central research questions imply a relationship between the empirical and theoretical parts of the study. The potential way in which my empirical findings may (or may not) impact on theory of design cognition research implies a multi-directional relation between practice and theory. In order to address my central research questions, I situated my research within a semi-experimental setting, thereby studying design protocols[5] of three expert designers via research. I also examined research methodology via design protocol. As such, my research questions do not merely revolve around the connections between embodiment-related actions, knowledge and use of multiple symbol systems of designers with particular properties shaping the design problem solving space, but also around practice and theory of methodology.

In order to address the primary research questions, I was guided by the following secondary questions:

- To what extent does the interaction between the embodiment principles of affordance, perception-action, intention-attention and specification, and psychological characteristics contribute to the dynamics of the problem solving space of expert designers?

- Which kinds of thinking in the early phases of the design process mechanises interactivity between the inner and outer worlds of the participants?

- How does the internal-external interactivity influence the control of the vertical direction of participants' thought processes?

- What is the nature of the relationship between embodiment principles and continued attention to thoughts?

- How does a theory of interactivity influence symbol systems theory in a design context?

- How might an integrated framework contribute to the development of novice designers?

The **first central research question**, with its methodological focus, are supported by the first sub-question. By quantitatively establishing the extent to which interaction between ecological

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[5] The theory behind analysing classical think-aloud protocol (TAPS)(Crandall, Klein & Hoffman, 2006) studies is that by asking a person to simultaneously perform a certain task and "think" aloud one can gain direct access to that person's thoughts and hence the patterns and sequences of the thoughts required for the task (Ericsson & Simon, 1993). Words "thought" aloud in this manner are thus regarded as being unconstrained by the necessity to communicate (Lloyd, Lawson & Scott, 1995).

and internal processing aspects of design behaviour presents itself, and qualitatively describing and explaining the scope of the observable interaction, I aim to demonstrate validity of protocol studies, when studied in this manner. I aim to draw inferences from statistically determined sequences and distributions of embodiment principles that intersected with internal psychological characteristics in the early phases of the participants' design process. I further intend to explore instances of multiple interconnections between the various psychological characteristics contributing to and confirming the complexity in the dynamics of the design process.

The **second central research question**, which has a theoretical focus, are supported by a combination of sub-questions 2, 3, 4 and 5, with the aim of explaining the dynamic cognitive processes of expert designers in the early phases of the design process. By exploring the kinds of thinking which mechanises interactivity and how interactivity influences the control of decision making in the vertical development of thought processes I aspire to lay bare some of the dynamic cognitive movements involved in design work. In addition, I intend to find information demonstrating a possible causal relationship between the participants' involvement in embodiment principles and the duration of their thoughts about particular themes. Finally, due to the rudimentary role of sketches in design work, I plan to explore the role of symbol systems, in particular that of early phase sketches, in a theory of interactivity. I believe that design cognition might be better understood when all these sub-questions are considered in combination. In order to understand the complexity of design behaviour, I furthermore believe it is necessary to view it from various points of view, driven by various questions.

The **third central question** aims to seek information providing reasons for the necessity to combine ecological and computational theories to understand design cognition and subsequently support the development of novice designers. Building on the information provided by the first and second central questions, as well as on my belief in the close interrelationship between the ecological and internal aspects in designing, I will argue that the reasons provided in the findings of this study, may guide answering sub-question 6 and vice versa. Finding information regarding the manner in which experts integrate their inner and outer worlds, may therefore pave the way to formulating multiple contributions of the theory of interactivity as well as guide practical application thereof in the context of novice design education.

1.3   POTENTIAL CONTRIBUTIONS OF THE STUDY

Theoretically, the findings of this study may add to existing literature on design cognition in general. More particularly, I hope to contribute to the design problem solving space theory of Goel and Pirolli (1992) regarding psychological aspects involved in processing information

within ill-structured task environments. By investigating how designers' direct perception in the task environment may interrelate with characteristic design behaviour, I hope to extend existing theory. I may be able to conclude how designers consider multiple and cross-correlations and interrelationships between the various socio-technological knowledge (De Vries, 2005; Goel, 1995; Love, 2002) and embodiment principles (Anderson, 2003; Gibbs, 2005). This may in turn inform literature related to the influence of accessing and transforming such knowledge in particular stages of the design process into representations. My study may also contribute to the knowledge base of design studies of experts' ability to often and quickly switch types of cognitive activity (Cross, 2004) and use different modes of thinking (Ferguson, 1992) and representation. I thus hope to contribute to theory building in design research.

Methodologically, design cognition researchers generally propose that think-aloud-protocol studies are reliable experiments simulating real design situations (Crandall et al., 2006; Ericsson, 2006; Van Someren, Barnard & Sandberg, 1994). In my endeavour to keep this study's experiments as natural and real as possible, I investigated designers working in pairs, which seems to be common practice amongst modern practitioners, while I acted as the client, within a controlled environment. As such, the study implies a potentially innovative approach to researching design behaviour in controlled naturalistic environments.

Besides the theoretical and methodological contributions, my study may inform practice in the field of design professions encompassing domains as knowledge grows from practice. The practice of design *per se* is one foundation of design knowledge. However, it is not only the practice but the systematic and methodical inquiry into the practice that, in part, constitutes design research. By systematically exploring and explaining what design experts do and how they do it when involved in a practical design experiment, I may be able to model ways of implementing expertise in design education. On a practical level, this in turn may enable design and technology educators to devise courses of action aimed at monitoring and revising existing education principles and procedures.

Therefore, I hope to make a theoretical, methodological and practical contribution with this study. I will attempt to contribute to the understanding of what constitutes expertise in design (Cross, 2004), with the long term aim of developing educational models of how novice designers' cognitive behaviour may mirror some expert abilities (Ericsson, 1999). Design educators and curriculum policy makers may subsequently use the findings of this study to revisit their teaching methodologies/content of their courses in order to align training outcomes to that of design experts' abilities. Expert participants may also gain some self-knowledge and new insights into the design process and socio-technological systemic theory inferred from their design practice. For a summary of the foreseen contribution of my study, refer to Figure 1.1.
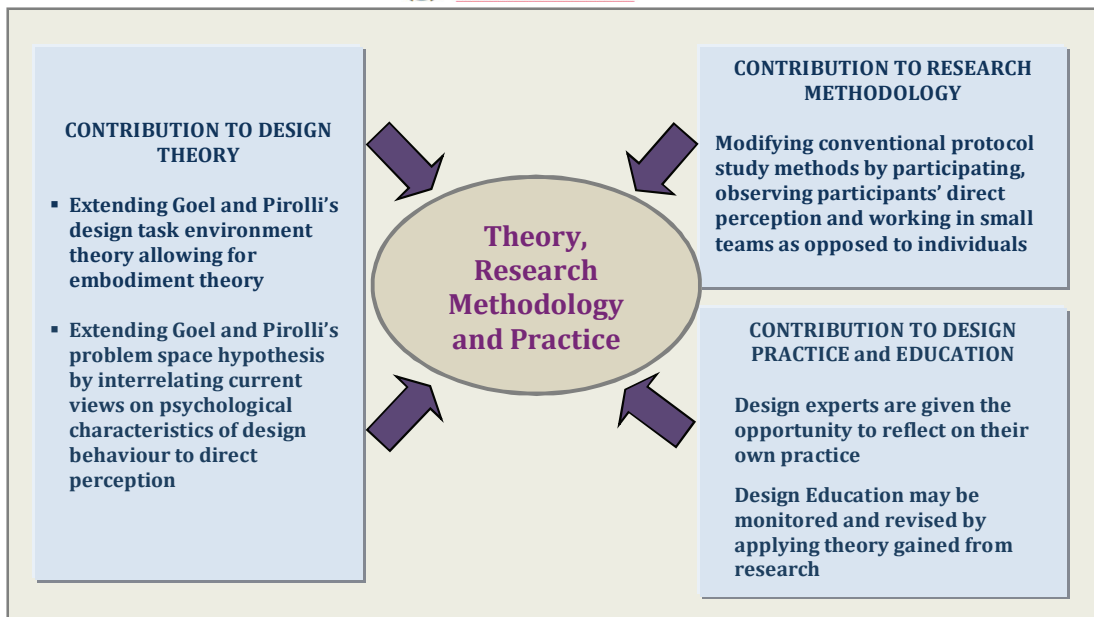
Figure 1.1: **Potential contribution of the study**

1.4 ASSUMPTIONS

Based on the literature in the fields of computational theories, embodiment principles and current extended cognition theories, I conducted this study assuming that:

▪ Designing involves a complex array of cognitive processes.

▪ The cognitive system is dependent on representations and operates in a cyclical manner from input symbols to output symbols, by mediating and manipulating symbols.

▪ Design problems differ from other types of problems. They are typically ill-structured and display their own unique set of characteristics impacting on the way designers think.

▪ Cognition is both internal and external. Information processing includes perceiving external information as well as internally located processes.

▪ Multiple types of symbol systems are used in designing which may be sequential, simultaneous and co-evolutionary in nature.

▪ Symbol systems and thought processes correlate with particular phases in the design process, and also influence one another reciprocally.

▪ External visual representations in a design context consist of unique characteristics which are different from external visual representations in other contexts.

▪ Designers' thought processes in the early phases of the design process can be investigated by studying their external representations focusing on socio-technological knowledge and embodiment principles.

- Participants would feel more comfortable when thinking in an environment as natural as possible, including investigating a real physical area related to the design problem, a working partner, as well as a client.

1.5   CONCEPT CLARIFICATION

In order to appreciate the purpose, focus and potential contribution of this study, it is necessary to understand the key constructs underlying the theory and assumptions of the study.

1.5.1   COGNITIVE DYNAMICS

Cognitive dynamics in this study refers to the generic way in which designers' thought processes manifest in the early phases of the design process. Thought processes are assumed to be influenced by the unique and ill-structured nature of design task environments (Simon, 1973) in order to conceptualise artifacts that could solve human problems and fulfil their needs (Goel & Pirolli, 1992). In particular, I add to this assumption the influence of perceptual stimuli on designers' flexibility to adapt to the design task environment.

As design problems are typically understated, designers need to access information in order to fully understand the requirements and scope of design tasks during the early phases of the design process. Designers access information by memory recall, as well as from perception of the physical environment as they structure the problem and generate preliminary solutions. These dynamic processes take place in a design problem solving space. Generic characteristics of such processes in the early phases of the design process include decomposing problems, forming abstraction hierarchies, using control strategies, generating and developing ideas through lateral and vertical thinking, committing to ideas and reversing direction of transformation functions (Goel, 1995).

1.5.2   SOCIO-TECHNOLOGICAL THINKING

Socio-technological thinking refers to the social and technological aspects that designers may consider during the design process. Designers typically require and use multi-disciplinary knowledge about the technical aspects of artifacts, social aspects of people, and the complex interaction between artifacts, people and the contexts in which artifacts are used (De Vries, 2006; Love, 2002). Such knowledge can facilitate an understanding of understated design problems and requirements of solutions, thereby suggesting solutions.

1.5.3 DESIGNING

The psychological characterisation of designing implies that one can generalise across intentional design procedures and tasks in different domains (Goel, 1984; Thomas & Caroll, 1979). However, although existing literature agrees in terms of this essential characteristic, much confusion in the theoretical and empirical accounts of designing exists. This confusion is present in the many definitions of 'design' that exist, often including notions yet not reflecting the complex nature of the act of designing (Visser, 2004).

I deem it is necessary to consider the concept 'design' from the context of its origins. The English word 'design' is a modern derivative of the Latin *designare,* denoting 'to 'mark or point out, delineate, contrive' (Mitcham & Holbrook, 2006, p.107), which implies a need for representation. As such, for the Greeks, human behaviour can be structured toward the production of material artefacts or nonmaterial goods signifying 'planned making or doing' (Mitcham & Holbrook, 2006, p.107), which implies goal oriented intentional or purposeful activity. This means that 'designing' implies having an intention[6] (Anderson, 2003; Simon, 1969) to solve problems or to fulfil the needs of people in a particular context by designing useful physical objects or artefacts that might change existing situations. Designing is therefore a knowledge-intensive, purposeful, non-routine, social and cognitive activity undertaken in a dynamic context (Simon, 1996) implying intention, flexibility and creativity (Mitcham & Holbrook, 2006).

In this study, I use the term 'designing' to refer to the notion of 'generic designing'. This notion implies firstly that an activity is conceptually and cognitively distinctly different from non-design activities. It is complex, requires flexibility of mind and adaptability to new situations. It further requires insight into intentions and alignment of particular information and knowledge with particular intentions. Secondly, when I use 'designing' it implies the possibility of abstracting 'designing' away from the specifics of a particular design discipline and can therefore be studied in its own right, on its own terms and within its own rigorous culture (Goel & Pirolli, 1989).

1.5.4 EARLY PHASES OF THE DESIGN PROCESS

The early phases of the design process refer to the cognitive phases of problem structuring and problem solving which typically occur during the beginning of the design process. Problem solving consists of sub-phases during which designers conceptualise a possible solution, add detail and refine solutions. To assist them in these processes, designers generate rough and

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[6] Intention is structured around two components, namely (1) a "psychological mode", or "attitude," and (2) the object or representational content of the attitude. This structure can therefore be defined as "representational content under a psychological mode" (Fodor 1981; Searle 1983). As such, each intentional state has direction of fit and conditions of satisfaction (Goel 1995).

ambiguous hand sketches, and rely on the physical environment in which a problem is situated to provide information (Goel, 1995).

During the early phases of the design process designers attempt to understand what is expected of them and determine the scope of the problem before they generate ideas that could solve the problem. Typical of this phase is the lack of information provided in design briefs, which lead to designers employing strategies to expand their knowledge base through questioning and direct perception. During the early phases designers furthermore link their existing generic and specific design knowledge vertically and laterally with newly acquired information through a complex process of intentional thinking, pattern recognition, and conduct control employing evaluative and normative thinking (Goel, 1995; De Vries 2005).

1.5.5 EXPERT DESIGNERS

In this study, 'expert' refers to the generic construct 'expertise' encompassing particular design disciplines. The concept 'expertise' denotes exceptional performance from which novices can learn (Christiaans & Venselaar, 2005). Essentially, expert designers exhibit outstanding critical thinking and visual thinking abilities, allowing them to access information and knowledge which they effectively transform into possible solutions (Vincenti, 1990).

Superior performances by designers are considered to be primarily acquired through many hours of deliberate practice and training spurred on by motivation, concentration, and the willingness to work hard on improving performance. In addition, experts seem to possess outstanding long term memories, exceptional insight and creativity which typically culminates in an automated process taking place on the non-conscious level (Cross, 2004; Ericsson, 2003; Ericsson & Charness, 1999; Simonton, 2003). In the context of this study, I considered experts as designers who demonstrate superior declarative and procedural knowledge and memory of domain, flexibility as events change and exceptional perceptual skills (Hoffman, 1992) (in section 1.9.4 I elaborate on how I selected the participants of the study).

1.6 CONCEPTUAL FRAMEWORK

The conventional Information Processing approach to protocol studies, studying design behaviour in a laboratory set-up, does not allow for observing designers in a naturalistic design environment. In addition, limited studies using think-aloud-protocol studies as a data gathering instrument include perception information accessing when reporting on the characteristics of the design problem solving space. Ericsson and Simon (1993) attribute this gap in the literature to the 'near' unmanageability of the large amounts of data that may be accumulated as a result.

In order to understand under which conditions problem solving spaces are shaped, I needed an underlying framework that could allow me to examine the influence of both the ill-structured nature of design task environments and perceptual stimuli. I subsequently expanded on the existing theory of problem solving space theory of Goel and Pirolli (1992), on which the framework of my study is primarily founded. I combined Goel and Pirolli's theory with elements from ecological psychology (Gibbs, 2005; Gibson, 1972). The manner in which I combined the said concepts and elements of the problem solving space theory and embodiment principles is summarised in my conceptual framework in Figure 1.2.
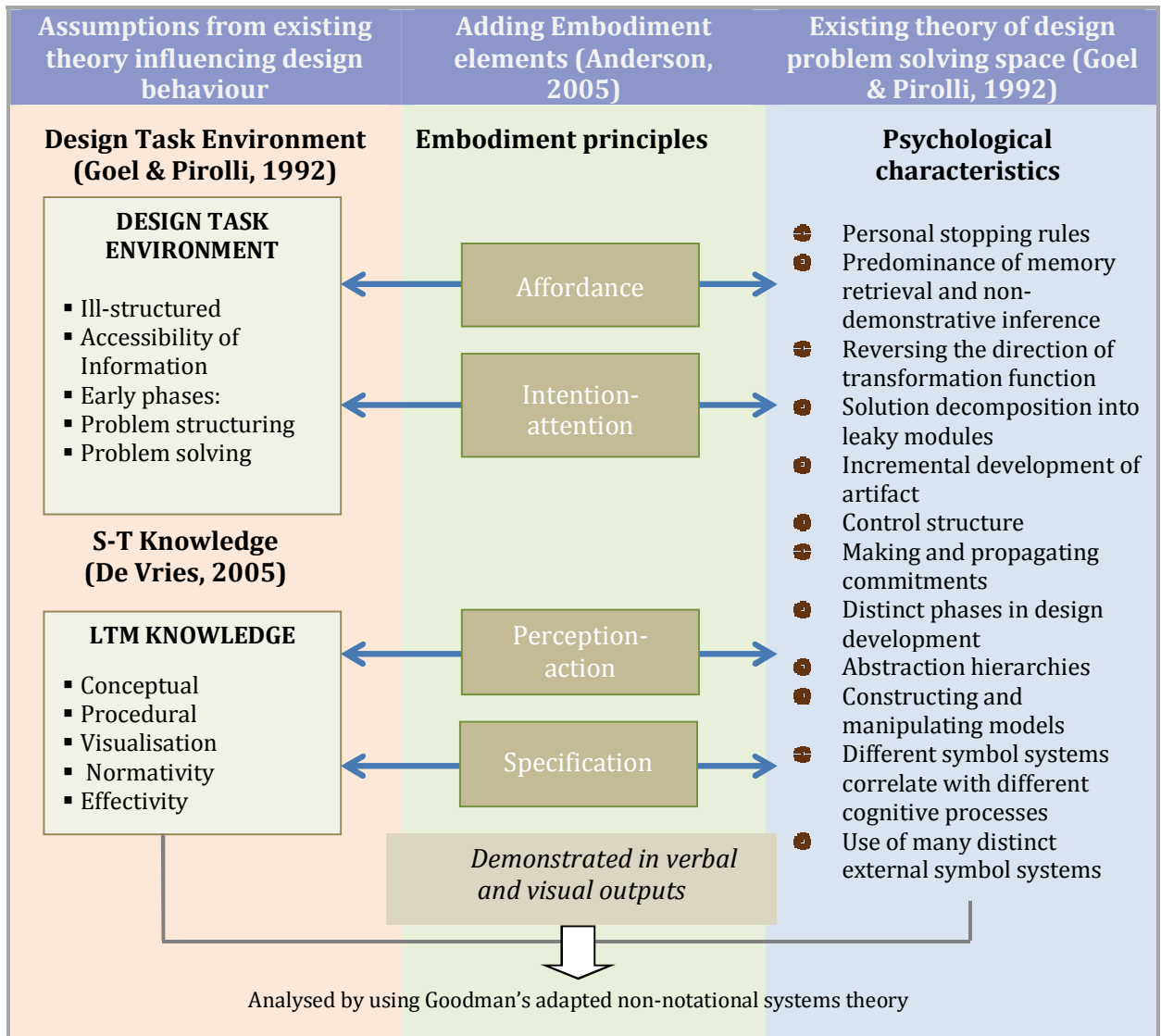
Figure 1.2:   Conceptual framework of the study

I thus relied on one branch of Computational Theories of Mind, namely the Information Processing System, as basic approach to my conceptual framework, focusing on representation of designers made during the early phases of the design process. The Information Processing System theory consists of three major theoretical constructs: (1) physical information processing system; (2) task environment; and (3) problem space (Goel & Pirolli, 1992), which I

explain in more detail in Chapter 3. The meta-theoretical assumptions underlying problem solving cognition assumes three states, namely a start state, a transformation or mediating state and a goal state (refer to Chapter 2). As this study focused on the early phases of the design process, I was primarily concerned with the start state and mediating state, and not with the goal state.

In interpreting my results, I used Goel and Pirolli's (1992) model for the psychological characteristics of the design problem solving space as included in column 3 of Figure 1.2. Information processing assumptions that are embedded in this model relate to design problems by nature being ill-structured and influencing the way in which designers access information, as well as the time it takes to solve problems (column 1 of Figure 1.2). In addition, the design problem solving space, also indicated in column 1, assumes that designers use socio-technological knowledge encompassing design domains which they access from their long term memories.

I believe that the system in which designers solve design problems could have the ability to connect (Gero, 1998) how designers access information that is not evident in the design brief to the physical environment within which the design problem is situated. Such a system would allow designers to use knowledge of the environment involved in the problem. I therefore extended the framework to include the embodiment principles of affordance, perception-action, intention-attention dynamics and the specification of information (Anderson, 2003; Gibbs, 2005). These principles represent some of the realities that ground ecological scale. They signify environmental facts of direct pertinence to stimulate designers' abilities to consider multiple inter-relational aspects influencing their decisions. I combined these elements with socio-technological knowledge to establish how the participants in this study adapted their behaviour from moment to moment according to changes in the problem solving situation (Ericsson & Simon, 1993).

I analysed and interpreted the verbal outputs generated by the participants, using the well-known theory of semiotics (Newell, 1980; Simon, 1969) to understand the structure and meaning of their thoughts. Due to the large amount of visual outputs generated when structuring and solving problems, I augmented the theory of semiotics with Goodman's (1976) idea of notational and non-notational systems, adapted by Goel (1995) for studying design sketches.

1.7   PARADIGMATIC PERSPECTIVE

In the following subsections I briefly introduce the world views that directed my study. These are contextualised in more detail in Chapter 4.

1.7.1   THEORETICAL PARADIGM

I view the world of 'design' as action, acknowledging that the mental processes involved in designing asks for multiple paradigms to fully appreciate the complexity thereof. My initial literature survey revealed an array of computational approaches, including information processing, each restricted to some subset of the totality of activities of human designing (Gero, 1999). In addition, the pilot study I conducted (refer to section 1.9.1) confirmed the necessity of examining and interpreting symbol systems from more than one point of view in order to answer the research questions. I therefore explored a variety of computational theories in an attempt to logically combine them with embodiment theories relevant to design behaviour.

Based on my specific area of research, I focused on the verbal and non-verbal symbol systems used by expert designers. As such, I relied on the phenomenology of semiotics, rooted in the ontology of representation, to examine the case of design cognition (Coyne, Newton & Sudweeks, 1993). My basic underlying overall belief was that designers work in both overt, rational and logic ways; and obscure and irrational ways, which are represented by the syntactics and semantics of their symbol systems. Although I used the principles of information processes as organising structure and its constructs as a-priori criteria for examining symbol systems, I acknowledge the fact that not all mental processes can be captured by representation and may be hidden in internal representations that cannot be accessed in an overt manner (Cross, 2001a; Goel, 1995). However, internal representation is not the focus of my study as I only examined external symbol systems used in the early phases of the design process. In Chapter 2, I explain my approach to symbol systems and in Chapter 3, I explain my selected theoretical paradigm in more detail.

1.7.2   EPISTEMOLOGICAL PARADIGM

In identifying the epistemology of socio-technological knowledge, I borrowed from the philosophical frame provided by De Vries (2005), Love (2002) and Goel (1995), discussed in section 1.6. Accordingly, in this study I viewed knowledge as involving symbol systems' semantic and syntactic relations to socio-technological knowledge stored in the long term memory and embodiment gained through direct perception. I was interested in where knowledge impacts on thinking, problem solving and representation. I further wanted to find out how different types of knowledge, in association with perceptual stimuli, may impact on the structure of thinking, problem solving and representation by designers.

I approached my study from a critical realist stance (Maxwell & Mittapalli, 2010), acknowledging specific realities co-constructed by designers and the societies they live and work in. A critical realist stance allowed me to "transform" my inquiry by using both theoretical subject matter and

practical activities (Shields, 1998)[7]. In Chapter 3 and Chapter 4, I elaborate on the epistemological paradigm I relied upon.

1.7.3   METHODOLOGICAL PARADIGM

For this study, I followed a mixed methods approach (Tashakkori & Teddlie, 2009), in order to empirically access the multiple elements involved in designers' cognitive processes in the study. When structuring problems and developing design solutions, the manner and frequency in which designers accessed and processed information in time yielded qualitative as well as quantitative data. I collected data by observing participants during the instances when cognitive processes became observable through their think-aloud-protocol studies tasks (Ericsson & Simon, 1993). In addition, participants generated sketches they made concurrently (Goel, 1995), which formed part of the raw data.

In following a mixed methods approach, I thus conducted a parallel QUAL + quan study (Creswell, 2003; Tashakkori & Teddlie, 2009), with the dominant part being qualitative, as indicated by capitalised letters. Quantitative data relates to the core quantitative data sheet on which time and frequency of instances of behaviour were recorded. Qualitative material consisted of words, pictures and their meanings, representing instances of cognitive behaviour. Quantitative data thus related to measurements of time, counts of utterances, distributions, sequences and values of density and ambiguity of symbol systems, which I interpreted both statistically and qualitatively. I aimed to identify the various phases of the design process. I individuated the psychological features characterising the different phases, identified instances where direct perception played a role, and where participants used socio-technological knowledge. I furthermore established instances where sketches supported the structure of thought processes and directional change of transformation in thought processes. For this purpose I used qualitative data, analysed some of the data in terms of simple statistical terms and concurrently transformed the quantified information back into qualitative interpretations (Morse, 2002). I quantified qualitative data, including the structural quality of sketches into quantitative information by grading values of density and ambiguity. Coding, analysing and interpreting the data qualitative and quantitatively enabled me to gain a deep understanding of my research problem (Johnson & Onwuegbuzie, 2004). I explain the methodological paradigm that I employed in more detail in Chapter 4.

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[7] The modern theories of designing as mental activity broke down the traditional divisions between theory and practice (Mitcham & Holbrook, 2006) as it existed in Greek culture where the philosopher was seen as engaging in contemplations and the artisan (e.g. sculptors and ship engineers) who were seen as being engaging in making (Shields, 1998). In this way techniques and theoretical concepts were united as a whole.

1.8   RESEARCH DESIGN

I used a case study design for conducting an adapted form of think-aloud-protocol studies as data gathering instrument. The reason for selecting a case study design was that it allowed me to study the phenomenon of design behaviour in depth and from multiple perspectives. Due to the determinant role context plays in protocol studies, I needed a design that would enable me to explore and explain each protocol on its own.

The primary characteristic of this research design was that some elements could be controlled while others were impossible to control. In Chapter 4 I explain the experimental features of this study in detail. In this section I broadly focus on the way in which I adapted the conventional verbal protocol study, which has proven to be a central instrument yielding scientific data, in the design context (Cross, 2001a; Goel, 1995) when conducted in the cognitive science paradigm.

During the 1980's and early 90's there was a large increase in the use of verbal data to study cognitive processes in various disciplines including psychology, education, and cognitive science. Since that time, concurrent verbal reports have generally been acknowledged as a major source of data on subjects' thought processes in specific tasks (Ericsson & Simon, 1993). Due to the fact that verbalisation cannot provide evidence of all the thoughts and thought structures when designing, design researchers became interested in the role visualisation in general, and particularly sketching, plays in aiding designers to think (Goldschmidt, 1991, 1994; Oxman, 2002). In his book *Sketches of thought*, Vinoid Goel (1995) provided evidence that design sketches, in addition to verbal protocols, are equally trustworthy as scientific data informing researchers about the structure of thoughts (refer to Chapter 2) when produced concurrently with the think-aloud-protocol studies (Chandrasekaran, 1997; Do, Gross & Zimring, 1999).

In this study, I requested the participants to produce both concurrent think-aloud protocols and sketches made simultaneously when completing their problem solving tasks. As such, generating verbal and visual data simultaneously had the advantage of aiding me to infer moment-to-moment cognitive processes underlying the actual concurrent sequences of thought (Ericsson & Simon, 1993). Designers' representations and actions in turn allowed me to gain access to their thoughts, accounting for moment-to-moment information processing. However, while conventional protocol studies are characterised by stringent experimental conditions, isolating individuals in unnatural laboratory settings (Lloyd et al., 1995), I allowed participants to work in small teams, engaging directly with the physical environment. In addition, I acted as participatory observer in my role as client, contributing to creating a naturalistic task environment that simulated real-world design environments.

1.9 BROAD OVERVIEW OF METHODOLOGICAL STRATEGIES

In this section I provide a brief overview of the methodology I employed. As an introduction, Figure 1.3 provides an overview of the basic research process and core elements.

ADDRESSING THE PRIMARY RESEARCH QUESTIONS

| 1. How can a combination of IPS and embodiment elements explain dynamic cognitive processes in the early phases of the design process (Theoretical contribution)? | 2. How can applying mixed methodology strategies contribute to the validity of TAPS in a design context (Theoretical contribution)? |

by

Applying an adapted form of a protocol study under semi-experimental conditions

and

Implementing critical realism principles

when — **when** — **when**

| **Conducting a pilot study** Testing theory and research methodology | **Selecting participants** Applying criteria for expertise | **Conducting preliminary interviews** |

and — **and** — **and** — **and**

| **Conducting a literature review** | **Collecting data** | **Capturing and documenting data** | **Analysing data** |
| - Information processing, symbol systems, design problem solving space theory, embodiment principles | - Literature study
- Generating verbal and visual data by conducting TAPS | - Verbal data: Transcriptions of video recordings + basic core time sheet
- Visual data: video recordings + original sketches
- Field notes | - Verbal and visual data
- Semantics & syntactics:
- A priori categories from conceptual framework |

Figure 1.3: **Overview of the basic research process and its core elements**

1.9.1 PILOT STUDY

Prior to collecting data for this study, I carried out a pilot study to test the suitability of the multi-methodological approach I adopted for this study. I conducted the pilot study in November

2008 with four design and technology education students (novice designers) enrolled for the module JOT210[8] at the University of Pretoria, taught by a colleague of mine. The module required students to solve a storage problem by designing a suitable artifact. I requested the students to participate voluntarily in think-aloud-protocol studies while simultaneously producing conceptual sketches. I video recorded their concurrent protocols while they were in the early phases of the design process, during which the cognitive focus was to structure the problem and generate preliminary ideas towards a solution (Goel & Pirolli, 1992).

The aims of the pilot study were multiple. Firstly, I attempted to confirm the suitability of my proposed research procedure. I wanted to find out whether or not it could perhaps make a difference (Ericsson & Simon, 1993) in the outcome of participants' final ideas if participants' talked to each other instead of only to themselves during talk aloud protocols. The reason why I wanted to test this idea was based on my assumption that participants might feel inhibited to speak to themselves. Secondly, I wanted to investigate whether original protocols were merely structured by input information, or whether they were indeed implicitly structured by the aims and goals of the design discipline (Goel, 1995; Oxman, 1995). References to concepts such as the design principles, design elements and design aspects as individuated by participants for their own purposes, could directly be related to the disciplinary motivations and goals of the technology education modules the participants are exposed to during the four years of their BEd programme. Thirdly, I aimed to determine whether or not my research methodology would allow me to focus on appropriate aspects to answer my research questions; therefore, whether or not my proposed methodology would allow me to observe in the best possible way, whether or not video recordings could be regarded as sufficient and whether or not I could integrate new ways of conducting protocol studies with conventional methods when undertaking this study (Cross, 2004; Gero, 1999).

I conducted the pilot study in a controlled environment, following the requirements of think-aloud-protocol studies (Ericsson & Simon, 1993). I video recorded the protocols in two recording sessions. Participants were requested not to discuss any of their preliminary ideas with others, and could only work on them during the recording sessions. They were not allowed to consult their lecturer for the duration of the recorded sessions. They were, however, allowed to do any research and bring information to the recording sessions that could help them structure their problems. Participants received their design briefs from their lecturer for their design project a week prior to the recorded sessions. I, as the researcher, therefore fulfilled the role of observer and did not guide their thinking processes. They were requested to talk aloud while they were thinking. They were not allowed to ask me (the researcher) any questions.

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[8] JOT210 is a second year module titled 'Design II' in the BEd (Senior Phase) programme offered by the Faculty of Education.

However, they could ask each other probing questions in order to stimulate idea generation and enhance the structuring of their problems.

The design tasks were designed in a way that physical investigation of the environment through direct observation did not form part of the pilot protocol study. I could therefore not ascertain whether or not experience of the physical environment influenced participants' thought processes. However, the transcription of the protocols and preliminary examination of the participants' concept drawings made during the early phases of their problem solving processes gave me an indication of the rigour and systematicity with which to execute my research for this study. I further learned from the preliminary examination of their transcriptions that the 'partnering effect' seemingly positively affected the use of socio-technological knowledge as well as the lateral and vertical direction of their thought processes, but did not make any difference to the decisions the participants took, which confirmed research findings in similar studies on expert designers (Cross, 2004; Ericsson & Charness, 1999).

Data obtained during my preliminary inquiry confirmed that the syntactic properties of the verbal data correlated with that of the visual data. In turn, I could deduct that the syntactic structure of the used symbol systems seemed to correlate with the phases of the design process, which confirms Goel's (1995) theory that a correlation exists between syntactic and semantic properties of concurrent verbal and visual symbol systems, verifying the cognitive phase of the design process during the time of representation. For this reason I decided not to test Goel's theory in my doctoral research project, as I initially wanted to do. Instead, it is now taken as one of the assumptions of my main study. Subsequently, I decided to focus on determining other potential influences, such as the ill-structured nature of design problems and perceiving the physical environment, as reflected in my secondary research questions.

1.9.2   PRELIMINARY INTERVIEWS

In addition to the pilot study, I conducted informal introductory interviews with potential participants of this study before commencing with data collection. The purpose of these interviews was to survey the field by testing the relevance of my research questions in order to affirm my rationale and conceptualise my study within the selected theoretical framework. During these interviews, all participants agreed on the fact that, in order to keep the protocols as naturalistic as possible, I, as researcher should participate in the protocols in order to enhance their thinking processes during the early phases of the design process. They emphasised the important role of perceiving the physical environment as part of the early phases of the design process.

These preliminary strategies enabled me to scrutinise literature informing me about how the current understanding of the nature of design cognition developed from classic computational approaches to current embodiment theories. This resulted in my initial understanding of the importance of design task environments including information internal to the design problem as well as information from the external environment that could be perceived by participants. Reviewing existing literature also allowed me to examine how theories about symbol systems and semiotic approaches developed from linear and rule-bound symbols (CTM related, discussed in Chapter 2) to flexible systems captured in the notion of notational and non-notational systems (Goodman's theory, 1976) (refer to Chapter 2). A preliminary literature survey enabled me to identify apparent limitations of existing research in design cognition. In addition, it contributed to my formulation of meaningful and appropriate research questions.

1.9.3   INITIAL LITERATURE SURVEY

In light of my definition for "designing" (refer to section 1.5.3), I explored literature related to the importance of expert design behaviour, highlighting the complexity of designing. In my initial selection of literature, I considered the important role that representation of information processing plays in structuring ill-structured design problems and preliminary problem solving in the early phases of the design process. I further consulted literature considering designing as a process of engaging with generic socio-technological knowledge. I searched for information that accounts for the multiple symbol systems used by designers in rational and irrational ways. I further considered literature focusing on studies of expert design behaviour, the relations between the different phases of the design process and the properties of the symbol systems designers use (Goel, 1995). Finally, I explored literature explaining designing as interactive representation (implying action-reaction cycles stimulated by direct perception) (Anderson, 2003; Richardson, Shockley, Fajen, Riley & Turvey, 2008). This view accounts for the way designers cognitively move (Cross, 1984; Ferguson, 1992; Gero & McNeill, 1998; Goel & Pirolli, 1992) in design task environments when directed by information and knowledge (Love, 2002) at their disposal.

These subfields of interest in design cognition contributed to my understanding of the uniqueness of the type of thinking that is typically associated with designing (Cross, 2007a; Simon, 1996; Vincenti, 1990), highlighting the different cognitive processes and mechanisms involved in designing (Goel & Pirolli, 1992). Furthermore, insights from my initial literature survey on the development of symbol systems into a notation systems theory enabled me to understand the potential usefulness of the notion 'notational systems' (Goel, 1995; Goodman, 1976) for the study of design cognition and how this might influence the design problem space. From examining the way in which the information in a problem statement influenced the

reasoning process of experts during the pilot phase, I could determine where and how affordance, perception-action, intention-attention and specification of information (Bickhard, 2008) potentially influenced the direction of thought processes. Furthermore, I was able to observe the actual relation of the properties of different symbol systems to particular mental states of designers. Although, at the initial stages of this research, I considered examining the role of voice data, such as voice tones and syntactic correlations with the mental stages during the early phases of the design process, during the pilot study I did not find this to significantly enhance other data types. Similarly, examining bodily gestures did not seem to add new directions to what was already found in existing studies.

The preliminary stages of my study entailed documenting my reflections and critical questions in my research diary (refer to Appendix K). This provided me with emerging insights in the complexity of design cognition theory. I also recorded my preliminary ideas about possible integration of theories and the implications for my research design. These ideas then served as initial grounding of the introductory interviews with networking partners as well as with the participants.

1.9.4   SELECTION OF PARTICIPANTS

I purposefully identified three potential expert designers from three randomly selected design domains, namely architecture, mechanical engineering and industrial design. Designers from these domains are considered as prototypical of the designers from various disciplines. Potential experts were identified using the theory of expertise as criteria (refer to Chapter 4).

I accessed the experts by approaching professional and academic institutions that I know through my personal association with design associations and through my work as fulltime lecturer in design and TE at the University of Pretoria. I relied on introductory interviews to clarify the roles of the participants and myself (the researcher). We also discussed the practicalities involved in establishing a natural task environment. All three participants wanted to work with 'thinking' partners, who could contribute to their natural way of thinking. Two of the participants agreed to work with one partner only, while the third participant requested to work with two of his regular 'thinking partners'. By deciding on design pairs/teams I managed to neutralise the possible effect of experts' individual personal design styles, priorities, motivation and the possible effect of personal psychological aptitudes on the objectivity of the data obtained (Reffat & Gero, 1999). I further agreed, on the participants' request, to take on the role of 'client' who would present the participants with a design task each, and provide additional information about the context of the problem participants had to solve. This decision added authenticity to the task environment.

I subsequently employed three protocol studies with three small teams of expert designers. The first team consisted of two architects, the second team of two systems engineers and the third team of three industrial designers.

1.9.5   DATA COLLECTION

My primary data collection strategy was the construction of think-aloud-protocol studies including participants' original conceptual sketches, captured in a semi-experimental setting. Initially I planned to conduct the protocol studies in a true experimental fashion, where the relationship between the researcher and the participants would be purely objective (Guba & Lincoln, 2008; Simon, 1996). However, as indicated earlier, I adapted the conventional true experimental nature of protocol studies in order to enhance naturalistic behaviour from participants (refer to Chapter 4). Enhancing their natural behaviour contributed to eliciting normal and undisturbed structures of the participants' thoughts and sequences of action. This changed my role to that of modified dualist, which is in line with my critical realist stance to this QUAL-quan type investigation (Cohen, Manion & Morrison, 2007; Guba & Lincoln, 2008).

I used the standardised method for conducting think-aloud-protocol studies protocols, which consisted of five steps, collecting verbal as well as visual data. Step 1 entailed preparing the three design briefs consistent with the requirements of ill-structured design problems, ensuring consistency in difficulty and the length of time it would require to complete. The tasks were designed to fit each of the participating groups' field of specialisation, namely architecture, mechanical engineering and industrial design. Each group was required to design an artifact that would solve a different need on the campus of the University of Pretoria and take between two and three hours to complete. Step 2 involved preparing the setting to enhance effective elicitation of expert design behaviour. Participants were welcomed in a studio where they received instructions to think aloud and make sketches. They were introduced to the camera technician, procedures were explained and they were asked if they needed a period of practicing the procedure. Participants subsequently studied their design briefs, when the video recording started. This was followed by step 3 that involved a period of physically exploring the terrain in which the problem was situated. Step 4 commenced after completion of the physical exploration. Two of the groups returned to the studio on the campus, where they started and completed the remainder of the problem solving process in this venue, while the third group went to their own private studio close to the campus where the researcher and camera technician joined them until the task had been completed. I did not interfere with their pace of thinking, or with participating in arguments, but only provided information on request.

The think-aloud-protocol studies provided quantitative and qualitative verbal data in parallel. Capturing the complete protocols on digital video format provided quantitative data in terms of

temporal information as well as qualitative visual information regarding gestures, processes and layers of thinking, supporting verbal data and sketches. The original sketches in turn provided qualitative data regarding the meanings and structure of participants' thought processes. In addition, I relied on my research diary, recording my observations and reflections during all the phases of research process. An important part of the data collecting phase of the research was the process of transcribing the verbal protocols captured on video. In addition, I made copies of the concurrent sketches made by participants as preparation for data analysis.

1.9.6   DATA ANALYSIS AND INTERPRETATION

Data analysis and interpretation commenced after completion of the recording of the protocols. In applying the principles of the selected critical realism stance (Danermark, Ekstrom, Jakobsen & Karlsson, 2006; Maxwell & Mittapalli, 2010). Both processes relied on the theory underpinning the conceptual framework of this study. I started data analysis by creating a core quantitative data sheet providing the textual transcriptions of the protocols indicating temporal measurements of instances and utterances. Secondly, data analysis involved extensive data structuring in terms of well described technical rules (refer to Chapter 4) derived from the conceptual framework. These rules provided a framework for preserving the quality of the study. In Table 1.1, I summarise the basis for the verbal and visual data structuring and subsequent coding I applied.

Table 1.1:   Theoretical basis for analysing and interpreting data

Structuring the design task environment	Design problem solving space theory	Socio-technological knowledge	Embodiment principles
Identifying the following cognitive phases of the design process (Goel & Pirolli,1992): • Problem structuring • Problem solving	Identifying characteristic psychological features modelled by Goel and Pirolli (1992): • Abstractions hierarchy • Control strategy • Commitment • Personal stopping rules and evaluation function; • Constructing and manipulating mode; • Develop artifact • Memory retrieval and inference • Reversing transformation direction	Identifying generic types of knowledge identified by de Vries (2005): • Conceptual knowledge • Procedural knowledge • Visualisation • Normativity • Efficiency and adequacy	Identifying instances when embodiment principles relevant to direct perception (Anderson, 2003) played a role: • Affordance • Perception-action • Intention-attention • Specification of information

I executed a preliminary content analysis based on time, cognitive phases and the mode of output. I incrementally and systematically added levels of analysis based on the a-priori categories provided by the conceptual framework of the study. Building on my conceptual framework therefore entailed analysing data in stages determined by the levels summarised in Table 1.2.

Table 1.2:   **Levels of data analysis building on the conceptual framework of the study**

Level	Variables
Level 1:	Cognitive phase + mode of output (verbal or visual)
Level 2:	Cognitive phase + mode of output (verbal or visual) + Psychological characteristics of the DPS
Level 3 (a):	Cognitive phase + mode of output (verbal or visual) + Psychological characteristic of the DPS + embodiment
Level 3 (b):	Cognitive phase + mode of output (verbal or visual) + Psychological characteristics of the DPS + socio-technological knowledge
Level 4:	Cognitive phase + mode of output (verbal or visual) + Psychological characteristics of the DPS + embodiment + socio-technological knowledge

I analysed verbal and visual data sets, relying on the theory of notational and non-notational systems (Goodman, 1976). Analysing the data involved comprehensive and systematic structuring to individuate the variables indicated in Table 1.2. Verbal and visual data each required their own coding trees guiding me through the analysis process. I therefore created separate coding trees for analysing verbal and visual data prior to the analysis by using Goel's (1995) analytical methods. Together with my theoretical notes in table format, using coding trees assisted me in reducing the large amounts of data in manageable chunks. Subsequently, I conducted detailed thematic analyses of the transcribed video recordings and sketches.

The final analysis was directed towards the emergence of instances, correlations between instances and the different phases of the design process. I further focused on transformations (processing) of semantics and syntactics, and interrelationships between themes. My interpretations relied on quality inferencing techniques (Maxwell & Mittapalli, 2010), as described in Chapter 4. I connected my interpretations with existing theory of design problem solving space and relevant embodiment theory in order to understand the role of participating researcher, thinking partners and socio-technological knowledge in the cognitive dynamics of expert designers in the early phases of the design process.

1.9.7   ETHICAL CONSIDERATIONS

During all phases of my research I considered research ethics, ensuring that I would not harm participants in any way. Participants were not deceived in any manner and were fully informed of my intentions, procedures and quality controls (Ericsson, 2006). I obtained informed consent

from participants prior to commencing with my study. Participants had the freedom to withdraw from the study at any stage (Cohen et al. 2007; Denzin & Lincoln, 1994). In addition, I took all measures possible to ensure equal spread of benefits to the research profession and design education fraternity. I also followed the guidelines in terms of confidentiality, anonymity and privacy. In Chapter 4, I elaborate on the strategies I employed in order to address ethical requirements.

1.9.8 REFLEXIVITY

Throughout the process of this research, I reflected in my research diary (Denzin & Lincoln, 2008). My reflections were primarily guided by my literature review, checking my arguments and trail of thoughts against my research questions and consulting with experts in the field of design research, as well as with my supervisors. On-going reflective conversations with practitioners, researchers and my supervisors served as useful strategy in establishing a firm grasp of the implications of the conceptual framework of this study, while an on-going literature review enabled me to confirm the position of my study in terms of the broader field of design research.

Visualising abstract concepts (Cohen et al., 2007) in my reflective diary included drawing concept maps. Organising and structuring the development of my understanding of the field and the findings of this research involved categorising and classifying information in tables and diagrammes (Crandall et al., 2006). Consulting with statisticians to discuss ways of processing qualitative data into quantitative information (Tashakkori & Teddlie, 2009) that could inform my study, contributed to accuracy and precision of creating codes and analysis procedures.

1.9.9 QUALITY CRITERIA

During the research, I aimed to address methodological challenges inherent to design protocol studies to add rigour to this study and to improve the quality and trustworthiness of my results. I adhered to the principles of qualitative and quantitative studies, embedded in the mixed method approach I followed. In particular, I relied on the requirements for drawing quality inferences based on theory (Onwuegbuzie & Teddlie, 2003). However, employing adapted think-aloud-protocol studies also required some flexibility, allowing me to capture and report on the complexities and multi-facetedness of the particular social phenomenon I researched (Creswell, 2003; Guba & Lincoln, 2008; Tashakkori & Teddlie, 2009).

Based on the methodological mixing, which required an inductive-deductive reasoning cycle (Tashakkori & Teddlie, 2009), I aimed to ensure quality by combining relevant criteria appropriately. In adhering to the demands of think-aloud-protocol studies (Ericsson & Simon,

1993), implying mixed methods, I strived to achieve inference quality. This means that I aimed at achieving a logic and appropriate integration (Onwuegbuzie & Collins, 2006) of rigorous and systematic qualitative and quantitative research strategies by attaining inference quality and inference transferability (Tashakkori & Teddlie, 2009). I attempted to accomplish this through a process of making meaning through systematic linking and interpreting findings (described in detail in Chapter 4), together with explicating the appropriateness of each step.

For the quantitative part of this study, I made use of basic descriptive statistical methods, ensuring reliability and validity of coding, interpretations and results. I strived to obtain internal consistency through inter-coding reliability (Morse, 2002). For the qualitative component of the study, I aimed to adhere to trustworthiness (Denzin & Lincoln, 2008) by continuously and systematically ensuring that the quality of the inputs (quality of data with an empirical foundation, research design and data analysis) was high by talking to my supervisors, colleagues and external supporters. I essentially strived to adhere to general core quality criteria by formulating research questions with future application value, based on their relevance and meaningfulness in contributing to existing design theory (Blessing & Chakrabarti, 2009; Dogan & Nersessian, 2010). In addition, I reported on my research process in an understandable manner; using my conceptual framework as terms of reference (Onwuegbuzie & Collins, 2006). I identified the challenges and potential limitations of my study and reflected on possible researcher subjectivity. This means that I acknowledged and reflected on the value-ladenness of facts (Maxwell & Mittapalli, 2010). I furthermore established and maintained relationships of trust between the participants and myself to the advantage of this study.

1.10   STRUCTURE OF THE THESIS

This thesis consists of seven chapters. In Chapter 2, I continue to discuss the theoretical concepts in design cognition literature which form the backdrop of the conceptual framework of the study. I discuss different approaches to studying design cognition, in particular the issue of representation. Literature alludes to the fact that computational approaches on their own are limiting and do not allow for studying the complexity of design cognition and the multiple types of symbol systems used by designers. Therefore, alternative approaches to studying symbol systems, as well as alternative theories for modelling cognition from an ecological point of view have been suggested. Building on discussions in Chapter 2, Chapter 3 entails a description of the conceptual framework, which consists of an integration of computational and ecological elements. In Chapter 3, I explain how conventional information processing theory allowed for integrating embodiment by considering this as part of the design task environment. Furthermore, I explain the validity of analysing sketching in addition to verbal data as indication of the structure of thought processes.

Chapter 4 provides a detailed discussion of how the study's research design, paradigmatic framework, sampling, instruments, validity issues, data generation and data analysis were conceptualised and conducted. The chapter concludes with ethical considerations taken into account and the role of reflection. Chapter 5 consist of a report of the quantitative findings, explaining how the data were interpreted. Chapter 6 contain a report on the qualitative interpretation of verbal and visual data. Both Chapters 5 and 6 provide the theoretical underpinnings related to the inferences I made to answer the research questions and situate the findings in current design cognition literature. In the final chapter of the thesis I conclude and make recommendations. I discuss the main findings in the light of the guiding research questions, literature and conceptual framework, and provide recommendations for developing design and Technology Education training programmes mirroring elements of expert design cognition.

1.11   CONCLUSION

In this chapter, I introduced the reader to the problem of design and Technology Education in general and in particular to the apparent insufficient appreciation of the cognitive demands involved in Technology Education in South Africa's national curriculum documents. I furthermore explained the limited application of empirically tested expert design behaviour when designing Technology Education curricula as underlying rationale for this study. I justified my focus on cognitive dynamics, socio-technological knowledge and the early phases of the design process, all of which relate to the requirement of designers to be flexible and able to adapt to changing circumstances during the design process. Relating these justifications to the rationale of this study, I subsequently presented the research questions, providing its purpose and possible contribution to the design research community, design and technology education, and design professionals.

By summarising the assumptions and clarifying concepts related to design cognition theories, symbol systems theories and embodiment theories, I introduced the reader to the conceptual framework of this study. I provided a broad overview of the paradigmatic perspective, and related my choices to the research design and methodological choices I made. I presented an overview of the research methodology and strategies against the background of grounding activities including a pilot study, preliminary interviews, literature survey and my selection of participants. In Chapter 2, I present key debates current in design cognition literature, framing the meta-theoretical issues underlying this study.

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CHAPTER TWO

Literature Review:
Alternative views of design cognition

2.1 INTRODUCTION

The purpose of this chapter is to explore three central arguments on expert designers' application of cognitive dynamics in the early phases of the design process which provided direction to this study. The complexity and richness of the cognitive processes involved in designing and the scale and density of all-inclusive descriptions or explanatory theories of how objects are designed necessarily creates methodological problems for researching design cognition (Stacey, Eckert, Earl, Bucciarelli & Clarkson, 2002). The implication is that design researchers are forced to focus on limited subsets of phenomena. The multiple interpretations possible for the same set of data, such as in a study conducted by Cross, Christiaans and Dorst (1996) provides evidence of the dilemma that design researchers typically face. In this study, I was interested in knowledge and embodiment as represented in verbal and visual data produced by three groups of designers. Therefore, for practical reasons, I focused on what happened in the early phases of the participants' design processes up till the stage where they conceptualised a preliminary solution to their design tasks. I did not consider what occurred during the later stages of final development and refinements of prototypes, although I acknowledge that much can be learned about design cognition in these later phases.

In order to understand the observed behaviour through the filter of my interests, in this chapter I discuss current debates around the application of alternative theories in design cognition, including computation, representation and the concept ecology (embodiment – discussed in more detail in Chapter 3). The aim of the current chapter was thus to theoretically combine two primary approaches to design cognition, namely computation and ecology, which could in turn contribute to the empirical part of the study.

Current design cognition debates include discussions on aspects such as representation, characterising the multi-faceted and confusing nature of design processes, as well as possible classifications and characteristics of design knowledge. Debates are embedded primarily in two different theories, namely computational theories (founded in a positivist approach) and ecological theories (founded in a constructivist approach). In this study, I attempted to combine the two approaches, instead of opposing them to one another. I believe that design processes contain certain linear and predictable elements, as well as unpredictable and nonlinear elements which should rather be described than prescribed (Blessing & Chakrabarti, 2009).

One of the primary debates in both classic computational literature as well as current constructivist approaches revolves around the role, nature and structure of representation (Anderson & Lebiere, 2003; Cardella & Atman, 2006; Gomilla, 2008) in cognition. Although I found some attempts at hybrid modelling of design processes in the literature I reviewed (Cross, 2004), there seems to be limited reporting on studies focusing on the integration of ecological

principles in existing theory about the problem solving space. Furthermore, reporting on the acquisition and processing of socio-technological knowledge encompassing computational and embodiment approaches seems limited. In creativity studies, two primary debates related to the way in which existing domain specific knowledge influence designers' ability to think creatively is on-going. The first view focuses on the need for existing information to be used as basis for generating ideas. The second view focuses on the connection of divergent memory categories to expand knowledge (Kilgour, 2006) . In dealing with experts in this study, I assumed that extensive domain knowledge formed the basis of the participants' design problem solving strategies and that the generic process of structuring problems and generating and developing ideas were infused with such knowledge (Sternberg, 1999). My interest in the role of domain specific knowledge involved the possible patterns in expert divergent internal thinking processes when applying and processing existing domain specific knowledge while constructing connections with perceivable external information embodied in task environments. Engaging in these processes could potentially lead to the participants' articulating their intentions, committing themselves to conceptual and procedural solutions and transforming their ideas (Goel, 1995) in their thought processes.

Many theorists and researchers agree that no designing can take place without designers representing their knowledge of the world (e.g. when considering design aspects related to people, objects and contexts). Such agreement is often, however, based on a superficial recognition of the particular nature of the represented situation and significant role it plays in the cognitive processing of information. In addition, a lack of deep understanding of the psychological mechanisms (Goel, 1995) mediating interaction between the 'world' and designers when expressing their views of the world through selection (Anderson, 2003; (Richardson et al., 2008) and decision making, also seem evident. As far as addressing the nature of knowledge and its role in design cognition, much research from domain specific perspectives have been conducted (Popovic, 2004), yet limited reporting has been done from a generic design perspective (Goel, 1995).

In this chapter, I set out to explain how conventional computational theories of cognition and representation on its own may fail to explain the complex phenomenon of design cognition and the particular role representation plays. I subsequently discuss the notion 'design cognition' as a discipline. Related to this, I discuss the contribution of critics of conventional Information Processing Systems (IPS) theory, such as Goodman (1976), who adapted conventional symbol systems theory into what he called 'notational and non-notational systems theory'. Building on these notions of Goodman, and expanding on IPS theory, I also discuss Goel and Pirolli's (1992) design problem space hypothesis which identifies invariant features of the problem spaces determined by the unique nature of design task environments. I explain how Goel and Pirolli's

problem space hypothesis seems to resonate with ecological theories of interactive representation. I explain the representational concepts of notational systems, design cognition concepts, the concepts of design task environments and the general characteristics of design problem spaces. Finally, I explore how meta-theoretical underpinning of selected embodiment principles, may explain design cognition in an alternative way. Following my discussions in Chapter 2, I discuss the potential role of knowledge and embodiment in shaping the design problem solving space (DPS) in Chapter 3.

2.2   HISTORICAL PERSPECTIVE OF RESEARCH IN DESIGN COGNITION

A desire to 'scientise' design can be traced back to ideas in the twentieth century modern movement of design (Visser, 2004), when theorising about design and designing started taking place. During this time, the design community aspired to 'scientise' design as a result of the industrialisation and integration of scientific knowledge in the design of new products such as motor car engines, steam engines and electric globes (Visser, 2004). Researchers regarded scientific knowledge as integral part of designing products.

The urge for 'scientising' design re-occurred during the 1960's with design theorists arguing that in order to construct new objects designers need an objective and repeatable design process. The implication of this argument was the abandonment of intuitive design processes (Cross, 2001b). Since the 1960's, researchers started reflecting on the fundamental concepts of design cognition attempting to understand the nature of designing.

The interest in design cognition lead to researchers reflecting and debating on the more fundamental and philosophical approaches to generic design methods for which they eventually turned to the psychological underpinnings of design behaviour (Love, 2000, 2002). A growing understanding of design activity as problem solving lead to insights into the unique nature of design problems having a determinate relation to the way in which designers 'know' and 'think' (Goel & Pirolli, 1992; Simon, 1973). By exploring its epistemology in terms of the underlying psychological aspects involved in design processes, a philosophy for design was being cultivated on which this study may build and expand.

In his seminal work, *Sciences of the Artificial* which was first published in 1969, with the latest edition published in 1996 (Simon, 1996), Simon suggested a close relationship between the nature of design problems and the complexity of design processes. The distinction between well-structured and ill-structured problems (Cross, 2007b; Goel & Pirolli, 1992; Reitman, 1964; Simon, 1973) and the classification of design problems as ill-structured problems (Goel & Pirolli, 1992; Simon, 1973) is central to my study. I believe that design problems are different from non-design problems and are characterised by the relationship between the availability of

information, the nature of the symbol systems used for representing and the complexity of design processes. I further believe that particular generic characteristics of design cognition exist (Goel & Pirolli, 1989), irrespective of the design discipline or type of artifact resulting from the process.

The outcome of the emerging consideration of psychology in design was a set of theories regarding the cognitive landscape of designing, which Cross (2001b, 2007b) labelled a 'designerly way of knowing'. The primary meta-approaches to studying design methodology or design cognition at the time were the positivist approaches dominated by classic computational models, including connectionism and dynamism (Bickhard, 2008; Coyne et al., 1993; Van Gelder, 1995) branching into representational and symbol systems theories. Of importance to my study is the second phase in modelling design processes, generally known as 'descriptive' models, which emerged from 1966 to 1973, which I discuss in more detail further on.

Currently some evidence of hybrid models, encompassing computation and ecology, experimenting with gains and benefits of both main approaches are emerging (Bickhard, 2008). Current debates attempt to pull together both ends, aiming to exploit the best of both worlds. However, little contradiction among findings of empirical research seems to be prevalent, not because findings are confirmed, but rather because they all address something different (Blessing & Chakrabarti, 2009). One of the aims of this study is to confirm that the use of discipline independent design knowledge (De Vries, 2006; Love, 2002) may offer the opportunity to build a conceptual bridge between Goel's post-modern adaptation of positivist IPS theory (Goel, 1995; Goel & Pirolli, 1989, 1992) and the constructivist theory of embodiment (Bickhard, 2008; Gibbs, 2005; Richardson et al., 2008). In this study I draw on the agreement that symbolic activity and representation is important in the design problem space. However, what these theories do not account for is the role of embodiment in the goal and mediating state of the problem solving space. In the following section I discuss the historical development of the notion of multiplicity of symbol systems, resulting in a theory of notation (Goodman, 1976) as opposed to that of symbol systems against the background of CTM (Goel, 1995). In the subsequent section I explain the meta-theoretical core of embodiment and argue why it is important to include this in an investigation of the characteristics of the early phases of design processes.

2.3   COMPUTATIONAL THEORIES OF MIND (CTM)

As the notion of 'representation' and the development of theories around it are central to understanding design cognition (Anderson, 2003; Simon, 1969), I commence by discussing the history of events that lead to symbol systems theories which relates to the development of a

theory of notational systems by Nelson Goodman. Thereafter, I discuss how Vinod Goel adapted Goodman's theory thus explaining my understanding of design cognition.

2.3.1   DESIGN COGNITION

The classic computational approach to cognition is based on the Cartesian notion of a theoretical duality of mind and body. Thinking about himself as a 'thing', rather than as 'body', the mind is considered as the real person, whose body may or may not exist with the mind being able to outlive the body. This sharp separation between mind and body has come to be known as Cartesian dualism (Robinson, 2002). However, despite Descartes defining this ontological distinction, he did insist that empirically these two components form an empirical unity and interact. Consequently his view is sometimes also known as interactionism. This view subsequently resulted in the positivist approach to cognition known as classic CTM, where human intelligence was compared with machine ('thing') intelligence (Simon, 1996).

'Computation' became popular in the early 1960's with concepts of representation and computation central to its modelling intelligence and problem solving. In these classic models of the mind, human intelligence is compared with a von Neumann structure (Anderson, 2003). As such, cognitive processing is linked to the computational manipulation of representational inner states (Bickhard, 2008; Goel, 1995; Newell & Simon, 1972). The standard classic model of representation requires a centralised representational medium (Bickhard, 2008), or a language of thought (Fodor, 1981) in which information can be represented and computations carried out according to rules. According to classical cognitivism, symbols are stored in the memory which are retrieved and transformed by means of algorithms that specify how to compose them syntactically and how to transform them. The proposed systematic and inferential coherence of human thought, among other things, results in a working hypothesis that an inference will provide the best explanation of thought processes (Fodor & Pylyshyn, 1988). Underpinning this notion is the idea that thought can be understood as some form of logic-like inferential processing system (Goel, 1995; Richardson et al., 2008). The result of endorsing computational classicism is accepting the notion of detachment of central cognitive processes from the perceptual and motor systems.

Computation further assumes that cognition includes rule-governed manipulation of symbols that Newell and Simon's (1972) *Physical Symbol System* epitomises. Classic CTM cognitive theories involve state-dependent systems operating in (mental) space. This means that the cognitive system consists of a set of properties that changes over time interdependently (Simon, 1996). The nature of the change in any member of a particular system depends on the state of the members of the system at that time (Van Gelder, 1995). According to this view, cognitive processing in turn involves internal information carrying states that mediate cognitive

processing. This computational approach to cognition led to the notion that human behaviour is dependent on internal processes based on rational, systematic and linear planning (Miller, Galanter & Pribram, 1960). It follows that a plan is believed to consist of a list of instructions that can control the order in which a sequence of operations is to be performed, implying a linear and sequential process.

In time, computation became known as the notion of 'artificial intelligence' (AI), referring to the human brain operating like a machine. This initial view resulted in the now generally agreed upon notion that some sort of information-carrying state internal to a cognitive system exists (Newell & Simon, 1972; Peacocke, 1995). Modern advocates of these theories include Simon's primary contributions in his book *Sciences of the Artificial* (Simon, 1969, reprinted in 1996), which served as basis for Goodman's (1976) notational theory, as well as Goel and Pirolli's (1992) problem solving space hypothesis.

These 'machine' theories constantly evolved towards a more sophisticated (Goel, 1995) image of the world of designers. For example, Coyne's metaphoric connectionist accounts for design cognition (Coyne et al., 1993). Until recently, connectionism was considered by some as a major alternative approach to cognition. However, despite different technical terminology, connectionism attempts to explain cognition in terms of the computational manipulation of sub-symbols, according to statistical rules (Van Gelder, 1995). This results in drawing connectionist networks. As such, connectionism can be considered as a form of cognitivism, in spite of the obvious architectural differences between symbol systems and networks and can, as a result, not be viewed as a proper alternative approach to cognition. However, the connectionist debate apparently seems beneficial insofar as contributions have added to some empirical gaps at algorithmic levels of description. Some critics, including advocates of the ecological psychological approach to design cognition, interpret these contributions as a "cognitive decathlon" (Anderson & Lebiere, 2003, p.591), where none of the arguments are convincing as a complete new approach to studying cognition (Calvo, 2005). Based on this criticism, I searched for alternative approaches not found in dynamism or connectionism, but rather in the ecological psychological notions of embodiment. I selected an ecological approach, not as alternative for a computational approach to this study, but rather as additional element filling in the gap on the design task environment level, allowing me to examine how designers acquire and process information in the early phases of design processes, which neither of the approaches on its own allowed me to do.

This section continues with a discussion of symbol systems theory and its relation to representation and problem solving in more depth. Throughout, I aim to clarify the meta-theoretical notions underpinning the emergence of alternative theories of notational systems and multiplicity of symbols systems used in designing.

2.3.2 REPRESENTATION

Representations are the kinds of things designers use to formulate their grasp of the world in order to solve design problems (Goel, 1995). The classic computational approach to representation ask questions about how features or elements of the outside world can be captured and re-presented inside the agent (Anderson & Lebiere, 2003) in such a way that it becomes meaningful to the agent and to others in problem solving situations. This view of representation assumes rationality and universality in the use of symbols, because a designer must have some rational and logic means of representing goals (or intentions) to solve a problem (or attain a particular state).

The notion of a symbol system was philosophised and theorised during the twentieth century. In essence, to be a symbol is to belong to a system of representation. In turn, a system of representation, or symbol system, consists of a scheme, a realm, and a relation. However, a scheme is a purely syntactic idea that can be described as a set of tokens organised into types. It is further possible to classify symbols into classes or types, depending on the existing relationship of instantiation (or membership) between marks, inscriptions or tokens. 'Membership' can also be described as equivalence classes of tokens. Such tokens are the individual marks or inscriptions, typically referred to as symbols, characters or expressions. Essentially, symbol systems can be depicted as consisting of a scheme domain and a realm domain, which stand in a particular relationship with one another (Newell, 1980) (Figure 2.1).
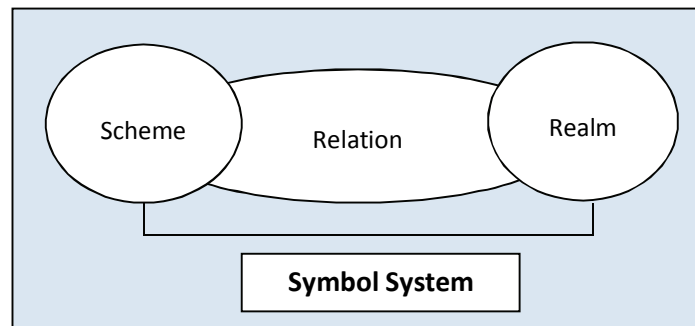
Figure 2.1: **Components and relation of a symbol system** (Goel, 1995)

Understanding problem solving as a fundamentally cognitive activity has benefited much from CTM for over fifty years (Goel, 1995). Since the early 1960's, problem solving and therefore designing, has been, and still seems to be considered as designers' ability to recognise dissatisfactory states of affairs (needs or problems) and to transform them into satisfactory states (solutions). It is assumed that a rational designer must adapt his response to the requirements and intentions of the task environment in order to transform these states. This means that designers, being in a dissatisfactory state when confronted with design tasks,

typically do not know how to solve design problems in order to reach a satisfactory state. It further means that solving the problem entails a rational process consisting of many steps[9] which are consciously followed in a linear way. During this process, designers use symbols to enable them to represent current 'states of affairs' and 'goals' while also aiding them to purposefully transform states as they adapt themselves and their thinking to solve problems. Computational theories seem to agree that the problem solving activity involves a sequence of steps, namely on exploration and decomposition of the problem through analysis, identification of the interconnections among the components, solution of the sub-problems in isolation, and taking into account any interconnections, and coming to partial solutions through synthesis.

In this study, I do not view design processes as predictable and linear. I therefore do not subscribe to the set of steps suggested by CTM theories. These steps refer to a process involved in solving well-structured problems, such as mathematics puzzles or a game of chess (Simon, 1969). However, as design problems are by nature ill-structured, with much information lacking in the various states (refer to Figure 3.2, p.74) they require designers to constantly move backwards and forwards between identifying unknown information, finding such information, restructuring the problem and finding suitable possible solutions. This backwards and forwards process differs from what happens when humans solve well-structured problems. In this study, I subscribe to Goel and Pirolli's (1992) notion that design processes consist of a number of distinct cognitive phases during which much overlaps and unpredictable simultaneous sub-activities may occur. I therefore consider design behaviour as taking place in a space consisting of cognitive phases (and not sequential steps), namely problem structuring and problem solving. The latter consists of three sub-phases: preliminary design, refinement and detail design.

I discuss these phases, how they relate to knowledge and representation, and how they might combine with embodiment theories in more detail in Chapter 3. In the following section I discuss two primary notions of symbol systems, namely semantic and syntactic properties of symbol systems from a semiotics point of view. It is important to understand the principles underlying the notion of semiotics as it provided me with a theoretical network in structuring the concept 'representation' and the resulting research procedure (refer to Chapter 4) involved in making meaning of representations of designers.

2.3.3 SEMIOTICS

Semiotics is a science about signs, signification, and symbol (sign) systems. Much of what is known about analysing representations in design work has been learned from the widely acknowledged theory of the linguist Noam Chomsky (1957) that people learn a system of rules

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[9] 'Steps' implies a linear, sequential and thus predictable order of activities; 'phases' implies cognitive phases consisting of compound, non-linear, overlapping and unpredictable order of cognitive activities (Goel, 1995; Goel & Pirolli, 1992).

(grammar) which contributes to the study of design cognition. Because design cognition researchers commonly believe that designers use multiple symbol systems, semiotics provided a powerful tool I could use to investigate the thought and transformation processes of the participants involved in developing artifacts in the environments they are required to function in (Goel, 1995; Kryssanov, Tamaki & Kitamura, 2001).

2.3.4   META-THEORETICAL CONSTRAINTS

Classical symbol systems theory, constructed under the meta-theoretical umbrella of CTM also known as information processing, stems from psychologists' use of the computer as a metaphor for explaining human cognitive behaviour leading to their modelling of different cognitive stages in which information of processing takes place (Reed, 2007). Newell and Simon (1972) define a cognitive system as a physical symbol system. As such, the symbol systems theory attempts to identify what happens during separate stages of information processing including acquisition, storage, retrieval and use of information.

The symbol systems theory is based on meta-theoretical principles requiring that the language of thought be a language with very stringent properties, also called computational properties. These properties require symbol systems to be rigid, precise, unambiguous and determinate. Symbol systems, from this point of view, further exhibit particular structures consisting of components illustrated in Figure 2.2, namely the information processing system, also known as a cognitive system or a physical symbol system, the task environment and the problem space.
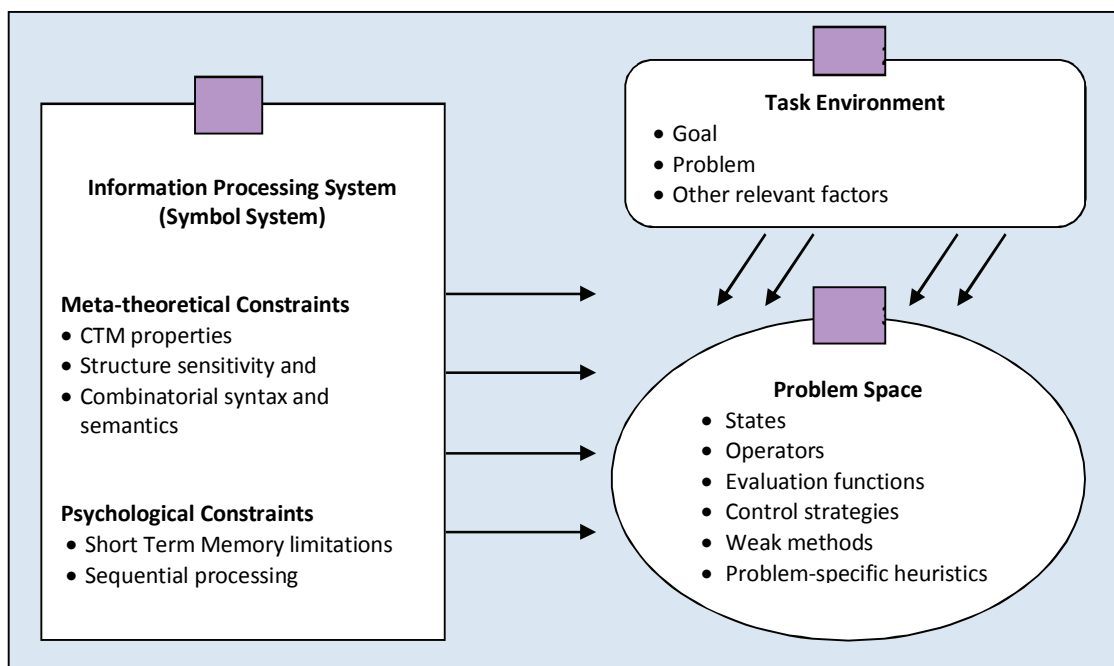
Figure 2.2: **Components of a symbol system characteristic of computational properties** (Goel, 1995)

Answering questions about where the semantic properties of symbol systems come from and how they could mean anything should be seen against the background of the original definition of designing, namely "devising non routine courses of action aimed at devising objects that would change existing situations" (Mitcham & Holbrook, 2006. p.216). This definition implies intention, flexibility and creativity, and points to designers having particular attitudes or intentional states when purposefully designing.

2.3.4.1 Attitudes and intentional states

Computational theories around representation are embedded in the ontology of intention as a state of mind, which in turn is directly related to the manner in which designers represent their intentions in the semantics and syntactics of the symbol systems that they produce. Because designing is driven by intentions to move from an unsatisfactory state to a satisfactory state, the state relevant to designing is that of intention (Goel, 1995; Mitcham & Holbrook, 2006; Simon, 1996). This notion of intentional states forms an integral part of my understanding of designing, as it allows me to integrate computational perspective with an ecological perspective. In this section, I discuss the notion of ontology of intention[10] as a state of mind and how it relates to design cognition and representation.

Intentional states contain representative content in a particular psychological mode. As such, intentional states represent objects as well as states of affairs (Searle, 1983) such as beliefs, needs and desires of people embedded in the problem task designers are required to solve. Just as a person's statement that a chair is comfortable is a representation of a certain state of affairs, so his belief that the chair is comfortable is a representation of the same state of affairs. In the same way, just as a client's requirement that the chair should also be beautiful, so his desire that the chair should be beautiful is about the chair and represents a certain physical property of the chair. As such, representations are described as 'parasitic on human intentionality' and 'exist and function in societal contexts' (Goel, 1995, p.24). Intentionality is defined as "… that property of some of our mental states that allows them to refer to, or be directed at, states of affairs beyond themselves".

In contrast to the relatively small set of psychological states that are attributed to the particular person (a client or a designer), these states can be directed at an infinite number of propositional contents (meanings). In this manner, the state and the content are causally or etiologically connected in the explanation of the behaviour of the agent. Considering the role that

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[10] The term 'intentional state' in philosophical terms has a different meaning than the definition used when referring to representation. In philosophical terms intention refers to the notion that at least two persons' intentions are involved: that of the person with a particular need or problem, and that of the designer commissioned to solve the problem (De Vries, 2005; Mitcham & Holbrook, 2006). From an embodiment perspective 'intention' refers to the notion of how successful artifacts embody the intentions of designers (Stanford, 2001).

intention may play in representation of thought processes of designers, intention holds a particular methodological implication for this study, as the principle unit of analysis are individual designers or team members sharing the same intention, participating in the study. In the case of this study, the psychological state of participants is attributed to designers attempting to understand the intention of a client (me as researcher) and then aligning their intentions to that of the client.

The **structure of intentional states** contains a relationship between intentional states and representation, implying representational content under a psychological mode. The assumption of this relation is that each intentional state is characterised by direction of fit and conditions of satisfaction as illustrated in Figure 2.3.
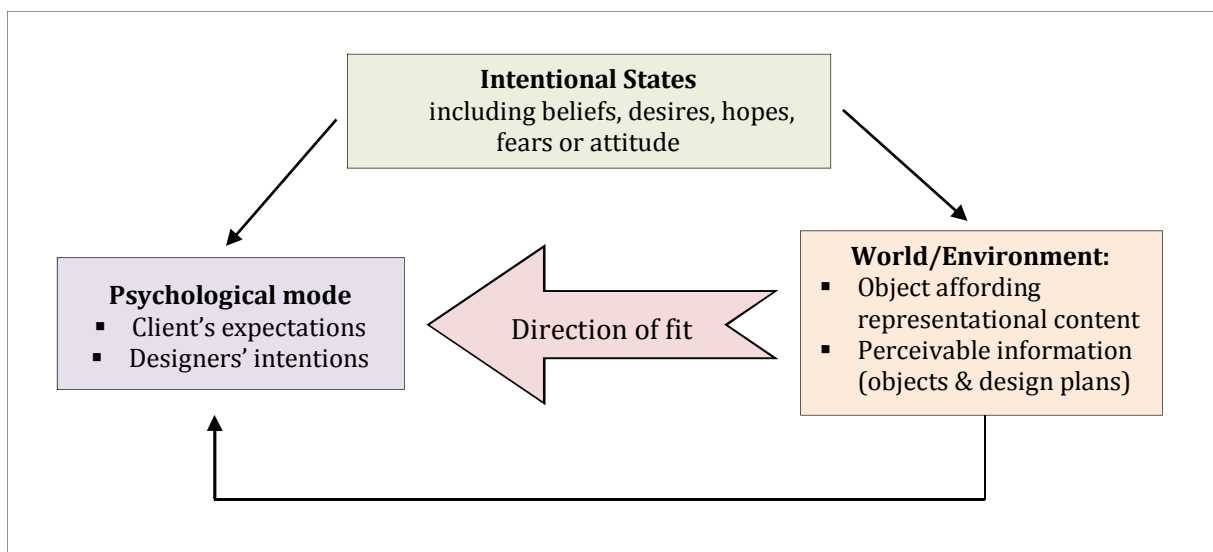
Figure 2.3: **Structure of intentional states as interactive mental representation** (Adapted from Goel, 1995)

Reference to the relationship between intentional states and producing representation(s) implies paying attention to the intention in order to produce a relevant subsequent representation, which allowed me to conceptually draw in the embodiment principle of intention-attention as discussed in Chapter 3. In addition, the reference to 'world/ environment: object affording representational content' in Figure 2.3 does not specify parameters for the notion 'world/environment'. Structurally it enabled me to include the ecological notion of 'physical environment' in my conceptual framework, to contribute to designers' perceptual access to information (Ericsson & Simon, 1993) regarding the psychological mode which is typically lacking in ill-structured design problems.

The conditions of a state of satisfaction show particular characteristics. Firstly, the conditions under which a belief or desire will be satisfied must be specified. This means that requirements and constraints embedded in design problems should be clear to designers. Secondly, conditions

are determined by representational content. The implication is that requirements and constraints should be afforded to designers through information with semantic value to designers. Thirdly, the notion of 'truth' is a special instance of the satisfaction relation when the direction of fit is mind-to-world (e.g. beliefs). 'Truisms', from a satisfaction point of view can also be seen as 'rightness' or 'appropriateness', which I consider to be determined by normative judgments (De Vries, 2005) as knowledge of designers.

I believe that computational theories contribute to design researchers' understanding of the cognitive role of intention in design problem solving when considering attitudes of designers during design processes. Searle (1983) argues that when considering intention ontologically, instead of thinking about its representational content, intentionality theories fail to account for the particular ways in which symbol systems might represent the many intricacies and unseen mental states of designers[11].

The following question arises: *How do the subsequent symbol systems (and their properties) used by designers to represent their particular way(s) of thinking, differ from that of other problem solvers?* In the following section I discuss how alternative perspectives on representation might provide researchers with information about the changes taking place in the psychological mode of designers, moving from intention to satisfaction, involving the investigation of syntactic and semantic properties of symbol systems.

2.3.4.2 Psychological modes and properties of symbol systems

Believing that the structure of unseen human mental states may be made visible by particular symbol systems, Goel (1995) postulated a design cognition theory that explains the way the structure of symbols systems may resemble the structure of particular mental states. His empirical research on expert designers' sketches gave evidence of the structural correlation between certain types of drawings made during particular cognitive phases of design processes and the mental states of designers.

As an alternative to computational explanation for the way in which representations could be associated with attitudes, other prominent modern researchers (Demarkin, 2005) argue that by analysing its semantics, one can get a perfectly good notion of representation. This seems to be possible by focusing on propositional content and does not have to rely on subagent processes for assigning attitudes. In addition, one should consider the structural sensitivity of symbol systems (Goel, 1995) by studying the syntactics corresponding with particular mental states during the different phases of design processes, which may allow researchers to detect possible resemblance.

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[11]Designers could, for instance, internally visualise or imagine images of an object that could possibly satisfy the need or desire of a client, or a client desiring particular objects, which is different from that of other problem solvers.

The phenomenon of syntactic correspondence is found in complex mental processes where mental representations are considered direct "objects" of attitudes. This means that such attitudes or mental states are structurally represented by complex symbols whose complexity lends itself to a syntactic and semantic analysis (Goel, 1995).

It follows that thoughts with particular properties could require symbol systems with appropriate properties, allowing the designer to represent them accurately. For example, the visual or functional concepts involved in a complex piece of machinery or building can better be represented by visual symbols used in a sketch than with verbal symbols alone. The structure sensitivity of the information processing system further manifests itself in the way the structure of thoughts changes from being vague and non-specific to detailed and specific, which in turn may affect the structure of designers' symbol systems. Conversely, as the structure of their symbol system changes, the structure of designers' thoughts will change (Fodor, 1981; Goel, 1995). This notion is central to my study and has important methodological implications. It means that I carefully studied sketches and verbal protocols to track down structural changes in order to establish whether these correlated with changes in the structure of participants' thoughts during particular phases of design processes.

Structure sensitivity refers to the notion that a close relationship exists between the structure of thoughts and the structure of the symbol systems people use. The argument is that, if there is a system of internal representation – a language of thought – then thoughts with certain properties will require symbol systems with certain properties. In addition, the properties of symbol systems will affect the properties of thoughts. As the structure of thoughts changes, the structure of symbol systems will need to change. Conversely, as the structure of symbol system changes, the structure of thoughts will change (Demarkin, 2005; Goel, 1995).

As such, I believe that symbol systems are not passive/transparent structures to which arbitrary concepts should be linked. Symbol systems vary in terms of their structural properties. These properties, in turn, constrain and filter the character of human thoughts and concepts. However, different subjects/disciplines display different characters of thought and concepts and therefore require different symbol systems (Fodor, 1981; Goel, 1995). It is for this reason that I regarded it necessary to examine not only verbal protocols, but to also study the sketches of expert designers made during the early phases of design processes.

I believe that the various external representations used by designers, including discursive language and non-verbal systems, involve a complex range of cognitive processes due to the structure sensitivity of the information processing system. Different symbol systems are used in a particular sequence, i.e. different symbol systems correlate with different cognitive phases and the structure of a system at a particular time. This in turn typically correlates with the structure

of thoughts in a particular cognitive phase of design processes. In the following section, I explain why conventional computation and information processing theories often fail to account for the exact way in which designers behave in the DPS.

2.3.5   FAILURE OF THEORIES OF COMPUTATION AND INFORMATION PROCESSING

Critique against computation relevant to this study relates to three aspects, leading to my combination of elements from three different theories (Figure 2.4). The first two theories are extensions of the meta-theory of CTM, which made the conventional idea of 'symbol system' more amenable to design cognition. The third theory is the ecological approach to cognition of which I selected elements in order to explain embodiment and perception.
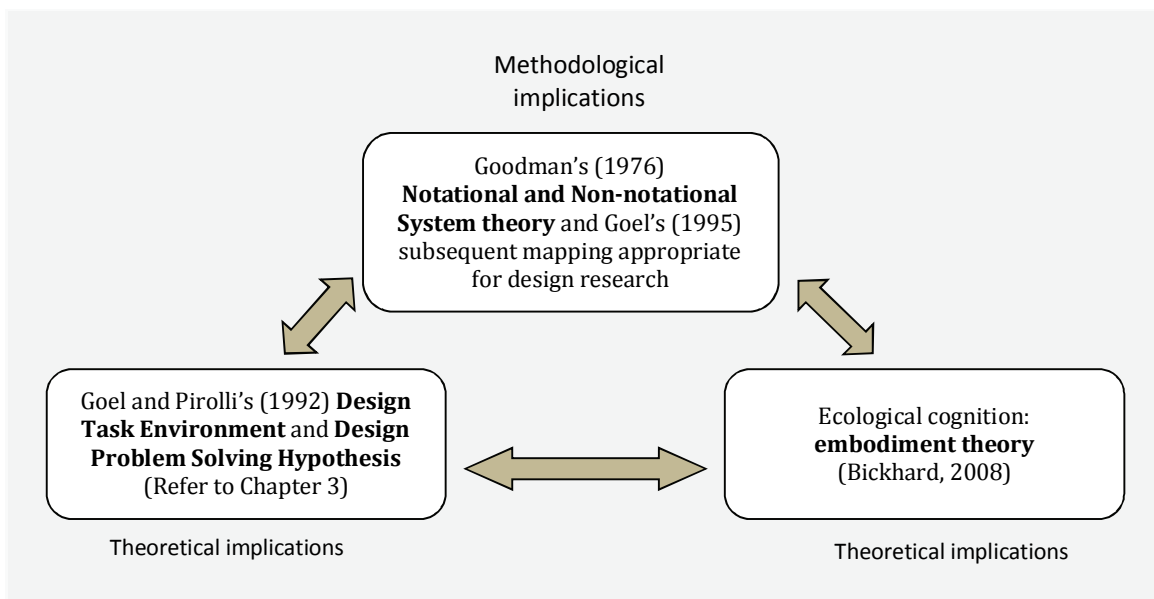
Figure 2.4:   Combination of theories towards a conceptual framework

Within the context of my research, the first limitation of computational theories involves the theory related to the properties of symbol systems and rationality. This theory is limiting as it does not seem to account for the way in which creative, and semantically rich cognitive fields such as visual arts, physics and designing, use multiple types of symbol systems. Computational theories are further limiting as they do not seem capable of explaining representation in non-rational and non-linear cognitive processes, such as associative thinking and metaphorical thinking. Due to the stringent properties it requires of symbol systems, a computational view of problem solving does not account for the way in which designers' thought processes correlate with the ambiguous and vague nature of symbol systems in the early phases of design processes. In looking for a theory that could frame transformation of thought processes made visible in representation (Gero & McNeill, 1998), I found a potential frame in Goel's (1995) mapping of Goodman's (1976) classification of notational and non-notational symbol systems. This mapping

allowed me to examine both discursive and pictorial symbols of designers' expressions denoting tangible and intangible ideas (Ferguson, 1992; Lawson, 2006).

The second aspect important to my study, in which the computational approach is limited, relates to accounting for human problem solving in general, in terms of the autonomy of an internal executor theory. The theory of computation distances natural human behaviour from the environment in which the behaviour takes place. Exclusion of the physical environment from the information processing system (refer to Figure 2.3, p.45) subsequently resulted in theories embedded in an ecological approach to cognition (Bickhard, 2008). However, constructivist theories, focusing on the problem solver as 'agent' (Anderson & Lebiere, 2003; Anderson, 2003; Richardson et al., 2008), seem to provide some reasoning apparatus for considering the significance of perception-reaction cycles in design processes that may contribute to explaining some of the cognitive activities not explained by computation. As such, combining computation-based theories with ecological theories had methodology implications for this study. It provided me with the opportunity to consider the physical environment as a source of information through embodiment during design processes. This aspect is addressed in more detail in section 2.5.

The third aspect central to this study, in which a computational approach fails to comprehensively explain design cognition, is embedded in the computation's limited ability to explain the unique nature of design problems and the correlation between the nature of the information available to designers, the properties of the symbol systems they use and the various phases of design processes. Explanations of these correlations can be found in the design problem solving (DPS) theory (section 3.4) constructed by Goel and Pirolli (1992).

In summary, I combined elements from three different theories in this study. I firstly relied on Goodman's (1976) notational and non-notational systems, and subsequently Goel's application thereof in design research. Secondly, I incorporated Goel and Pirolli's (1992) DPS (refer to section 3.2). Thirdly, I relied on embodiment theories founded in ecological cognition (refer to section 2.5 and section 3.4.5). I discuss the emergence of the first, notational and non-notational theory in the following section, against the historical background of the computational view of symbol systems.

2.4   EMERGENCE OF AN ALTERNATIVE APPROACH TO SYMBOL SYSTEMS

Conventional computational theories on the properties of symbol systems seem to have evolved around the notion of discursive language being the language of thought. As such, a symbol system is seen as one in which atomic symbols are strung out sequentially (Simon, 1978). However, CTM does not consider the need for discursive language to comprise an expressive

scope as well as possess the mechanisation of reasoning (Goel, 1995; Stenning & Oberland, 1995). The implication is that CTM is unable to account for creative activities in which symbol systems such as pictorial systems are used in disciplines such as visual arts, physics, engineering design and architecture. This inability gave rise to a growing need amongst design-related cognitivists to find suitable and sustainable explanations of symbols systems other than those used in discursive language. The failure of classical computational theories involving the structure and classification of symbol systems necessitates a different criterion that can be applied to the multiple types of symbol systems designers typically use (Goel, 1995).

Although I have highlighted some valid critique of the restrictive nature of the CTM approach to problem solving, it is important to understand that even though there are alternative views developed by questioning some aspects of CTM, much of the latter's principles grounded the development of alternative theories. One such principle grounding Goodman's (1976) theory of notationality is the meta-theoretical notion of structural sensitivity and combinatorial syntax and semantics of symbol systems embedded in the Fodorian (Fodor, 1975) insights in language of thought, as discussed previously. The essence of this grounding insight is that a system of representations is physically realised in combinatorial syntax and semantics and is influenced by mental states. Based on his belief that CTM assumptions of representation are too restrictive to explain the many 'marks' and their numerous properties, Norman Goodman (1976) developed a theory of symbols enabling him to identify various types of symbol systems other than those characterising discursive language. In addition, he showed that different types of symbol systems are characterised by their different modes of reference.

2.4.1   GOODMAN'S NOTATIONAL SYSTEMS THEORY

Symbol systems ground the (embody) computations that people use to represent their thoughts (Newell, 1980). Symbol systems encompass any physical occurrence that instantiates a symbol, whether verbal or nonverbal types of instantiations, including symbols, characters or expressions. It follows that the term 'character' is not limited to an element of the alphabet, but can be any symbolic expression from any symbol (Goel, 1995). Goodman's (1976) investigation of the varieties and functions of non-verbal symbol systems used in creative arts filled an important gap in the conventional computational literature focusing on discursive symbol systems. Goodman's expansion of existing symbol systems theory adds important insights into understanding how multiple types of representations account for cognitive processes (Dogan & Nersessian, 2010; Neiman, Gross & Do, 1999).

Goodman's (1976) theory is based on distinguishing between hundred and thirty two different types of notational systems applicable to art and design work. From this distinction of systems, which he also termed 'modes of reference' I considered three modes, namely denotation,

exemplification and expression relevant to design visualisations (discussed in sections 2.4.1.1-2.4.1.3). I selected these three modes as they applied most directly to early phase sketching in design work. Understanding these three modes, contributed to my appreciation of some of the principles of visual representations as 'visualisation', widely acknowledged as one type of knowledge inherent to design ability (Ferguson, 1992; Neiman et al., 1999; Oxman, 2002; Purcell & Gero, 1998).

Three main themes of the computational stream of thought feeding into Goodman's theory also seem to be basic assumptions of current studies on the role of visualisation (and sketches) in design cognition. The first relates to the recognition of the cognitive significance of symbol systems. The second is the notion that symbol systems shape concepts. The third theme entails recognition of the multiplicity of symbol systems and attempts classifying them. However, the main theme distinguishing Goodman's work from analytical conventions of rationality during the 1970's, which attempted to quantify cognitive processes, is his sensitivity to, and appreciation of, the qualitative elements involved in the representations of creative fields such as engineering and architecture, which indeed also constitute genuine cognitive activity.

Goodman's (1976) characterisation of visual representation, which he later extended into the idea of non-notational systems (discussed in the following section), played a central role in my study for three reasons. First, it contributed to my search for the systematic inquiry into the variety and functions of visual symbol systems which informed me about the psychological realities shaping my understanding of the structure of mental representations. Second, the psychological credibility of Goodman's characterisation played a central role which questioned the suitability of conventional computation accounting for the types of symbol systems used by designers and their cognitive functions in design processes. Third, it provided a theoretical basis for claiming the validity of my analysis and interpretation of participants' sketches in this current study.

2.4.2   NON-NOTATIONAL THEORY

Goodman (1976) developed the idea of non-notational symbols systems in terms of different modes of reference that lack CTM-properties, and are mostly represented pictorially. Understanding sketches as non-notational systems played an important role in my examination of participants' design behaviour because of the characteristic overlapping of the semantic and syntactic properties of sketches with that of mental states. In this section, I discuss the three characteristics of sketches, namely denotation, exemplification, and expression which are explained by Goodman's theory of non-notational theories.

2.4.2.1 Denotation

Denotation refers to sketches being considered as representations[12]. This means that sketches can represent any object or stand for it in a literal sense. However, it also means that no degree of resemblance is sufficient to establish the requisite relationship of reference. It further means that resemblance is not necessary for reference, implying that almost any mark a designer makes may stand for any idea or object. It follows that denotation is the core of representation and is independent of resemblance (Goodman, 1976). This characteristic of sketches played an important role in my structuring of data, analysing vague and unclear marks participants made in their sketches. My understanding of this characteristic also contributed to my interpretation of the cognitive function of marks that participants assigned to different meanings at different moments in design processes.

However, an important insight by Goodman is his observation that denotation is not the sole notion of reference. He distinguishes between denotation, exemplification and expression. Vinod Goel (1995) recognised the potential of Goodman's theory of notational and non-notational systems for application in design cognition research. He subsequently articulated a detailed specification for mapping Goodman's (1976) classification model with computation in his study *Sketches of Thought*, giving credibility to the conceptual links between two seemingly opposing perspectives on symbolic functioning. In the following section I explain how Goel contextualised Goodman's theory for design cognition. In order to understand the theoretical underpinning of the cognitive role of sketches in design processes in this study more comprehensively, I also considered exemplification and expressive properties of sketches, both of which notions involve figurative or metaphoric elements of meaning.

2.4.2.2 Exemplification

Exemplification refers to the notion that pictures (sketches) pictorially suggest labels[13] or verbal descriptions of objects as e.g. 'shape', 'relative size', 'relative location', 'fluid', rigid', or 'elegant' (Goel, 1995). As sketches are considered as a symbol system with distinguishing descriptive characteristics, they are able to *exemplify* such descriptions. Descriptions can be literal, e.g. 'the concrete is hard', or 'the landscape is symmetrically organised'. In the case where a pictorial representation serves as exemplification of a metaphoric or figurative property of an object, e.g. 'the building is the '*heart*'' of the campus,' the sketch of the building is simultaneously an exemplification of the building and expression (refer to the next section) of the figurative property 'heart'.

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[12] "A picture (visual symbols) denotes what it represents, while a predicate (verbal symbols) denotes what it describes" (Goodman, 1976, p.51).

[13] 'Labels' are properties (literal or metaphoric) predicated by natural language. This means that sketches can exemplify a sample of such a property.

As such, sketches do not only represent properties of objects, they also possess (embody) these properties. This means that if an object, e.g. a brick from a wall, is at issue, the brick does not only represent certain (but not all) properties of the wall from which it was taken (including colour, texture, weight of the brick); it actually possesses, hence exemplifies, these properties. This notion of exemplification had methodological implications for my study. In order to classify or code a particular sketch in terms of a particular type of knowledge or reaction to a perceived property of an object, I had to recognise the similarity between the said property of a sketch and corresponding labels in the spoken words it exemplified.

2.4.2.3   Expression

As mentioned earlier, expression refers to metaphorical statements, while 'denotation' refers to the literal meaning of something represented by a particular symbol system. When the instantiation (representing an abstraction by a concrete instance) of a label is metaphorical, the symbol/sample is said to express the label (e.g. 'the concrete used in a building'). This means that the properties that an object metaphorically possesses are transferred onto the sketch from another realm, and thus are actually possessed by the sketch, meaning that they are considered to belong to the symbol (Goodman, 1976).

Expressions can range from being very simple, to very complex, and are found in both verbal and non-verbal symbol systems. The methodological advantage of this 'wide' view of what constitutes symbol systems for my study was that it allowed me to consider the expressive value of symbol systems, and not only their denotative content. In considering the expressive qualities of symbol systems used in the sketches participants made, I found meaning in some of the lengthy discussions of participants' verbal protocols, or in individual statements made, or in a gesture with a hand. I could also find meaning in the expressions made through simple line drawings, as well as complex, detailed and multi layered drawings in the different stages of design processes. This implied that I analysed and interpreted data yielded in the protocol studies and sketches not only in terms of literal meaning and denotation, but also in terms of its ability to exemplify samples of objects or properties thereof and metaphorically express abstract properties and qualities of objects perceived or experienced by the participants.

Building on Goodman's characterisation of the exemplification and expressive abilities of sketches, and highlighting the way that a study of the properties of sketches can help researchers to understand the cognitive role of sketches in design processes, Goel extended the theory of non-notational symbol systems. His extended theory includes the ability of sketches to represent an object or its syntactic and semantic properties on a grading scale ranging from vague, ambiguous and dense to precise, transparent and unambiguous. Of importance to my study is the notion of ambiguity, density and vagueness, as these properties are typically found

in the sketches made during the early phases of design processes. In understanding the significance of Goel's extended theory, it is necessary to consider the general role that sketches play in design cognition as discussed in the following section.

2.4.3 SKETCHES AND THEIR COGNITIVE ROLE IN THE EARLY PHASES OF DESIGN PROCESSES

Central to the current study lies appreciating the cognitive role of sketches, as a form of visualisation[14] could play an important role in the early phases of design processes. In order to understand the role of visualisation in design work, researchers have formulated theories from a spatial point of view (Suwa, Tversky, Gero & Purcell, 2001; Tversky, 2005), from an imagery perspective (Block, 1981; Kosslyn, 1981; Massironi, 2002) and from psychology of graphics (Arnheim, 1954, 1986; Massironi, 2002). More recently, theories about design cognition and the role of sketches in design processes have emerged (Dogan & Nersessian, 2010; Garner, 1994; Goel, 1995; Neiman et al., 1999; Purcell & Gero, 1998).

It is widely acknowledged across various theories that sketches play an important role in planning an intended design to the extent that the concept 'design' has almost become synonymous with sketching, drawing or visualisation (Bertoline & Wiebe, 2006). Along the same lines, modern literature indicates the significance of visualisation (De Vries, 2005; Ferguson, 1992; Vincenti, 1990) in the cognitive processes involved in planning (designing) artifacts. It is widely acknowledged that outstanding designers are invariably outstanding visual thinkers (Vincenti, 1990). However, despite current work in understanding visual reasoning in design (Oxman, 1997), the way conceptual and social mechanisms operate in design sketching are still unformulated.

Whereas early protocol studies in design cognition included the verbal protocols of designers, other studies in design cognition that emerged since the early 1990's (Ferguson, 1992; Goel, 1995; Goldschmidt, 1994; Oxman, 1997; Purcell & Gero, 1998) reflect and theorise on the cognitive role of sketches. Some researchers approach this from a computational point of view and others from embodiment, while limited evidence is found of conclusive modelling of integrating the two approaches (Oxman, 2002). Such studies acknowledge the physical and functional dynamics involved in symbols systems attributing this to the fact that these can radically vary in terms of their structural properties. These properties seem to constrain and filter the character of a designer's thoughts and concepts. This also means that designers use different types of symbol systems to aid them in clarifying ideas, understanding concepts, testing and evaluating ideas, and communicating ideas to others (Goldschmidt, 1991; Neiman et al., 1999).

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[14] 'Visualisation' is widely acknowledged as one of the types of knowledge designers use (De Vries, 2005), and is discussed in Chapter 3.

Literature on design studies indicate that the complexity of design is closely related to the properties of the symbol systems used in particular types of sketches and drawings, as well as to the cognitive phases of 'finding' appropriate problems and 'solving' them. This includes substantial activity in problem structuring and formulating, rather than merely accepting the 'problem as a given' (Cross 2001). The correlation between different symbol systems used by designers and different design phases are illustrated later on in sections 2.5 and 2.6. In the next section, I discuss how Goel's extended theory of the properties of sketches, correlate with mental states and phases of design processes.

2.4.3.1 Correlation of sketches with phases of design processes

The theory presented here assumes that there is no reason to believe that a privileged symbol system could exist that is capable of expressing every possible human thought content (Fodor, 1975; Goel, 1995; Goodman, 1976; Peacocke, 1995). Natural language has been found to be the most prominent during the problem structuring phase, whereas sketching typically dominates the preliminary design phase. Multiple cognitive researchers focus on the importance of sketches for understanding cognitive processes (Goel, 1995; Neiman et al., 1999; Oxman, 1997; Purcell & Gero, 1998). The structure of designers' sketches and drawings (plans) changes according to the structure of their thoughts. The implication of this for my study is that I was able to identify the changes in the structure of designers' thoughts and then correlate these according to the phases of design processes at a particular point in time. Therefore, the syntactic properties (structure) of the sketches made in a particular phase by a participant were typically different from those of sketches made during other phases.

It is, however, not only the properties made during the various phases in design processes that differ from each other. Designers also seem to use different modes of reference during the different phases of design processes. During the problem structuring phase designers typically use natural language, where semantics denote the goals that need to be met. Semantics also play an important role in revealing the behaviour of the artifact designers need to design in order to result in intentional goal satisfaction. In this study, I argue that semantics play an important role in demonstrating designers' intentions, while syntactics seems to reveal the extent of their commitment to suggested solutions.

During the problem structuring phase, discursive language often denotes designers' analyses of design briefs. They typically ask questions and engage in discussion, attempting to understand the scope and essential core of a particular design problem. However, limited use of diagrammes and sketches is not completely ruled out during this phase. Designers may use these visual modes of reference to explore the requirements of a problem (Lawson & Dorst, 2009; Vincenti, 1990). They also figure out their visual understanding of the perceived environment

(Goldschmidt, 1991) and consider the multiple social and technological aspects involved. Visualisations may furthermore assist designers to establish which factors might add to the complexity of a design problem or influence the decisions they make further on in design processes. In this current investigation I contend that much processing of information accessed through perception during the problem structuring phases takes place internally, and is not necessarily externalised.

During the second phase relevant to my study, the problem solving phase, designers generally use multiple visual symbol systems such as diagrammes and schematic or nonspecific sketches (Oxman, 2002). They use these systems to explore different layouts suggesting positions and orientations of functional elements, often not being specific in their depictions (Garner, 1994; Goel, 1995). During this early phase of problem solving, the systems used by designers are typically schematic and vague with little detail denoting any object in specifics. Ideas often seem to be triggered by either perceived visual information stored in their short term memories or by shapes emerging from their sketches (Suwa & Tversky, 1997). These characteristics are discussed in more detail in section 4.3.2.2. The necessary mediating role of vagueness, density and repleteness in allowing designers' mental states to transform from one state to another, as modelled by Goel (1995) is illustrated in Figure 2.5 (see p.57) and Figure 3.2 in Chapter 3 (see p.74).

Goodman's apparatus is based on his notion of the intrinsic syntactic and semantic properties of symbol systems, which can take on degrees of density, ambiguity or vagueness depending on the phase of design processes, as illustrated in Figure 2.5. Goodman's study, supported by Goel's work, confirms that visual (non-notational) symbol systems are powerful and productive. Much of this power seemingly rests on the fact that non-notational systems can be non-disjoint, ambiguous, dense and replete. In the following sections I discuss these features, namely density and ambiguity and repleteness.

2.4.3.2   Density and ambiguity

Density in symbol systems refers to a particular quality characterising the system as syntactically and semantically disjoint with densely ordered marks, resulting in ambiguity (Goel, 1995). A typical dense symbol system is the sketch(es) of designers. This means that each mark (symbol or token) designers use to represent their ideas might belong to more than one sketch at the same time. It further implies that the particular marks designers use in drawings can also be used in other drawings, implying that the marks might all look the same and that one may therefore not be distinguished from the other. However, density and ambiguity are a matter of degree. This means that one sketch can be more dense or ambiguous than another, or that the density or ambiguity of a particular sketch can be changed (made less dense or more dense) by

changing the quality of the marks used or adding or taking away some of the marks, which in turn will change the structure.

Designers typically make dense sketches during the early preliminary problem solving or conceptual phase of design processes (Ferguson, 1992; Goldschmidt, 1991; Herbert, 1988; Neiman et al., 1999). As they move from preliminary design to refinement, sketches lose density as the structures of the sketches become more constrained until they become full-fledged drafting systems during the detail phase (Goel, 1995; Purcell & Gero, 1998), characterised by specificity and transparency. Figure 2.5 illustrates the correlation between the various phases and the distinct number of symbol systems used in this complex process of information transformation.
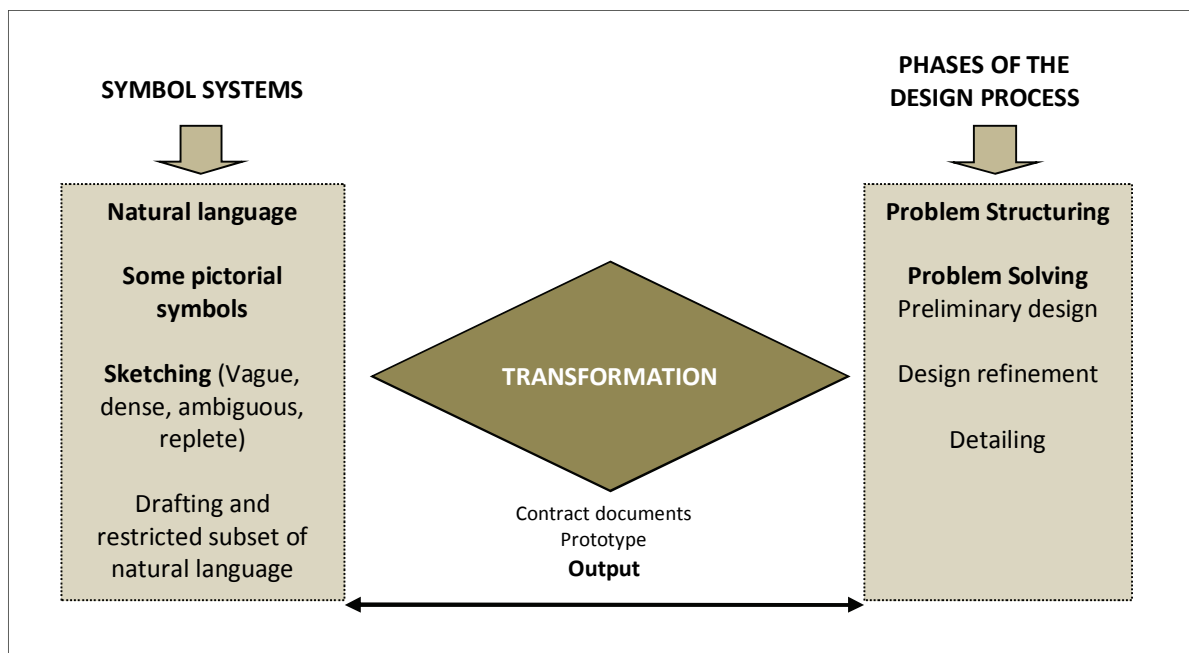
Figure 2.5: **Correlation between different symbol systems and design phases** (Adapted from Goel [1995])

Figure 2.5 indicates that designers depend on multiple symbol systems to solve design problems, allowing them flexibility to explore ideas and develop these incrementally. It further shows that different types of symbols systems are necessary during different phases of design processes. In the case of the preliminary problem solving phase, the use of conceptual sketches are particularly useful to designers because it allows them to represent the direction in which their thoughts are constantly shifting, transforming their ideas by moving in a lateral or vertical direction.

These types of systems play an important role in human cognition, and are considered as a possible foundation of human creativity[15] (Ferguson, 1992; Goel, 1995). Understanding the inherent characteristic of vagueness and density of sketches made during the preliminary problem solving phase of participants' design protocols enabled me to identify the necessary cognitive functions that sketches played when participants not only moved from one mental state to another, but also denoted the way they changed the direction of transforming information and developed artifacts incrementally. It follows that distinguishing between sketches on the grounds of density and ambiguity had important implications for this study. It namely helped me to determine the cognitive phase in which the participants were functioning at particular points in time during the protocol studies. It furthermore contributed to my detection of the difference between lateral and vertical transformations in the different phases of participants' thought processes.

2.4.3.3   Repleteness

Repleteness in visual representations relates to the idea that little can be considered as irrelevant. This means that the notion of repleteness is a matter of degree. It is not general like a discursive symbol. It is entirely independent both of what a symbol stands for and of the number of symbols used. Repleteness is a particular syntactic quality and refers to those features of a symbol (mark or token) that are part of a particular scheme but which are dependent on the context of the rest of the marks, and are in actual fact irrelevant in terms of the semantic information it represents on its own (Goodman, 1976).

In the case of the current study, the methodological implication of repleteness was that I had to consider each formal element constituting the syntactics of designers' sketches, as well as their relation to one another (Goel, 1995). This means that I considered formal elements including the thickening or thinning of lines, their colour, the contrast with the background and their size. It further means that I had to be vigilant about possible irrelevance or redundant elements. Repleteness as a matter of degree had important implications for the analysis of the pictorial symbol systems that participants used in their problem solving protocols. As was mentioned earlier, the characteristics of relative density, ambiguity and repleteness play an important role in design processes in allowing designers to change sketches from being very dense and ambiguous to being less so. In the following section I explain how this syntactic feature of sketches may contribute to designers' creativity by allowing them to change the direction of their transformation and move between lateral and vertical changes.

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[15] Creativity, for the purpose of this study, refers to the cognitive process that generates solutions to a task, which are novel or unconventional and satisfy certain requirements (appropriate) (Kryssanov et al., 2001).

2.4.4 SKETCHES AND THEIR TRANSFORMATIONS

Whereas Goodman's theory of notational and non-notational systems was developed by studying artists, Goel (1995) built on his theory of density, ambiguity and repleteness of visual symbol systems and mapped it onto design behaviour. As such, Goel conducted detailed research on the act of sketching by expert designers who were required to solve design problems. He identified two types of transformational operations occurring between successive sketches in the early phases of design processes, namely lateral transformations and vertical transformations, as illustrated in Figure 2.6.
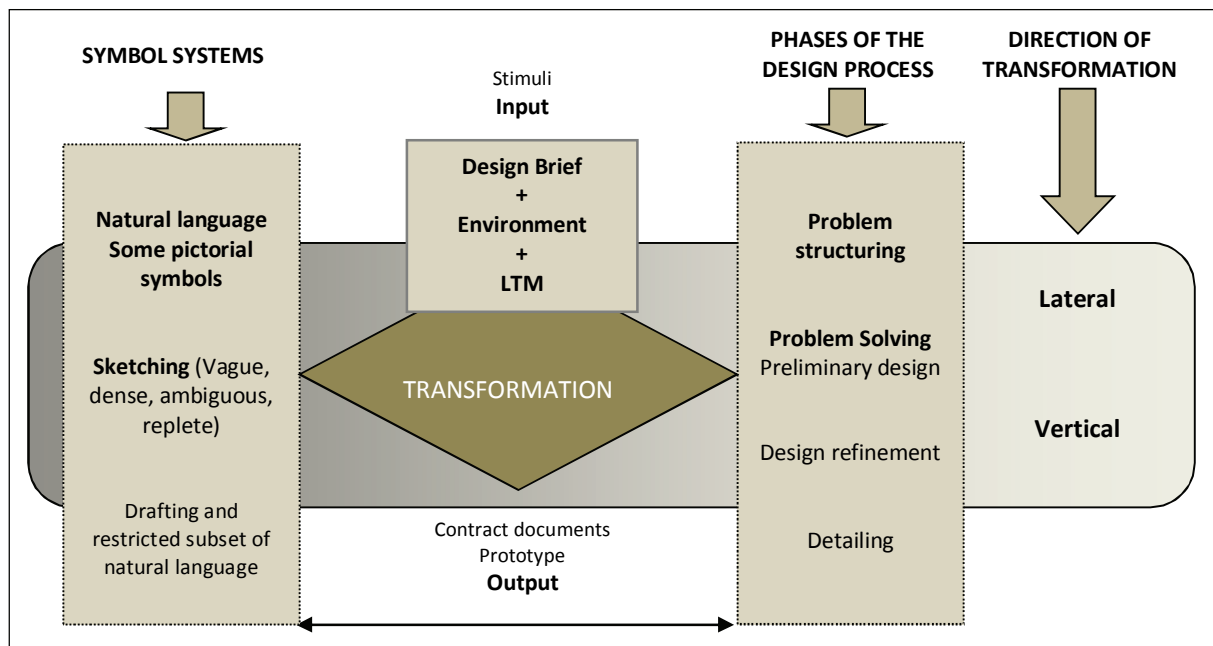
Figure 2.6: **Mapping direction of transformation in the early phases of design processes** (Adapted from Goel, 1995)

'Lateral' transformation refers to movement from one idea to a slightly different idea. Designers generally engage in this type of transformation during the preliminary problem solving phase as it allows them to explore many possibilities. This is the phase during which designers do not yet commit themselves to a particular concept, but are experimenting with different possibilities. Goel (1995) emphasises that lateral transformation needs to occur in the preliminary phase of design problem solving. It seems that the syntactic and semantic density and ambiguity of the symbol system of sketching facilitates the cognitive operations involved in lateral movement during this phase. In 'vertical' transformation, on the other hand, designers conceptually move from one idea to a more detailed and specific version of the same idea. Therefore they do not generate new ideas, but rather clarify and develop existing ones in greater detail by adding visual information. Vertical transformations typically occur in the refinement and detailing phase as designers start committing themselves to a particular concept. As such, vertical

transformations are based on previous ideas where designers reinforce and develop these ideas by means of iteration.

This typology of the way in which researchers can identify the change in direction of thought processes by carefully studying the spatial and semantic detail or meaning of the sketches of designers is central to my research methodology. It provided me with a tool to analyse and interpret the sketches of the participants. Analysis and interpretation in turn contributed to my action of correlating the properties of sketches to that of the verbal protocols, strengthening the validation of my classification of the different cognitive phases in design processes of participants. However, to understand the intricacies involved in how and why particular properties of sketches manifest as they do in the early phases, I also needed to consider the cognitive function of the physical environment in which design problems are situated (Ericsson & Simon, 1993). This requirement of my study led me to consider the relevance of embodiment theories related to representation, namely ecology (Bickhard, 2008).

2.5   INTEGRATING COMPONENTS OF THE ECOLOGICAL APPROACH

Although the computational approach to cognition generally acknowledges the involvement of perception of the environment when solving problems, the problem of the autonomy argument lies in the fact that it distances human behaviour from the environment in which the behaviour takes place, resulting in theories of embodiment underpinned by ecological psychology (Bickhard, 2008). The implication of this limitation of computation for explaining design behaviour is that it does not account for the important role that exploration of the physical environment in which the design problem is situated, plays.

A group of critics finding CTM's wide-ranging applicability and the success of its theoretical apparatus as insufficiently accounting for cognition, came from the domain of ecological psychology from which embodiment theories were developed as originally conceived by J. J. Gibson (1977). Gibson introduced an approach that would not require recourses to central executives or representations. As might be expected, the ecological approach opposes the separation of organism and environment. This approach stems from the mundane observation that a cognitive agent has a body, inhabits an environment and lives by the constraints of both.

Gibson is generally acknowledged as a pioneer of this approach, emphasising perception of the world, from which embodiment theories developed (Anderson, 2003; Clark 2006). The essence of Gibson's (1972) argument lies in the idea that animals and humans (agents) stand in a 'systems' relation to the environment. As such, to fully explain design behaviour (design problem solving space) as it manifests in the protocols of the participants of this study, it was necessary to consider the environment, as source of information, in which this behaviour took

place. Gibson (1972) subsequently suggests a model of knowledge and problem solving that requires thinking through 'doing' or 'acting' rather than through storage and retrieval of conceptual knowledge as suggested by CTM. It follows that cognition cannot be separated from its context.

Taking into account Goel's (1995) contention that the nature of design task environments influences the structure of designers' thoughts, I argue that the physical environment, being part of designers' natural task environment during the early phases of design processes, also influences the structure. As such, perception contributes to characterising the design problem solving space. For the purpose of my study, I derived the working assumption that it is necessary to consider both the internal processes as suggested by the computational approach, as well as the interaction of processes with external environments. This idea contributed to my understanding of the richness of information processing which influences thinking and representation in the early phases of design processes. I regard 'design task environment' to include the design problem as well as the physical environment in which it is solved.

In my view, the reality of designing may be better understood by combining and integrating different approaches within computation and ecology, rather than opposing the one against the other. For this reason, I integrated a particular branch of the ecological approach to cognition, namely embodiment, because of the emphasis it places on perception-action cycles in representation (Bickhard, 2008), which resonates with the CTM emphasis on representation. Combining these approaches allowed me to investigate perception, talking and sketching.

2.5.1   EMBODIMENT AND SITUATED DESIGN COGNITION

Embodiment cognitive researchers explain cognition in terms of agents who mediate understanding through disengaged presentations and the physical environment (Anderson, 2003; Bickhard, 2008, Gomila & Calvo, 2008). As such, it does not acknowledge a central executive as computational theorists do, but views cognition as integration of the world (environment) and organisms (human cognitive system). Focusing on problem solving, embodiment theories assert that, in a dynamic cognitive process, perception and action seem to occur through the body being in the world, resulting in interaction between perception and action when solving problems. This primary assumption of embodiment refers to the way in which the world and human cognitive systems are integrated. Underlying the kinds of plans designers conceive as suitable solutions to problems in the world, is their particular grasp of the world (Goel, 1995). This means that, in order for designers to form representations of their grasp (such as verbal descriptions or sketches), designers attempt to understand the world (design problem task environments) by actively interacting with it, and that they deal with the things in it (solving design problems) (Anderson, 2003).

Well-known situational studies were initially based on reflective studies (Schön, 1983; Blessing & Chakrabarti, 2009). However, many researchers from the computational orientation do not consider reflective approaches as sufficiently scientific and objective to be considered productive (Oxman, 2002). Building on the criticism of seeming 'unscientific' situated studies, studies with information processing underpinnings emerged, including works by Gero (1991), Gero and Fujii (2000; 2003), Gero and Kannengieser (2004), Gero and Maher (eds. 2005), Clancey (1997) and Oxman (2002). Gero and Fujii (2003) argue that many design studies attempt to explain what computationally happens when designing uses a framework that is too narrow to account for transfer of earlier results as the design changes, the use of domain knowledge and task knowledge. I agree with this view of the typical computational models used, including the model used by Goel and Pirolli[16] (1992), which I use as the basis for my conceptual framework. Therefore, from the existing ecological literature, I identified four primary notions or embodiment assumptions in ecological cognition theory which guided my conceptual framework (discussed in Chapter 3) which I now introduce.

2.5.2   RELEVANT ASPECTS OF ECOLOGICAL PSYCHOLOGY

Anderson (2003) identified four aspects, namely physiology, evolution, practical activity and socio-cultural situatedness, all centred around the notion of interaction with the environment. The implication of such a view is that it considers the basic sequence of events, namely seeing-acting-seeing as epistemic activity (Anderson, 2003). The first three aspects relate to designers' perception and activity in design task environments, implying objective conceptual (including domain specific knowledge) and implying procedural and visualisation knowledge. In contrast, the fourth aspect relates to designers' socio-technological interpretation and inferences of the context of design tasks, implying value-laden knowledge as well as objective domain specific knowledge. I now discuss these aspects and explain their implications for this study. As an introduction, Figure 2.7 provides a summary of the components of epistemic activity and the role these four aspects fulfil.

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[16] Goel and Pirolli's (1992) model of design problem solving space acknowledge the designers use of domain specific knowledge, linking it with long term memory, but does not consider how the interaction with the environment/situation triggers the recall and use thereof.
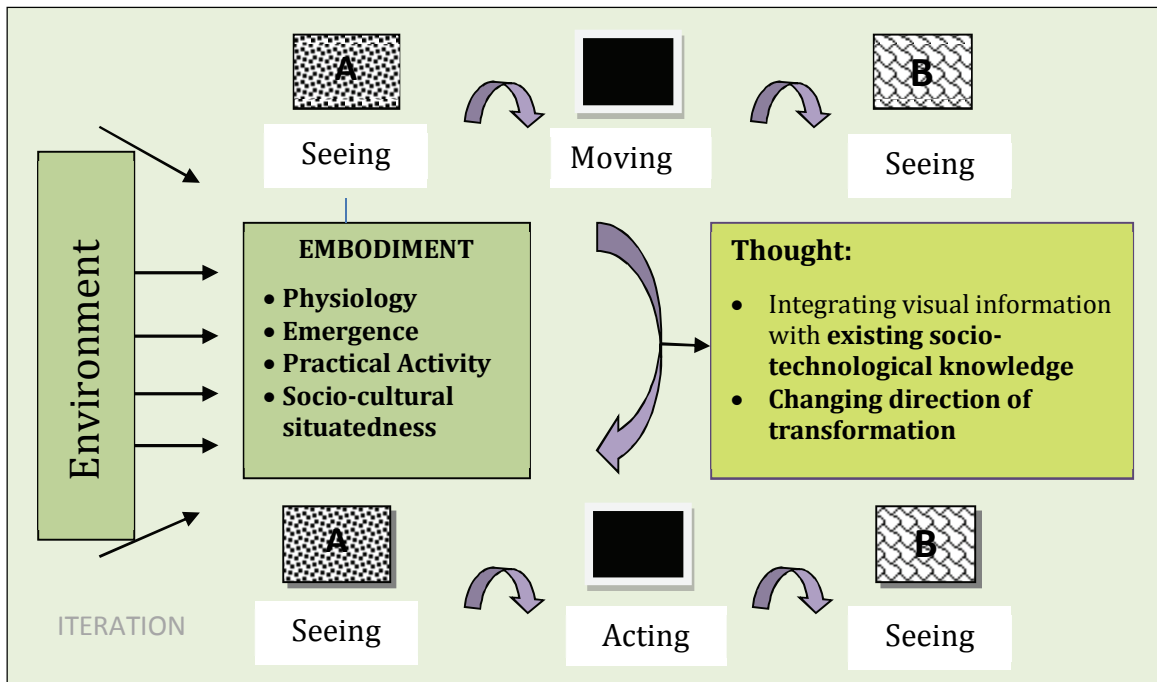
Figure 2.7: **Components of epistemic action** (Adapted from Gero, 1999)

The notion of 'epistemic activity' emphasises the methodological importance of visual interaction of designers with the environment in this study. Whereas conventional protocol studies, conducted in the computational paradigm, rely on laboratory conditions for validity (Cross, 1999; Simon, 1996), I provided the opportunity for designers to interact directly with the environment. In this way, participants were able to perceptually explore the environment in which their design problems were situated. In turn, this provision allowed for a free epistemic flow between environmental stimuli and existing socio-technological knowledge from domain-specific environments stored in their LTM. In this manner, this study acknowledges the difficulty of explaining designers' need for visualisation as well as the kind of cognitive and motor strategies needed to solve design problems (Anderson, 2003; Richardson et al., 2008) during the early phases of design processes.

2.5.2.1   Physiology

Physiology characterises cognitive processes as neurally instantiated. This means that the particulars of perceptual and motor systems play a key role in concept definition and rational inference. Lakoff *et al.* (1999) are primary supporters of the embodiment approach and maintains that human sensor organs are dynamic instruments of exploration, which explains why the immediate output of, e.g. the visual system, can be explained as a series of sensory changes related to the movements of the eye, head and motions of the object received. The implication for design cognition is that what designers see/perceive is determined by the set of changes occurring when they move their eyes over an object. For my study, this means that I

acknowledged the important role of iterative viewing of objects in the physical environment in which design problems are situated and how it contributed to the participants adapting their behaviour accordingly. I focused on instances in the protocols where designers could be observed accessing and using generic and domain specific knowledge by constructing conceptual relations between new information perceived and existing knowledge from their long term memory (LTM) (Gibbs, 2005).

2.5.2.2 Emergence

Embodiment theorists link emergence to physicality and evolution (Gibbs, 2005; Oxman, 2002). The argument is that abstract reasoning builds on and makes use of forms of perceptual and motor inference. Lakoff *et al.* (1999) maintain that the very structure of such reason comes from the details of embodiment. This implies that the same neural and cognitive mechanisms allowing humans to move around in space also create conceptual systems and perception networks. The implications for design cognition are that designers' conceptual reasoning abilities would be constrained by their physiological make up in the same way that their perception is**.** This also implies that the mode of cognitive constraint and its effect on the knowledge of designers is related to source domains of their knowledge. It therefore follows that, if designers are presented with a perceivable environment, the environment and what designers perceive in it, may serve as important source of information. Although the focus of my study was not on the physical neurological structures enabling and characterising design cognition, this aspect helped me to understand the important role that the physical activity of perceiving the environment directly plays in solving design problems.

Classic studies in emergence allude to the important relation between perception and visual representation of the world (Marr, 1982). Recent computational studies revisiting the concept of emergence in design cognition by Oxman (2002) and Suwa (Suwa, Gero & Purcell, 1999) in particular refer to the role that shape recognition and structural recognition may play as triggers for designers structuring and solving problems. Emergence of shape and structure in this context seem to refer to the basic underlying geometric shapes which are only vaguely and mostly ambiguously recognised. This characteristic of emergence in the context of perception and visualisation contributed to my understanding of the necessity of participants to repetitively and iteratively visually revisit the physical environment and change their sketches.

Understanding the notion of emergence in the manner described here had important methodological implications for my study relating to analysing semantic and syntactic properties of both verbal and visual data. Searching for participants' description or sketching of a particular perceived object's shape/structure assisted me to identify moments of perception associated with participants' socio-technological (conceptual) knowledge of objects perceived,

recalled or sketched/described (visualisation knowledge). It further contributed to my identification and explanation of co-occurrences of perception-describing/sketching-perception cycles. It allowed me to identify and explain the changes in direction of transformation in thought processes of participants (refer to section 3.4.3 for theoretical explanations).

Emergence through perception-action cycles seems to be inherent in design reasoning through applying inference and abstraction (Kryssanov et al., 2001; Oxman, 2002). It follows that the inference rules that are instantiated in designers' knowledge, are activated by the dynamic interaction between basic perceptual and visualisation capacities, including LTM and perceptual triggers in particular environments. Such interaction seems to stimulate abstract pattern recognition, knowledge associations, metaphorical expressions and interrelationships. This insight had important implications for my study when considering the types and sources of knowledge that designers represented in their design protocols. Understanding how the mode of reasoning relates to one type of knowledge, interacting with design task environments and influencing emerging relations to other types of knowledge was important when I analysed design reasoning at times when participants applied multiple types of knowledge.

2.5.2.3   Practical activity

The third aspect of embodiment relevant to my study, and closely related to the notion of perception-activity cycles is practical activity. Dynamic agent-world interaction is regarded as being dependent on practical activity in order to avail information required as part of problem solving routines (Anderson, 2003, Gibbs, 2005). Such activity, including looking at objects, space or environment from different angles, organising spatial layout and frequently revisiting the environment, is called 'epistemic activity' (refer to Figure 2.7) (Kirsh & Maglio, 1995). The implication of the nature of these types of activities for this study is that I had to consider that designers do not necessarily plan each step that they take systematically or base it on rational analysis, as suggested by computational theories. I believe the role of activity in design cognition rather suggests involvement of intensive cooperation between computation and internal representation and repeated environmental interactions relevant to design task environments. The physical aspect of embodiment therefore seems to suggest that the cognitive strategies designers employ when involved in design processes are constrained and shaped by the performance characteristics of their bodies as a whole, by their brains' computational resources as well as by the properties of the environment.

Acknowledging the importance of forming representations through active interaction, the conditions for being an agent are that problem solvers are engaged in coping with the world and that they are dealing with the things in it, attempting to understand and come to grips with it. In

an effort to formulate disinterested pictures and coping with things, agents are required to experiment, observe and control conditions (Anderson, 2003).

2.5.2.4   Socio-cultural situatedness

The fourth aspect of embodiment relevant to this study, which is the most complex, relates to the socio-cultural situatedness of cognition and explains the overlap between embodied and situated cognition. The key relevance of socio-situatedness to this study is that designers' interactions with the environment are situated in the context of the design task environment. It is not within the scope of this study to consider the broad aspects of the designers' as individuals' situatedness in particular socio-cultural groupings. I rather considered participants' interactions with the design task environment encompassing individual objects and existing concrete and abstract cultural and social structures embedded in the task environment (Anderson, 2003). The methodological consequence for my study was that I identified references to elements in the environment, as part of their socio-technological knowledge, e.g. physical and functional properties of objects (De Vries, 2006) and their social contexts (Love, 2002). This implies that there is a two-directional relationship between designers' actions and the environment (De Vries, 2006; Mitcham, 2002). On the one hand, the objects resulting from designers' actions might impact on the (social-technological) environment, but on the other hand the environment may constrain and stimulate designers' cognitive actions (Anderson, 2003; Love 2002).

Considering interrelationship between designer and task environment are often an integral part of design tasks, even though they are not necessarily specified in design problem statements. In this study, I particularly formulated design problems in which designers were required to consider the multiple socio-technological aspects embedded in the environment in which the problems were situated. I believe this may contribute to explaining some of the complexities involved in structuring problems and may necessitate designers to access and apply relevant knowledge from multiple domains, besides their domain disciplinary knowledge. Considering the situatedness of authentic problems and the intricacies involved in conceptualising, its impact on problem solving processes in design work is largely absent in the curricula of the technology and design programmes in South African schools. I therefore believe that my study may potentially lead to modelling such situated thinking in these programmes. In this study, I therefore had to design protocols that included epistemic activities involving opportunities for designers to interact with the design task environment and also make inferences about the social and cultural aspects of the design task at issue.

I aimed to examine the possible cognitive role of repeated interaction, including participants' sensations with and conceptions of the environment for perceptually acquiring information

which could play a role in designers' understanding and solving of problems. I attempt to explain the psychological characteristics of the design problem solving space in terms of the relationship between embodiment aspects and socio-technological knowledge in the particular cognitive phases of design processes in Chapter 3. From the four meta-theoretical assumptions underlying embodiment theories, I selected four principles relevant to Goel and Pirolli's (1992) modelling of design task environment and their theory of design problem solving space. The integrations of these four principles and two theories form the basis of my conceptual framework discussed in Chapter 3.

2.6   CONCLUSION

Against the meta-theoretical assumptions discussed in this chapter, I explore the theoretical role of embodiment theory in design problem solving situations in Chapter 3, attempting to compensate for the limitations of computational theories when in isolation. Conventional symbol systems theories have focused on restricting representation as a purely rational activity in order to discover the linear, computational sequences of thoughts under rigid laboratory conditions of experiments. In previous sections of this chapter, I have highlighted how classical computational conventions established the superiority of the experimental approach and prescribed the implementation of controlled studies in which every variable must correspond to and be explained by a particular element of theory (Simon, 1996).

In contrast, embodiment theory determines that the 'true nature' of human behaviour can only be studied naturally as it occurs (Clark, 2006). This resonates with the notion that representation takes place in a symbol system which determines reciprocal sensitivity of properties of semantic and syntactic structures and the nature of the environment in which information is processed. In addition to studying representation in a symbol system as it naturally occurs, the theory of multiplicity of symbol systems suggests that the phenomenon (in this case, representing in design cognition) is much broader in scope than design cognition researchers have been prepared to recognise in the past. In essence, it requires the study of representing not only as the study of discursive language and pictorial data, but also to include other types of non-verbal symbol systems used by designers, namely speech data and body language. It calls for an approach to design cognition that appreciates the various ways in which the natural context, as representative of the initial conditions of the symbol system, is co-responsible for the phenomenon of representing in designing.

Based on the embodiment approach, emphasising that the human body reacts on perception of the environment, and that bodily reactions also represent ideas and attitudes towards information accessed through perception, I extended Goel's (1995) theory of multiplicity of symbol systems within the context of this study. In Chapter 3, I discuss this, arguing that Goel and Pirolli's (1992) modelling of design task environments and problem solving space also allows for the incorporation of embodiment aspects. I subsequently present the conceptual framework of the study.

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CHAPTER THREE

Dynamics of Design Cognition:
Towards a conceptual framework

OVERVIEW

REFINED RESEARCH PROBLEM:

Conventional Information Processing Theories do not sufficiently explain the complex nature of design cognition

REFINED RESEARCH QUESTION:

What is the influence of information processing on representation in design cognition theory?

SUB-QUESTIONS

1.
Which characteristics of design cognition emerge when viewed from the perspective of conventional symbols systems theory?

2.
Which generic characteristics of task environments emerge when viewed from the perspective of ill-structured problems and embodiment theory?

3.
Which generic characteristics of the problem space transpire when viewed from the perspective of ill-structured task environments?

4.
How might the combination of different theoretical approaches, information processing and representation inform us about design cognition of experts in early phases of the design process?

3.1   INTRODUCTION

In the previous chapter, I discussed the manner in which the psychological theories of cognition and the study of design cognition were shaped over time by means of changing paradigms in the cognitive science. The aim of this chapter is not to discredit current theories of design cognition, but rather to reflect on the restrictions in which such current theories function. Based on the discussions thus far, I construct and propose a model combining elements from different theories, with a dominant component from Goel and Pirolli's (1992) design problem solving theory, yet extending this to include selected[17] embodiment principles from ecological psychology and categories of socio-technological knowledge from de Vries (De Vries, 2005). This model guided me in planning my empirical study and interpreting the results I obtained.

For the purpose of this chapter, I focus on Goel and Pirolli's (1992) design problem solving theory (Goel, 1995). In using this particular theory to structure my investigation of the nature of the design problem space and the role of representation in the early phases of the design process, I did not consider design cognition as predictable, sequential computation. I rather view it as a set of complex interrelationships between multiple variables, including the ill-structured nature of design task environments, and properties of symbol systems contributing to the use of knowledge, interpreting the problem, committing to ideas and transforming these into intentions.

I am of the opinion that Goel and Pirolli's characterisation of the design task environment does not sufficiently explain designers' reactions, or its mechanisms, to sources of information in the environment and connections with LTM knowledge. Based on this view, I extend Goel and Pirolli's (1992) characterisation of the design task environment by considering embodiment principles (Richardson et al., 2008). One advantage of such integration of theories is that it could allow me to also consider the role of designers perceiving the physical environment and representations of the environment (Kilgour, 2006) during their design protocols. A further implication is that I could examine adaptive design behaviour by separating embodiment elements as independent and interactive components of the design task environment, as illustrated in Figure 3.1, section 3.3, p.74.

In my discussions, I attempt to illustrate how Goel and Pirolli's (1992) theory of design problem solving, which originated in CTM, might be combined with elements of constructivist theory of embodiment (T. Gomila & Calvo, 2008; Richardson et al., 2008) in order to investigate the constructivist processing of information in the early phases of the design process. I believe that

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[17] In this study I focus on a selection of embodiment principles only, namely affordance, perpection-action, intention-attention, specificity (T. Gomila & Calvo, 2008) to test my modelling of the design problem solving space which is aimed at filling the gap in the design literature reporting on these principles in combination with knowledge.

such a hybrid conceptual framework might lead to a deeper understanding of the complexities involved in real world design thinking, problem solving and representation.

By combining concepts from seemingly opposing theories, namely computational and ecological frames, I acknowledge the possibility of living in a world where the principles of classical computation and contemporary embodiment both hold under different conditions. It is possible to live in a world in which human cognition can be regarded as being rational and illogic, transparent and dense, and specific and ambiguous, depending on the conditions under which it is examined.

In the next section, I define the notion of "problem" in a design context. Thereafter I present the framework that I applied for the purposes of my empirical investigation and analysis, as explained in Chapter 4.

3.2   DESIGN PROBLEM SOLVING

Designing is a problem solving activity considered quintessentially complex. Goel and Pirolli (1992) view this feature of the act of designing as a consequence of the ill-structured nature of design problems resulting in non-linear and unpredictable thought processes that include illusive decision making processes. Much misunderstanding about the nature of the problem solving activity is induced due to different interpretations of the technical meaning of the term 'problem' (L. T.M. Blessing & Chakrabarti, 2009; Visser, 2004). In general, design problems require a designer to intentionally solve human problems by conceptualising artifacts that will be manufactured or constructed by someone else at a later stage (Goel, 1995).

In spite of various different design domains, such as architecture, graphic design, engineering and industrial design, which differ in domain specific particulars, a common core of knowledge, skills and ways of thinking seems to typify design professions (Liikkanen, 2010; Visser, 2004). It is important to understand though, that embedded in the generic ways of thinking is the infused domain specific knowledge that experts have and apply when solving design problems (Popovic, 2004; Sternberg, 1999). Solving design problems therefore assumes a dependence on domain specific knowledge. Following from this assumption, one of the central themes in my study is the exploration of a potential common core set of cognitive activities, including the way designers use their individual domain specific knowledge that particularise their design processes to construct an understanding of what unites them as designers.

I consider problem solving as encompassing a wide range of cognitive activities, involving application of multiple types, forms and sources of socio-technological information common to all design disciplines. This argument results from the design problem space model (Goel &

Pirolli, 1989) as well as expertise studies focusing on common psychological characteristics (Ericsson, 2003; Sternberg, 1999) that might be applied to any design discipline.

The activity of design problem solving involves the mental formulation of future states of affairs, or possible solutions to problems in the form of functional artifacts. The products of design activity are external representations of such possible future states (Goel, 1995) in the form of multiple symbol systems ranging from verbal statements to a variety of visualisation types particular to the specific cognitive phase of the design process in which the designer is at the time of representation. At the core of understanding the interrelationships between representations and such future states in the current study lies an understanding of the cognitive function of accessing and using information and knowledge when structuring and solving design problems as modelled in the design task environment and design problem solving space theories.

The broad notion of design problem solving in this study is a derivative of conventional symbol systems theory (Chapter 2) and consists of three components. The first component contains the information processing system governed by its meta-theoretical constraints, including structure sensitivity and combinatorial syntax and semantics. Psychological constraints are also included such as short term memory limitations and sequential processing. For the purpose of this study I did not consider this first component, but focused on the second component (the design task environment), and the third component (the design problem solving space) (refer to Figure 2.2, p.43).

3.3   DESIGN TASK ENVIRONMENT

Kirsh (2009, p.266) describes task environments as "theoretical projections that let researchers interpret problem-solving activity in concrete situations". Newell and Simon (1972) proposed the notion 'task environment' to indicate an abstract structure corresponding to a problem. As such, the term 'problem' and 'task' are substitutable (Kirsh, 2009). 'Environment' refers to people attempting to improve their task performance by adapting their behaviour to environmental constraints. The implication is that what designers know and do not know, and what information they can access and use and what not, forms part of their task environments. A task environment furthermore demarcates the primary task. As such, it consists of the problem existing in a task environment and functioning in the symbol system. The task environment typically consists of a goal, a problem, and other relevant external factors (Simon, 1973) involved in the symbol system illustrated in Figure 3.1.

Symbol System (Scheme + Relation + Realm)

PROBLEMS

GOALS

OTHER RELEVANT FACTORS
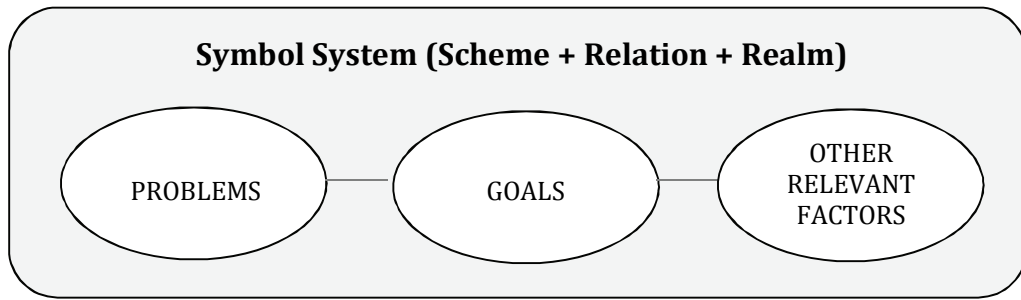
Figure 3.1: **Components of design task environments**

Understanding design task environments requires appreciation of the nature of design problems. The ill-structured and well-structured distinction is based on the distribution of information within each of the three states shown graphically in Figure 3.2. Problem statements, in which each of the state components are underspecified, characterise the ill-defined or ill-structured category. Ill-structured problem task environments thus consist of ill-defined goals, states or operators. This means that such tasks involve underspecified goals and operators. It follows that the knowledge that may enter into a design solution is practically limitless.

PROBLEM STATEMENT   PROBLEM STATEMENT   PROBLEM STATEMENT

Input

START STATE
Insufficiently specified

MEDIATION STATE
Completely unspecified

GOAL STATE
Insufficiently specified

Output

Symbol System

PROBLEMS

GOALS

OTHER RELEVANT FACTORS
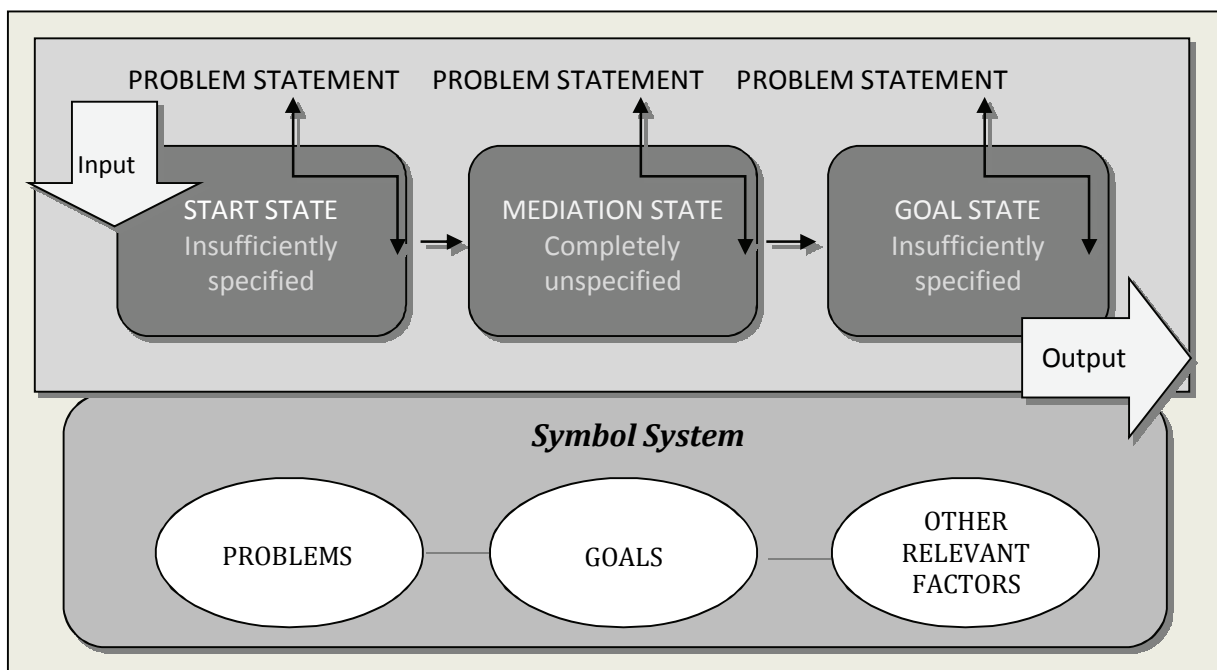
Figure 3.2: **States in design task environment operating in a symbol system**

Goel (1992) explains that the different states of mind of designers correspond with three components of design problems (Simon, 1996). First is the *start state,* which is incompletely specified (Cross, 2001b; Simon, 1996; Vincenti, 1990), second, the *goal state* that is specified even less, and third, the *transformation state* mediating between the start and goal states, also unspecified (Maher & Tang, 2003; Mehalik & Schunn, 2006; Meng, 2009). It is widely acknowledged that all three states of design problems lack information. Therefore, due to this

apparent insufficiency of information in the various states, designers experience uncertainty during most of the design process. Subsequently they need to continuously gather information[18] in order to decrease uncertainty about the input and to help them structure the problem. Experience and expertise usually leads them to generate hierarchies of knowledge/information and recall store-up knowledge (Liikkanen, 2010; Vincenti, 1990). The gathering and processing of information result in 'leaky cognitive modules' (Goel, 1995), where designers constantly move between problem structuring and generating design solutions until the two processes converge to the commitment of a suitable solution. It follows that this constant movement between certainty and uncertainty seems to allow for the characteristic cognitive dynamics typical of generic design problem solving, necessitating designers to interactively access, process and represent their socio-technological knowledge.

Whereas conventional information processing theory specifies what constitutes legitimate actions counting as problem solving behaviour in a task environment, ecological theories consider any action taken by a problem solver during the course of the problem solving process as potentially able to influence the process. This means that external tools can be used as internal scaffolds. The premise in this study is twofold. First, design problems are ill-structured (Reitman, 1964) and are meant to encompass theories or models that generalise across design tasks (Goel & Pirolli, 1989). Second, any external action taken by a person in a particular task environment as a reaction to externally perceived physical objects and elements counts as legitimate problem solving behaviour. The implication of this characterisation of design task environments for my study is that the design of the TAPS meant that participants were involved with physical objects relevant to their internal task environments which were driven by the invariant features of ill-structured design problems as discussed further on.

As a whole, the design problems contained in design projects are characteristically large and complex demanding months, even years to conclude (Goel & Pirolli, 1992; Maher & Tang, 2003). Built into its complexity is the observation that design problems always consist of different parts. Research, however, indicates that little in the structure of design problems prescribe exactly how the designer should decompose a problem. Such decomposition is rather determined by the practice and expertise[19] of the designer (Goel & Pirolli, 1992; Maher & Tang, 2003; Vincenti, 1990). The components or parts of design problems are not logically interconnected, despite many contingent interconnections between them (Goel & Pirolli, 1992). In addition, it is widely accepted that design problems do not have right or wrong answers

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[18] The formulation of design task environments acknowledging a structural space for a conscious search for information, opens the door for me to include the notion of an interactive process of perception through which designers access information from the environment, as explained by embodiment theorists (Anderson, 2003; Bickhard, 2008; T. Gomila & Calvo, 2008).

[19] The way in which expert designers decompose design problems is also central to answering my main research question. Decomposition forms part of the notion of 'problem structuring' which is discussed as part of the conceptual framework of my study in a later section.

(solutions), only better and worse ones (Goel, 1995; Herzig & De Lim, 2006). The 'best answers' are described in terms of their 'appropriateness' or 'fitness' (Goel, 1995; Simon, 1996).

During the problem solving phase, no 'genuine' feedback is provided by the outside world. Real-world feedback comes only after the design has been completed, the artifact constructed and its functioning experienced in the intended environment. At this point, feedback cannot influence the current design project, but only the succeeding comparable project (Goel & Pirolli, 1992). Once an artifact operates in the real word, penalties for weak design decisions can be costly and might affect users, the environment and the designer. Design problems require the artifact that has been produced through the design process to function independently of the designer (Goel & Pirolli, 1992). In the goal state, there is a clear conceptual distinction between the specifications of the artifact from its construction. Lastly, there is a temporal separation between the product specification in the goal state and its delivery. In other words, the specification and delivery/construction of the artifact are separated in time. The implication is that the design specification thus precedes delivery of the end product (Goel & Pirolli, 1992; Maher & Tang, 2003).

I used Goel and Pirolli's (1992) interpretation of the design task environment as a template to structure my empirical investigation. However, these invariants should not be viewed as necessary and sufficient conditions for design activity, but rather as some salient characteristics common to the task environment of problem situations that are consistently recognised as good examples of design activity (Goel & Pirolli, 1992). I concentrated on the first seven invariant characteristics discussed because these seem to fall in the focus area of this study, namely the early phases of the design process. My primary focus was on the sixth invariant, namely that of input/output, specifically on two aspects therewithin. The first is on the content of the information forming part of the input, which guides my discussion of the socio-technological knowledge further on. The second aspect relates to what Goel and Pirolli's (1992) characterisation of the design task environment implies, but does not expand sufficiently on that. Although these authors specify the internal source, namely the design brief, and only by implication allude to 'other external environmental factors' (Goel, 1995), they do not explain how it might be incorporated in their characterisation of design task environments. I attempted to bridge this apparent limitation by incorporating some embodiment aspects, as discussed in Chapter 2 and expanded on later in section 3.4.3.

Despite their usefulness, Goel and Pirolli's (1992) design task environment and design problem solving space theories also pose some limitations (Coyne et al., 1993; Gero, 1998; Van Gelder, 1995). One limitation of their modelling of design problem solving is the fact that it merely explains the invariant characteristics of the problem space in terms of the influence that features of ill-structured problems might have on the behaviour of designers. As such, it does not

consider the complexities and richness that constructivist approaches offer. A further limitation is the view that problem solving is characterised as a sequential and cyclical process (Coyne et al., 1993; Van Gelder, 1995). This characteristic implies that the process could be replicated, which contradicts the constructivist belief that it is not possible to repeat a particular design process (Cross, 1994) because of its situatedness in a unique problem space and task environment.

3.4 DESIGN PROBLEM SOLVING SPACE

It seems important to differentiate between what constitutes design task environments and design problem solving spaces in this study. A task environment relates to the core problem, inclusive of the external environment in which the information processing system operates. On the other hand, problem spaces can be seen as the "representation people are assumed to construct when they understand a task correctly" (Kirsh, 2009, p.266). As such, a problem space can be viewed as a modelling space moulded by the psychological characteristics of the information processing system and the task environment (Ericsson, 1999) resulting in design strategies of designers, including the use of external resources.

On a meta-theoretical level, a problem space can be defined in terms of a state space in which a problem solver (designer) searches for an appropriate solution. Viewed as such, a problem space involves operators that allow movement within space, evaluation functions that measure how close a given state is to the goal or some sub-goal state, and control strategies that guide the search (Simon, 1969). Goel and Pirolli (1992, p.92) developed their problem space theory assuming the notion of 'generic design': "Problem spaces exhibit major invariants across design problem-solving situations and major variants across design and non-design problem-solving situations".

The theory of design problem solving space as modelled by Goel and Pirolli (1992), and the features of the design problem solving that they identified thus do not exist at the level of states, operators or evaluation functions as in the design task environment. The interrelationship between the design task environment and the design problem solving space is significant as each feature of design problem solving space is a higher-level psychological construct which can be explained or justified by relating it to the structure of the design task environment and the information processing system. In this study, I followed Goel and Pirolli's (1992) characterisation of the DPS, considering higher level abstraction in terms of a set of invariant features accounting for generic or universal characteristics of all design problems. This means that I did not consider the characteristics of a design space in terms of states, operators and evaluation functions as is commonly done in many cognitive studies (Simon, 1996).

3.4.1 INVARIANT PSYCHOLOGICAL FEATURES OF THE DESIGN PROBLEM SOLVING SPACE: ROLE OF THE DESIGN TASK ENVIRONMENT IN THE DESIGN PROBLEM SOLVING SPACE

The invariants characterising a DPS can be explained by referring to the structure of the symbols system (see Figure 3.1, section 3.3, p.74) and the salient unique features or invariants characteristic of the task environment of design problems (discussed in section 3.3). These two sets of constraints result in a particular structure of the problem space being a function of the task environment. It can be claimed that design situations exhibit characteristic invariants which collectively constitute a design problem space (Goel & Pirolli, 1992).

Goel and Pirolli (1992) identify twelve invariant features common to all design problem spaces, which played a central role in my research methodology. As discussed extensively in Chapter 4, I analysed the core data sheet consisting of a transcription of participants' verbal protocols in terms of these twelve invariant features (treated as dependent variables in Chapter 4). Following this analysis, I explored which knowledge and embodiment principles could be associated with each feature during the protocols. In Table 3.1, I outline the core of each invariant feature.

Table 3.1: **Outline of invariant psychological characteristics of design problem solving space**
(Adapted from Goel & Pirolli, 1992)

1.	**Problem structuring**
2.	Distinct phases in design development
3.	Reversing direction of transformation function
4.	Solution decomposition into leaky modules
5.	Incremental development of artifact
6.	Control structure and evaluation functions
7.	Making and propagating commitments
8.	Personal stopping rules and evaluation functions
9.	Predominance of memory retrieval and non-demonstrative inferences
10.	Constructing and manipulating models
11.	Abstraction hierarchies
12.	Use of many distinct external symbol systems (Symbol systems correlate with different cognitive processes)

The lack of information in the three states involved in the structure of the symbol system (Figure 3.1, p.74) and subsequent ill-structured nature of design task environments (Figure 3.2, p.74) requires extensive problem structuring. This means that the task structure is typically not well specified in advance and the constraints are non-logical, allowing the designer to negotiate, enlarge, narrow, or simply change problem parameters. The design problem solving phase can

be subcategorised into preliminary design, detailing and refinement. This is probably due to the size and complexity of design problems and the qualitative shift that is required between the input and output information. Given the size and complexity of design problems and the limited capacity of short-term memory, one would expect that problems would be broken into many modules or sections. However, as connections between modules are mostly provisional, designers usually attend to some connections and ignore others. Interim design ideas are nurtured and developed incrementally until they are appropriate for the task. They are rarely discarded and replaced with new ideas. Principal reasons for this are the size and complexity of problems, the sequential nature of information processing, and the fact that there are no right or wrong answers.

Designers typically use a limited-commitment-mode control strategy that can enable them to generate and evaluate design components in multiple contexts (Goel & Pirolli, 1992). Since design plans and specifications are usually required to be produced in a finite amount of time and interpreted by third parties, designers are required to make, record, and propagate commitments. Because there are no right or wrong answers in designing and no real direct feedback from the world, the evaluation functions and stopping rules that designers use will be derived from personal experience and immersion in the project by a designer (Goel & Pirolli, 1992). Since few logical constraints exist regarding design problems, deductive inference usually plays only a minimal role in the problem-solving process. Most decisions result from memory retrieval and non-deductive inferences.

The qualitative difference between input and output information and the several distinct problem-solving phases result in orthogonal abstraction hierarchies (Goel & Pirolli, 1992). Because design typically occurs in situations where it is not possible or feasible to manipulate the world directly, designers usually manipulate representations of the world. Given the size and complexity of problems, the need to construct and manipulate external models and the need for several abstraction hierarchies, designers make extensive use of many distinct symbol systems. Different symbol systems used by designers have different properties that could facilitate or hinder certain cognitive processes.

The benefit of this characterisation of the design problem space for my study is its abstract, yet finely grained calibration that allowed me to conduct rich data analyses and interpretations of the cognitive behaviour of expert designers. Firstly, I could explain participants' behaviour in terms of the logical differences between the participating group's different design task environments resulting in psychological differences at the level of the problem space (Goel, 1995; Goel & Pirolli, 1992; Maher & Tang, 2003). These differences involved the particulars of the design tasks they were required to solve. Secondly, I could explain their behaviour in terms of the cognitive function of each groups' interaction with the environment, the particular socio-

technological knowledge they were required to apply and of the symbol systems they used. Thirdly, it allowed me to draw associative interrelationships between the variables influencing the psychological characterisation of the design problem solving space in a systematic, controlled and unambiguous manner (Goel & Pirolli, 1992). In order to understand the nature of accessing and processing knowledge in the early phases of the design problem solving space, it is, however, necessary to understand what is meant by 'early phases' and their typical characteristics.

3.4.2   EARLY PHASES OF THE DESIGN PROBLEM SOLVING SPACE

Problem structuring and preliminary problem solving is the focus of this study. These early phases are considered as relatively chaotic and uncertain resulting from the usual lack of information. Cognitive aspects during these phases relate to the understanding of:

- strategies that participants employed to expand their knowledge base through direct perception,
- factors that generated their search for information,
- types of socio-technological knowledge they related to their queries,
- how accessing information influenced their adaptive behaviour during the problem solving processes, and
- the cognitive function of the symbol systems they used.

Of further importance to this study is the assumption, based on observation by many cognition researchers (Goel, 1995; Zeiler, Savanovic & Quanjel, 2007), that there is a distinct correlation between the structure of designers' representation and the different phases of the design process. This correlation implies that the representations made when structuring a problem will show different characteristics than the ones designers make during problem solving, as explained in Chapter 2.

Goel (1995) emphasises that designers are usually able to distinguish between the types of information needed in these two phases. As problem structuring is not a clearly distinguishable phase of the design process, but rather an activity designers need to repeat regularly, distinguishing between problem structuring and problem solving is relatively difficult. Goel and Pirolli (1992) found that, in each of these two phases, the nature of the information available at the outset of the process will influence what designers do and why they do it in a particular manner. In my study, I aimed to demonstrate how this theory (Goel & Pirolli, 1992) of the early phases of the design process may accommodate embodiment elements, with the purpose of establishing how the physical environment and representations thereof may serve as triggers for accessing particular types of information when structuring and solving problems.

3.4.2.1   Problem structuring phase: preliminary design

Although some structuring is required in all problem solving situations, one of the hallmarks of design problems is that they require extensive structuring (Goel & Pirolli, 1989; Newell & Simon, 1972). As explained earlier, design problems are typically ill-structured, requiring designers to extensively structure a problem in order to understand its context and scope. Even though problem structuring is a widely recognised concept, it is often unclear as to how it differs from preliminary problem solving. In terms of the design problem solving space theory, the differentiating phenomenon can be identified on the levels of the aspects involving people, objects and contexts of the design considered, the primary source of knowledge, as well as the degree of commitment made to output statements as evidenced by the quantity and character of written output and operators (Goel, 1995).

Problem structuring is regarded as a process during which designers rely on their knowledge from various sources to counteract the missing information in a problem statement and apply this knowledge to construct an ill-structured problem space typical of design problems (Goel & Pirolli, 1992; Simon, 1973). The reason for this is that design problems are usually incompletely specified (start state and transformation state), but also that the specifications (goal state) require complete information about start states, goal states, operators and evaluation functions. Designers thus need to obtain complete specifications in order to construct the problem space (Liikkanen, 2009; Lloyd & Scott, 1994). As design problems are incompletely specified, designers have to compensate for the incompleteness. They compensate by retrieving information from their long-term and external memory. In addition, designers typically heavily rely on the client and design brief as sources of information. During this phase, designers usually consider information at a higher level of abstraction but generally do not commit easily to a particular decision. However, existing theories that developed from classical symbol systems theories do not consider information that designers might access through perception in the physical environment. Therefore, these theories do not sufficiently explain the critical impact that this kind of information might have on design cognition during the problem structuring phase. The cognitive dynamics of designers at this stage involve adding concepts and proposing ideas.

Problem structuring in itself is not considered a problem-solving activity. However, the extent to which it is successful determines the number of sub-problems designers can engage in. In addition, the extent to which problem structuring is necessary and successful determines the nature and extent of the problem solving that occurs. Although some studies indicate that the process of problem structuring typically proceeds through many minute steps (Goel & Pirolli, 1992), for practical reasons of this study, I only focus on the two steps involved in my empirical study. The first step relates to the way in which designers access knowledge to structure design problems. The second step entails the way in which designers negotiate knowledge through

transformation of direction to generate and develop preliminary solutions. In the following section I discuss the problem solving phase, with the focus on preliminary design. This study did not focus on the later phases of problem solving, namely refinement and detailing, as they are not considered as the early phases of the design process (L. T.M. Blessing & Chakrabarti, 2009; Goel & Pirolli, 1992).

3.4.2.2   Problem solving phase: preliminary design

According to Goel and Pirollis's (1992) model, the second phase of problem solving is the preliminary design phase. Here designers generate and explore the alternative solutions emerging during the problem structuring phase. Contrary to my preconceptions, literature abounds that experts usually do not consider many alternative solutions because of their vast experience and ability to make connections with knowledge stored in their long-term memory (Ericsson, 2006). The solutions generated are often only superficial and vaguely developed at the time of generation. Possible solutions emerge through gradual expansion and transformation of a few core ideas involving people, objects and contexts. These core ideas are usually solutions to other problems that an expert designer has encountered previously. Ideas may also stem from other life experiences suggested by associations with ideas and images brought into the problem space. Ideas may thus be out of context and even inappropriate.

Designers also often iteratively adapt their behaviour by changing the direction of transformations laterally and vertically, involving many backwards and forwards movements (Goel, 1995) thereby making copious unusual and unpredictable connections and associations with new and old information. Designers will transform these in order for the ideas to become useful and appropriate for a current problem (Goel, 1995). Transformations during this phase of the process are more likely to be lateral than vertical due to the exploratory nature of the phase. The duration of the incremental development process of solutions is considered a function of the information available (Newell & Simon, 1972) to designers. In the case of experts, it is therefore assumed that, because expert designers possess more and better developed mental resources in the form of long-term memory and working knowledge, they would complete the preliminary design phase in less time than inexperienced designers (Popovic, 2004; Simonton, 2003).

Although much of what is known about the design behaviour of designers in the early phases of the design process is derived from the computational notion that designing is a linear and sequential process consisting of two primary phases, namely problem structuring and problem solving (Simon, 1996), much evidence from empirical research indicates convincingly that in reality there is no clear division between the two early 'phases'. These phases constantly intermingle and overlap or even involve simultaneous cognitive activity, which Goel (1992) calls 'leaky modules'. This means that design problem solving is not a linear process going from

analysing 'the' problem specifications to synthesising 'the' solution. Problems do not pre-exist to solutions, both are built up and elaborated simultaneously (Visser, 2004). It has further been found that, even in the event of the design brief being satisfied by a design being highly specified, design situations are always partly indeterminate (Goel, 1995). In order to structure a design problem by redefining it, designers typically frame a problematic design situation by setting its boundaries, selecting particular elements involving people, objects, contexts and their relations for attention (Vincenti, 1990). In this way designers tend to impose a coherence on the problem space that guides subsequent problem solving activities (Bickhard, 2008). Research further highlights that the actual process of designing will continuously trigger awareness of new criteria for design: so-called 'problem solving triggers' (Visser, 2004) which might include the knowledge accessed by perceiving the physical environment (Ericsson & Simon, 1993; Gibbs, 2005).

The methodological implication of this notion is that even though coherence guided me in the analysis process and discussing the early phases of the design process in two separate sections, it does not imply that I believe that the two phases take place sequentially. I rather consider them as incessantly intermingled, with much cognitive and temporal overlap. At times, even simultaneous cognitive activity, which Goel (1992) calls 'leaky modules', is evident. This means that designers constantly move between the two phases. By incessantly interacting with various sources of information, designers adapt their behaviour and direction of thoughts which enable them to navigate between the phases in multiple directions. These adaptations might be seen in the construction and manipulation of designers' representations.

In order to find more information that may help them structure design problems and search for preliminary solutions, designers usually rely on sources in the external environment (Gero, 1999; Gibbs, 2005). Such sources, including physical objects perceived or representations, contribute to filling the gaps in information received through design briefs. Subsequent design actions can therefore be ascribed to both internal and external sources of information which are processed internally. In this study, making sketches and talking played a central role as two types of design activity. These activities provided evidence of their semantic value thus informing me about the topics that designers paid attention to at particular times during their protocols. Due to its structural sensitivity, the syntactics of visual representations and verbal notational symbol systems, the participants' sketches and verbal protocols furthermore informed me about their structural correlation with the continuously changing structure of the participants' mental states.

In this study, I argue that investigating the physical environment is an inherent part of the design problem solving space. Together with the ill-structured nature of design problems, it influences and constrains the mental states of designers in the same manner as making sketches,

and by the inferential and selective demands made on their knowledge and experiences stored in the memory (Goel, 1995; Newell & Simon, 1972), as illustrated in Figure 3.3.

EXTENDED INFORMATION PROCESSING SYSTEM

COGNITIVE PROCESS → Input · Transforming information · Output

MENTAL STATES → START STATE ↔ MEDIATING STATE · GOAL STATE

INFORMATION (Resources/Products) → Brief / Client / Environment · Perceiving, sketching / Retrieving knowledge / Making inferences / Applying knowledge · Solution / Specification / Working drawings / Blueprint

STRUCTURING PROBLEM ↔ PROBLEM SOLVING

Figure 3.3:   **Proposed model of extended design cognition**

Even though I believe that designers act on what they see, I also support the view that processing information, including perceptions and experiences that serve as continuous inputs from many sources, take place internally (Goel & Pirolli, 1992). I do not consider such inputs as necessarily unified into single objects of consciousness, but that they are integrated in the various states in such a way that they may serve as triggers which will be evidenced in multiple types of representations of designers' thought processes.

In light of design task environment theory and design problem solving theory, interpreting participants' access, transformation and use of knowledge in this current study meant that I assumed that different types of knowledge were used during different states in the design process (Goel, 1984; Vincenti, 1990). Knowledge in the start state is available to the designer in the form of a design brief stating the design task, together with additional information that the client provides either in writing or orally on the request of the designer. This information primarily involves the people who will use the required artifact/system (solution), some specification related to the artifact needed and the context in which the artifact will be used. This means that the design task contains some information about the goals people want to have

satisfied, and the design 'behaviour' the envisaged artifact/system needs to facilitate in order to satisfy those goals (Goel, 1995; Mehalik & Schunn, 2006). However, the information entering the design process through the brief and the client is usually insufficient. Designers therefore need functional information consisting of useful and appropriate knowledge (Ropohl, 1997). Transformation of such information takes place in the mediating state between the input and the output information.

The first premise of this study is that information provided in the design brief is insufficient. The second premise is that expert designers are superior in realising what information they need to understand the nature and scope of a problem required to solve. The third premise is that, in the process of searching for appropriate information and finding a suitable solution, designers interact with the environment while also considering multiple socio-cultural and technological features and aspects involved in the design related to people, objects and contexts. In the following section, I discuss the constructs regarding the knowledge that I considered in examining the cognitive role that knowledge types played in the TAPS of the participants.

3.4.3   KNOWLEDGE TYPES USED IN A GENERIC DESIGN CONTEXT

Design expertise implies the ability to adapt to non-routine tasks and knowing how to utilise knowledge in such tasks (Popovic, 2004). This adapting ability (Ericsson & Lehmann, 1996) of designers is described by Goel (1995; Goel & Pirolli, 1992) as the ability of designers to relate their existing knowledge and prototypical knowledge of expert design behaviour intentionality (Vincenti, 1990). In order to achieve this, designers firstly need to find out what the socio-cultural aspects of the world for which artifacts are intended entails. Secondly, it means that they need to consider the technical aspects of the designed products that are intended as the solutions to problems, and thirdly, it implies analysis of the logic or methodology of their design processes (Mitcham, 1984; Ropohl, 1997; Vincenti, 1990), which includes internal as well as external factors surrounding the design situation (Goel, 1995).

Studying experts' thinking of multiple features and aspects of a design at the same time relates to the study of their superior knowledge levels (Goel, 1995). In the case of this study, such levels relate to expert designers' conscious and tacit knowledge of how they process domain specific and generic socio-technological knowledge through perception, conceptualisation and representation. The specific problem and its context requiring a particular type of artifact, however, determine which knowledge designers would use (Vincenti, 1990). This means that designers need to consciously and subconsciously select appropriate knowledge. This selection involves multiple sub-processes (Sternberg, 1999) involving visualisation, making normative judgments and evaluation, modelling performance, making commitments, decomposing solutions, forming abstraction hierarchies and using multiple symbol systems.

The knowledge that designers use to structure ill-structured design problems and conceptualise possible preliminary solutions have discernible forms and are organised in rich, intricate chunks or schemas. Two forms can be distinguished, namely general and domain-specific schemas. Generally, no schema explicitly surfaces in protocols, although both are easily inferred from the situation-specific statements that subjects make. General schemas contain knowledge about the way the world is. They are acquired over the course of a lifetime and are the primary means of dealing with the world. They consist of at least procedural knowledge, abstract conceptual knowledge, and knowledge of patterns including pictorial and linguistic ones (Goel & Pirolli, 1989). Knowledge of patterns is knowledge stored in such a direct way that much of the original pattern or form is preserved, which implies that there is little generalisation or abstraction. Research (Goldschmidt, 1994; Suwa & Tversky, 2003) shows that instances of specific patterns are visible in protocols. My view is that conscious and unconscious recall of such patterns can contribute to designers being able to visualise and construct metaphoric and literal associations, which can in turn contribute to their conceptualisation of problems and finding solutions.

Domain-specific schemas are built on top of general schemas. They constitute the knowledge acquired during the years of professional training and also consist of procedures, abstract conceptual knowledge, and patterns. Again, such procedures are not visible in protocols. Abstract conceptual knowledge seems to be less fragmented and more theoretical than in the case of general schemas. This is not a surprising fact considering that abstraction is acquired as an organised, systematic body of knowledge (Goel & Pirolli, 1992).

Considering that artifacts are the outcome of design processes in which many different kinds of knowledge are applied requires an understanding of the types of knowledge that may play an important role (De Vries, 2006). The nature and categories of this knowledge have been much debated (Pavlova, 2005; Ropohl, 1997; Vincenti, 1990) resulting in researchers widely acknowledging that technological knowledge has its own unique character (De Vries, 2005; Love, 2002; Vincenti, 1990). Philosophical and epistemological studies show that knowledge used when designing is multi-disciplinary (De Vries, 2005; Popovic, 2004) and encompasses conceptual knowledge as well as procedural knowledge. Based on its logic relations within this study, I considered generic design knowledge as conceptual and procedural knowledge, visualisation, normativity and efficiency, and adequacy, as discussed in the following section.

3.4.3.1 Conceptual knowledge

Abstract conceptual knowledge refers to the generalised knowledge (principles, laws, heuristics) that designers extract and carry away from the totality of their worldly experience. Although much structure and coherency exists in the organisation of this knowledge, it does not

necessarily constitute a theory. It is perhaps better characterised as knowledge fragments or 'knowledge in pieces'. It is discernible in the problem space as situation specific conceptual knowledge.

For the purpose of this study, I considered conceptual knowledge as declarative knowledge about the functional efficiency achieved by selecting particular physical and structural elements of objects including shapes, size and materials. Understanding objects as systems forms an important part of the conceptual knowledge of designers, drawing interrelationships between the different parts of objects functioning as a whole (De Vries, 2005). Depending on the level of expertise, designers also know much about non-technical aspects of a design including economic, social, and juridical, gained through personal and professional experience (De Vries, 2005). In this study, conceptual knowledge does not refer to technical aspects of artifacts only, as is usually the case in engineering studies, but also to non-technical, social and cultural knowledge used by architects and industrial designers as conceptual knowledge guiding their intentions for artifacts.

Knowledge about non-technical aspects in general contributes to designers' understanding of the complex practical and psychological interactivity between artifacts and people (De Vries, 2006), determined by the context of particular design problems (Love, 2002). In this study, I aimed to investigate participants' conceptual understanding of the interrelationships between aspects and how it influenced their problem structuring and problem solving. Identifying conceptual knowledge in the data generated in my study, assisted me to link specific temporal and structural instances in the protocols to designers forming abstraction hierarchies. It also allowed me to recognise designers' access to different sources of information, namely LTM or the environment.

3.4.3.2   Procedural knowledge

Procedural knowledge refers to the knowledge that enables a designer to go through the process of designing in various levels of sophistication dependent on the designer's level of expertise (Oxman, 1997; Popovic, 2004), as well as other external factors characterising the totality of the design task environment (Simon, 1996). In the design process, procedural knowledge includes the ability to collect, compose and manage communication between role players in the context of a problem solving process. Procedural knowledge means that designers constantly manage the flow of information and identify, bring together and manage expertise relevant to the context of a problem (Love, 2002). The many different procedures the participants in my study employed, allowed me to draw associative links with the way in which they mentally structure problems, break them down into manageable chunks, move laterally and vertically and construct and manipulate their visualisations.

It is widely acknowledged (Hubka, 1992; Vincenti, 1990) that procedural knowledge of experts often becomes tacit, which means that they may execute activities embedded in their long term memories which have become 'automated'. In this study, I attempted to demonstrate how participants' procedural knowledge may also be associated with their knowledge of conducting perception-related actions stemming from embodiment principles (section 3.4.4).

3.4.3.3 Visualisation

Visualisation is a fundamental skill in the design process and is described as the ability to 'see' and externally 'make visible' (representing) knowledge embodied in multiple symbol systems used. Recent research into expert visualisation skills explains this skill as a 'marriage of perception and conceptual processes' (Suwa & Tversky, 2003) playing an important role as driving force for solving design problems. It does not fall within the scope of this study to discuss the complexity of visualisation. However, the dynamic role that sketching plays as an activity, but also that a sketch as object plays in the early phases of the design process, is central. This means that I considered visualisation as the act of sketching. I further considered the products of the activity, namely the sketch, as an object which in turn could be perceived and interacted with by the participants in my study. It follows that, by considering sketching as a form of visualisation, and simultaneously viewing a sketch as an object affording information, I particularly focused on the cognitive function of visualisation. By linking its cognitive functions to the sketch as object, I could make theoretical associations with the embodiment principles relevant to my conceptual framework (section 3.4.5).

3.4.3.4 Normativity

How designers use their technical and non-technical conceptual knowledge is not a straightforward process. It is intricately interwoven with their knowledge of functional and technical norms, but also influenced by their belief and value systems (De Vries, 2005; Love, 2002). Explaining the complexity of the role of belief and values in decision making during the design process does not fall within the scope of this study. My primary concern is designers' application of functional and technical norms in the early phases of the design process. As such, I consider 'normativity' in this study as the knowledge about norms applied to functionality, gained by practical experience (De Vries, 2005). By considering the application of normativity in my study, I could make conceptual and theoretical links to participants' evaluation functions and personal stopping rules, both part of the psychological characteristics of the design problem solving space.

3.4.3.5 Efficiency and adequacy

Conceptual knowledge of efficiency and adequacy is intrinsically an engineering concept and refers to knowing when something will work, or be effective, as gained by practical experience. However, knowing when something will work does not only refer to knowledge about the functionality of artifacts or parts thereof. It also includes personal knowledge about the efficiency and adequacy of procedures (De Vries, 2005) typically guiding designers to make evaluations and judgments on which design procedures to follow. As in the case with normativity, efficiency and adequacy could be linked to evaluation functions and personal stopping rules of designers.

In different design domains 'efficiency and adequacy' seem to have different meanings and applications. I thus treated this concept in an open way. This means that I considered different driving forces playing a role when designers' cognitive processes involved evaluation and personal stopping rules. It is by applying all the different kinds of knowledge that designers are able to structure design problems and generate preliminary concepts about solving them. However, they do so in the context of the particular nature of design task environments, determining the cognitive strategies involved in the process (Goel & Pirolli, 1992).

During the early phases of the design process, designers typically rely on their LTM for accessing visual information that might assist them in conceptualising and structuring problems, as well as triggering ideas for solutions. One source usually available to designers in real world design problem solving tasks is the terrain in which the problem is situated. In the following section, I discuss some embodiment principles underlying the assumption that designers use perceptions of the environment as source of information.

3.4.4 PERCEIVING INFORMATION FROM THE ENVIRONMENT IN DESIGN PROBLEM SOLVING

Interacting with the environment in which a design problem is situated seems to be an assumption often taken for granted and not often integrated into computational models (Oxman, 2002). In this section, I explain how I expanded on existing theories of both computation and embodiment in developing a model that could allow me to consider both in one study. The premise of embodiment is that whenever people encounter a situation, they use a combination of experiential (domain specific knowledge) and situational factors to assist them in defining the situation (Lovett & Anderson, 1996). The implication for my study was to investigate the relation between existing knowledge (stored in the LTM) and situational information in structuring the design problem.

Considering embodiment elements is based on ideas from ecological psychology claiming that what people perceive, how they conceive, and what they do develops simultaneously and is adapted to the environment. Recently, cognitive science has provided some insight into human activities where cognition and knowledge are emergent properties of the interaction of an individual with the environment, i.e. the current situation (Clancey, 1997; Gero, 1998). Gibbs (2005) states that human perceptual experience is often considered to arise from the input of information from the world through the five senses to different regions of the brain. The implication of this view is that all human activity involves embodied correlations and cannot causally be related in a linear way. Although I agree with the 'non-linear' argument of embodied perception, I exploited systematicy of computational analysis as a strategy to explore non-linear processes, searching for a logical manner of structuring the data (refer to Figure 2.7). This means that I did not use computational methodology to explain causality, but rather as a way to investigate and structure the complexity of simultaneous and interrelated cognitive activities.

Within the context of this study, I therefore assume that for a model to be useful for researching design cognition, it must have the ability to associate how designers access information that is not evident in the design brief to the physical environment within which the design problem is situated. In constructing a transparent model for describing design behaviour in greater detail, I find Goel and Pirolli's (1992) model of design task environment (derived from computational notions) vague in terms of explaining 'other relevant factors' as one of the components of task environments (Gero 1998). I consider 'other relevant factors' to include embodiment elements and their role in the early phases of the design process. The combination of design problem solving space theory and embodiment notions is graphically illustrated in Figure 3.4. Following the figure, I explore possible ways of integrating selected embodiment notions in my study against the background of Goel and Pirolli's explication of the design task environment and design problem solving space.

START STATE
Underspecified goals and operators

Knowledge entering design solution including
1. DESIGN BRIEF containing some, (but underspecified) information about:
   - PEOPLE who will use the OBJECTS
   - goals they want to have satisfied, and
   - the design behaviour the OBJECTS needs to facilitate in order to satisfy those goals
   - the CONTEXT in which PEOPLE will use the OBJECTS
2. Psychological constraints, including MEMORY (long and short term) containing stored knowledge obtained from previous experiences.
3. PHYSICAL ENVIRONMENT and REPRESENTATIONS affording information and contributing to memory construction.

No logic interconnections

MEDIATION STATE
Underspecified goals and operators

Filling the gaps in the information through structuring the problem including questioning and perceiving

TRANSFORMING INFORMATION AND KNOWLEDGE
through a search process and interactions with the
ENVIRONMENT and REPRESENTATIONS

GOAL STATE

Underspecified goals and operators

OUTPUT: Artifact SPECIFICATION

No logic inter connections

Figure 3.4: **Adapted structure of design task environments allowing for embodiment elements**
(Adapted from Goel & Pirolli, 1992)

Embodiment principles underlying the approach illustrated in Figure 3.4, relevant to my study, are namely affordance, perception-action, intention-attention and specification of information, selected from Anderson's (2003) *Embodied Cognition: A field guide* because of their ability to guide me through a naturalistic search for insights in the interaction between existing knowledge and situational knowledge. The methodological value of focusing on these notions was that it allowed me to identify how the participants, guided by their intentions, and construction of associative connections between existing and new information heeded the situation. The processes involved in considering the environment have also been described as key to the cognitive processes of 'pushing-and-pulling' involving interactive sensation, perception and conception (Gero, 1999) of participants during the early phases of the design process. Although this list is not exhaustive of ecological psychology's view of embodiment, I selected these particular principles as they seemed to resonate naturally with my interest in the

relationship between perception and existing knowledge. It further allowed me to expand on Goel and Pirolli's (1992) theory of design problem solving space and fills the gaps in explaining the connections between perceptions of the situation, accessing knowledge in the LTM and constructing new knowledge in the design task environment. Such explanations may assist me in adding facets to existing understandings of the design problem solving space characteristic of expert designers from an information processing point of view.

3.4.4.1 Affordance

Affordances are real, discoverable properties of the environment and objects in such environments independently of them being perceived. Researchers have thus far not been successful explaining how designers purposefully perceive such properties in the environment in order to fill the gaps in information (Gero, 1999) entering the start state of the design process. In this study, I aimed to explain how participants purposefully searched for such information through perception in order to structure the problem more effectively.

The claim is made that affordances are neither physical nor mental (Gibson, 1977). The world and everything in it is viewed as neutral. This implies that affordance is neither an objective nor a subjective property. As such, the environment presents possibilities for action. This means that by discovering properties of the environment, designers will be able to act upon it in an informed manner. In this study, I aimed to explain how perception and different types of knowledge, including that of patterns and abstract knowledge, can interact during the mediating state through affordance (Gibbs, 2005).

Even though embodiment studies indicate that designers only react to information which they consider relevant to the design task, these studies do not account for the complex process of establishing what is relevant to the problem through continuous search processes (Cross & Dorst, 1998). Existing studies lack explanation of the multiple possible engagements in considering irrelevant affordances due to a lack of information in the different states of design task environments. They further fail to show how designers, when describing the environment, may transform the notions of the properties of substances, surfaces, places, objects, and events observed (Gibson, 1977) into preliminary solutions. In this study, I aimed to demonstrate how the realities of the observed environment grounded at the ecological scale may influence designers' ability to consider multiple inter-relational aspects when taking design decisions. For example, substances vary in size, shape, viscosity, density, cohesiveness, elasticity, and plasticity-variations. This has implications for the suitability of material chosen for a design and can therefore serve as opportunities or possibilities for action by designers (Gibson, 1986; Michaels, 2003). In order for designers to perceive what an environmental surface, substance,

place, object, or event offers requires of them to interpret what their observations mean (Reed, 1982; Reed & Jones, 2009).

Although affordance theories do much to sensitise researchers about the significance of perceptual information in the design process by relating it to the surface (physical) features of the environment, these theories fail to relate affordance to the functional nature of objects. It therefore does not account for how designers may relate their perceptions to their knowledge of the dual nature of objects (De Vries, 2006; Mitcham, 2002), namely its physical nature and their functional nature. I set out to augment this apparent limitation by integrating affordance theory with Goel and Pirolli's (1992) conceptualisation of accessing knowledge in design task environment in this study.

3.4.4.2 Perception-Action

The notion of affordance is logically related to that of perception, as affordance implies that properties are perceived. The embodied view of perception is that perception cannot be understood without reference to action. Gibbs (2005) explains that people do not perceive the world statically, but by actively exploring the environment. In a design context, this notion of interactive perception seems to be confirmed by many reports of researchers following situated design (Gero, 1998; Schön & Wiggins, 1992), information processing (Ferguson, 1992; Goldschmidt, 1994; Tversky, 1999) and epistemology (Vincenti, 1990).

Of importance to my study is the notion of perception-action resulting from embodiment's understanding that all human activity involves embodied correlations. This means that perceptual systems facilitate humans' interaction with a real, three-dimensional world. As such, perception is an act of perceptually guided exploration of the environment. The function of vision is therefore seen as keeping the perceiver in touch with the environment and to guide action, and not produce inner experiences and representations (Gibbs, 2005). Affordance therefore enables designers to recognise what objects, parts of objects or properties of objects, which are part of the physical environment in which the problem task is situated, can be used to guide them in the decisions they take. The implication of this notion of perception-action for my study is that I looked for instances when participants came to understand the nature and scope of their design problems through epistemic knowing and knowledge as perceived, rather than conceived (Richardson et al., 2008; Shaw, 2003). While computational theories rely on centralised representational-computational processing results in the view that perception and action are distinct and separate processes, embodiment theories determine that they are part of the same continuous and cyclical process (Anderson, 2003). This embodiment insight determines that designers, their knowledge and the environment are part of the same continuous and cyclical process. This in turn results in the notion of continuous and cyclic

perception and action, assuming that designers perceive and act with intentionality at all times (Cross & Dorst, 1998).

Although I support the epistemic notion of knowing, the cognitive function of perception and perception-action theory's regard of the environment as what is to be known, I find the definition of 'environment' as 'surface' environment to be limited. I also find embodiment's requirement of three-dimensional objects limiting. In my study, I view 'environment' as a design task environment as a whole, including many more sources of information than only the 'surface' of the environment. This implies that I will consider 'environment' encompassing two and three-dimensional objects, including representations of the environment such as photographs, individual objects, sketches and verbal descriptions of interpreting perceptions.

3.4.4.3 Intention-attention dynamics

Closely related to the idea of affordance, and perception-action, is that of intention-attention. The latter notion aims to answer the question related to 'how it might be possible for designers to act on their perception'. Key to answering this question is the notion of intention-attention dynamics and its relation to symbols, which resonates strongly with the classical computational theory of mind notion of intention as discussed in Chapter 2. Both approaches acknowledge that 'intention' on the whole means to solve a problem, or reach a particular goal (Bickhard, 2008; Goel, 1995; Visser, 2004).

From an embodiment perspective, the process involved in intention-attention dynamics seems to, involve possible direct acts of labelling, which can create a new realm of perceptible objects (the associated tags or labels) for designers. It is the actual presence of such tags or labels, or even of their imagistic counterparts, that seems to alter the computational burdens involved in certain kinds of problem-solving. Embodiment theories explain that the role of symbols further includes helping de-couple designers from the immediate pull of the physical ecological scene encountered and perceived. Explaining the cognitive function of the role of symbol systems used by expert designers as such, resonates with the psychological understanding of the interaction of (internal) goal intentions and external implementation intentions. Gollwitzer and Schaal (1998, p.121) state that:

> *When people furnish their goal intentions ("I intent to attain goal x") with their implementation intentions ("I will initiate the goal-directed response y when situation z arises"), the initiation of goal-directed responses becomes automatized.*

These authors attribute such acts of will as 'strategic automisation' being embedded in their procedural metacognition. This means that experts know when to use their drawings to aid them in reminding them of prior intentions which were interrupted by other thoughts or information. This insight is supported by Suwa and Tversky (1997) in a study exploring the way

architects shift their attention from one thought/item to another. The theory also implies that experts know where to look for useful information and pay attention to possible physical aids, and know when to use them to facilitate their focusing on their intention.

In my study, this means that I looked for symbols such as labels, affording new perceptible targets that designers selectively pay attention to and thus find a new focal point controlling action supported by much research in the area of the role of sketches in design (Garner, 1994; Goel, 1995; Goldschmidt, 1991; Oxman, 1997). It further implied that I identified the contextual use of object names (Clark, 2006) or depictions in sketches, as well as processes of attention giving, that relate to pattern recognition providing guidance for action (Anderson, 2003). I attempted to relate the semantic elements of sketches and verbal protocols to the different types of knowledge from an intention-attention point of view, which Goel (1995) implies in his significant work, *Sketches of Thought*, but does not explicates in these terms.

I distinguished between intentions explicating the end goals of the participants' envisaged artifacts and their own implementation intentions, based on cognitive science theory (Dewitte, Verguts & Lens, 2003; Gollwitzer & Schaal, 1998). The goal intentions in my study denote end goals of artifacts, whereas implementation intentions denote the plans the participants made in order to attain goal intentions through activities. The various subclasses of their intentions centered on the empirical data generated by the protocol studies associated with theoretical concerns (see Chapter 4). In interpreting the data, I argued that in order to secure intentions, designers had to generate and develop thoughts that were consistent with one another and with their intentions. Bratman (Kieran, 2011) calls this 'principles of means-end' coherence.

The embodiment principle of intention-attention played an important role in my distinguishing between higher order and medium order intentions and lower order external elements. The higher order goal intentions were referred to as an abstract conceptualisation of physical and/or functional properties of an intended artifact; whereas medium order implementation goals refer to participants articulating how they intended to achieve such goals. Goal intentions could originate from the client or the participant reversing the client's intention or adding supplementary intentions of their own. The intentions can be associated with the information processing theory (Goel, 1995; Simon, 1969). In turn, the external elements can be linked to embodiment theories dealing with situated cognition (Kirsh, 2009; Robbins, 2009). When the participants persistently paid attention to lower order thoughts that conformed to their higher order goal intentions, this indicated to me that they were driven by an overarching internal goal (Dewitte et al., 2003; Searle, 1983). In order to find out how the participants used the information embodied in the external lower order situational elements that they perceived and their internal knowledge when incrementally structuring their design tasks and develop

solutions, I further connected the participants' use of such knowledge to their medium order implementation intentions and higher order goal intentions (Dewitte et al., 2003).

3.4.4.4 Specification of information

One of the implications of the notion of 'affordance' (discussed in section 3.4.5.1) is that information accessed by designers perceiving environmental properties is specific in nature. In this study, I argue that it is this specification of information that contributes to designers' ability to structure a particular design problem as the environment affords information lacking in the start state of the design process. I further argue that it is the specificity of such information that stimulates recall of knowledge of patterns, which contributes to designers generating possible solutions.

Specificity of information involves the rendering of certain patterns found in ambient energy arrangements as unambiguous with respect to certain properties of the world (Runeson, 1988). Because embodiment theory assumes specification, it allowed me in this study to explain how participants perceived the nature of accessed information (Richardson et al., 2008). This means that the notion of 'information' is reserved for perceiving (and recalling) patterns that uniquely specify properties of the world (Richardson et al., 2008), which do not represent themselves in ambiguous terms as the information in design briefs do. By considering the patterns or similarities between old and new ideas that participants referred to, I could make associative links between specificity of information and their formation of abstract hierarchies (Goel's (1995) pattern recognition).

I therefore agree with the embodied view that the physical world typically affords specific information about itself. However, when designers receive their design briefs, they often find a discrepancy between the specificity of the requirements in such briefs and what they actually perceive when they perceive the real world in which the problem is situated. The objects they perceive afford much perceptual detail regarding the physical nature of objects. In my study, I attempted to identify moments where perceiving physical specificity of objects could be associated with deliberation about the functionality of objects. In contrast with the specificity of information afforded by perceived objects, the information of objects referred to in the design briefs participants received was typically underspecified (Goel & Pirolli, 1992) (as discussed in section 3.3). This discrepancy often led to an interesting interplay between the information given in the design briefs and that which the environment affords. I attempted to establish what this interplay involved and what the cognitive function of the specificity of the information, embodied in the physical environment was. The implication was that I considered multiple sources including participants' sketches (as objects), and not only that of the environment, and

that I regarded the dual nature (physical and functional) of the physical world as significant for interpreting design reasoning.

I furthermore acknowledged the possibility of integrating embodiment theory of affordance, perception-action and intention-attention notions with information processing theory as characterised by design task environment, and modelled by Goel and Pirolli (1992). This implies that designers could be seen as being compelled to explore both the physical environment, and other sources of information in a particular design task environment.

Thus, my argument in this study is that designing is a process experienced within the environment which a designer encounters through the context of a design task. Accounting for the environment entails that accessing information cannot be limited to the internal components of a design task at hand but has to take the whole environment in which the task has to be integrated in the transformation process. Such insight into designing implies the notion that 'where you are, when you do what you do, matters' (Clancey, 1997, p.291). In the following section I illustrate how I integrated embodiment principles with Goel and Pirolli's (1992) modelling of the characteristics of the design problem solving space in my conceptual framework.

3.5   CONCEPTUAL FRAMEWORK OF THE STUDY

In Chapters 4 and 5 I apply the hybrid conceptual framework explained in this section. The aim is to demonstrate the cognitive behaviour of participants as listed here:

- How and where they found perceptual cues as sources of their action.
- What the flow of information was.
- What and how knowledge guided their decisions.
- How they detected missing information.
- How they accessed missing information.
- What sequencing connections between sub-processes were made.
- How information and knowledge changed the direction of transformations.
- Which factors contributing to solving problems, co-existed.

In Figure 3.5 I illustrate the hybrid conceptual framework that guided my empirical research and interpretation of the results that I obtained, in terms of the cognitive behaviour discussed in section 3.5.
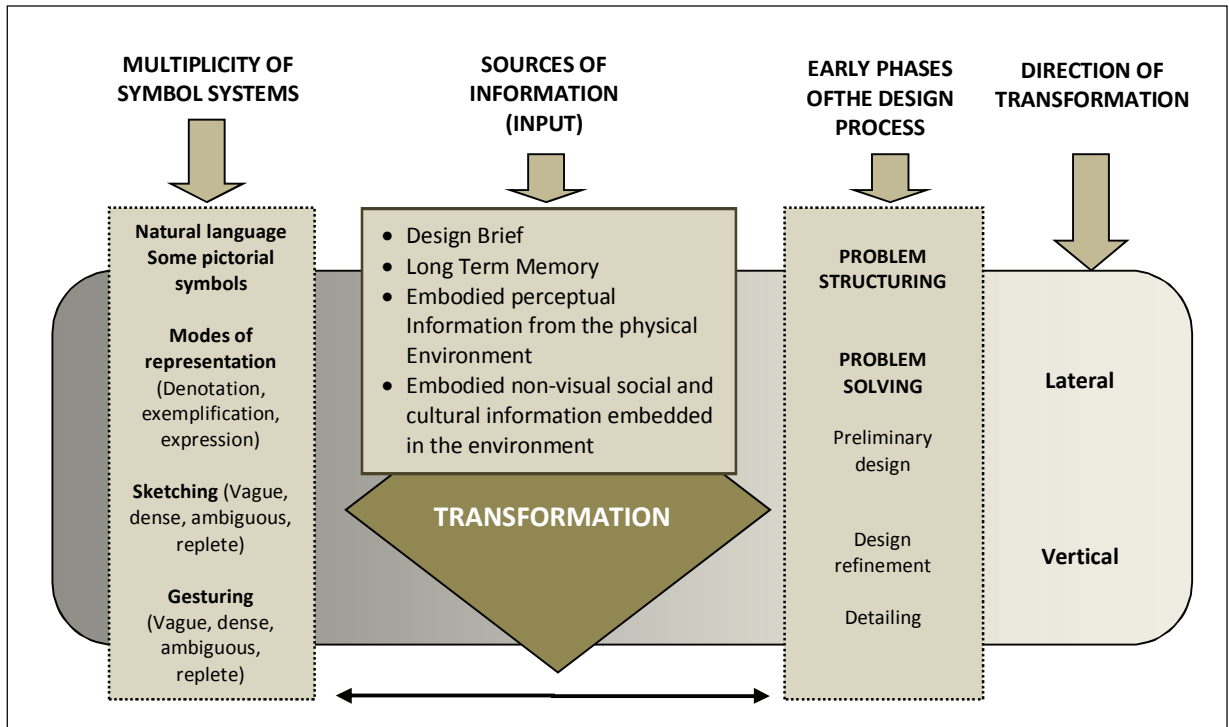
Figure 3.5: Hybrid conceptual framework integrating computational theories with constructivist theories

Next, in Table 3.2 I summarise the theories underpinning Figure 3.5 and the implications thereof for my study.

Table 3.2 **Summary of the theory of multiplicity of symbol systems**

MULTIPLICITY OF SYMBOL SYSTEMS (Goodman, 1976)	
THEORETICAL COMPONENTS Notational and non-notational Theory	**THEORETICAL ASSUMPTIONS**
• Notation implies multiple use of multiple symbols, including verbal and non-verbal types.	• Symbol systems play a significant role in design cognition.
• Symbol systems can thus be regarded as 'modes of reference', which can exemplify, express as well as denote meaning	• Symbol systems shape concepts.
• Properties of symbol systems indicate/correlate with the properties of mental states: Density, ambiguity, vagueness.	• Structure of symbol systems consist of three components called 'states': Start state, Mediating state and Goal state.

The implication of Goodman's (1976) multiplicity of symbol systems theory for my study is that I considered both notational (verbal) and non-verbal (visual) symbols systems used by the participants as equally significant and valid in representing the psychological characteristics of

the problem solving space. This means that I used the transcriptions of participants' think-aloud verbal protocols as well as the sketches they produced concurrently as data about their cognitive processes. The methodological implications of this assumption were that I analysed each symbol system in terms of its semantic and syntactic properties, considering each exemplified, expressed and denoted meaning. Semantic properties allowed me to interpret the meanings and conceptual themes participants talked about or sketched. From the semantics, I could infer which socio-technological knowledge participants used to reason and which embodiment principles played a role in changing the direction of the transformation as well as the properties of participants' thoughts. Syntactic properties allowed me to detect structural correlations between the observable symbol system used, e.g. ambiguity and vagueness, and the different states involved in the problem solving process. The theoretical implication of this assumption is that I could link the properties of the symbol systems to participants' 'states' during the design process. If a symbol system that was used during the start state and primary mediating state, when designers are typically uncertain, the symbol system usually displayed vague and ambiguous properties. It follows that the more certain and committed designers get as the design process progresses, the less ambiguous and more specific the structural properties of the symbol system, may be. In Table 3.3 I present a summary of the theory of the design task environment (DTE) integrating embodiment principles.

Table 3.3:   **Summary of the theory of DTE integrating embodiment principles**

1. SOURCES OF INFORMATION (INPUT)	
THEORETICAL COMPONENTS **Design Task Environment + Embodiment principles** (Goel & Pirolli, 1992)	**THEORETICAL ASSUMPTIONS**
• Design task environment is different from other types of problems. • Underspecified 'states': Start state = design problem Goals = specifications for solution Mediation state = no information • Sources of information: Design brief Client LTM Environment ▪ Physical elements embody. ▪ Perceptual information based on selected embodiment principles (affordance, perception-action, intention-attention and specification)	▪ Design problems are complex, ill-structured and have no right or wrong answers. ▪ Constraints are involved, requiring the use of knowledge when considering design aspects. ▪ Nature of design problems influences the cognitive structure of the design process and psychological characteristics in the problem solving space. ▪ All mental states in the DTE lack information and knowledge. ▪ Designers access various sources of knowledge. ▪ Cognition and knowledge are emergent properties of interaction with the environment.

The implications of the DTE theory (Goel & Pirolli, 1992) for my study was that I assumed that the particular nature of the design tasks that I required the participants to complete had a direct influence on the type of information they were lacking at the start of their protocols. I further assumed that the ill-structured nature of these design tasks required them to access information from various sources at their disposal, including the design brief (which was underspecified), the client (underspecifying information), LTM relying on stored generic experiential and domain specific knowledge stored, and information embodied in the environment. The methodological implication of this theory was that I had to formulate design problems that could allow the participants to access the various sources of knowledge that would contribute to shaping the psychological characteristics involved in the design problem solving space. By formulating the design tasks as such, and allowing the participants to interact with the environment physically and perceptually, I was able to create a naturalistic quasi-experimental situation yielding naturalistic behaviour.

I considered the assumptions of the design task environment theory, including the embodiment principles, as independent variables influencing the design problem solving theory discussed further on. The implication of this decision was that I had to individuate moments in the protocols when I observed participants interacting with the environment to access perceptual information not provided in the brief or by me (the client/researcher). I further had to be sensitive to the actions following such moments of interaction and what the implications were for the way in which the participants adapted their thought processes and actions. The theoretical implication for being cognisant of the influence of the nature of the design task environment was that I could link embodiment principles with phases of the design process, as well as with knowledge participants accessed through their long term memories. In Table 3.4 I summarise the salient characteristics of the early phases of the design process relevant to this study.

Table 3.4: **Summary of the theory of design problem solving space in the early phases of the design process**

THEORETICAL COMPONENTS **DPS** (Goel & Pirolli, 1992)	THEORETICAL ASSUMPTIONS Psychological characteristics of the DPS

• Generic characteristics encompassing all design disciplines.
• Design process consisting of cognitive phases:
  Early phases:
    Problem structuring
    Preliminary problem solving
  Middle phases:
    Developing solution
    Refining solution
	• Problem structuring.
	• Distinct phases in design development.
	• Reversing direction of transformation function
	• Solution decomposition into leaky modules.
	• Incremental development of artifact.
	• Control structure and evaluation functions.
	• Making and propagating commitments.
	• Personal stopping rules and evaluation functions.

• Leaky modules	• Predominance of memory retrieval and non-demonstrative inferences.
	• Constructing and manipulating models.
	• Abstraction hierarchies.
	• Use of many distinct symbol systems which correlate with cognitive structure of phases.

The implications of the DPS theory (Goel & Pirolli, 1992) for my study were that it allowed me to study designers' behaviour encompassing design disciplines and to focus on generic design behaviour. By considering the theory involved in defining the notion of early phases of the design process, I could focus in depth on the cognitive structures of the participants' behaviour when structuring and solving problems until completion of the conceptual, preliminary solution. However, the theory of design problem solving space also assumes that there is no clear cut delineation between the cognitive phases, and that 'leaks' occur. This means that an overlap often occurs between the cognitive phases when designers 'leak' issues. The methodological implication was that I individuated the problem structuring and problem solving phases in the protocols, and that I had to be sensitive for 'leaky' modules (episodes in time when designers heed to a particular theme). I considered the assumptions of the theory, identifying the psychological characteristics of the design problem solving space as the dependent variables which could be influenced by the design task environment. This decision required that I structured the verbal and visual data in such a way that I could individuate each of the assumptions of design problem solving space, not only in temporal measurements, but also in the various cognitive phases of problem structuring and problem solving. In Table 3.5 I summarise the theory of direction of transformation.

Table 3.5:   Summary of the theory of direction of transformation

2. DIRECTION OF TRANSFORMATION CHANGE	
THEORETICAL COMPONENTS (Goel & Pirolli, 1992)	**THEORETICAL ASSUMPTIONS**
• Reversing direction	• Reversal visible in utterances.
	• Transformational operations between successive sketches visible.
	• Derived from manipulations of sketches.
• Lateral transformation	• Lateral movement: movement from one idea to a slightly different idea; use to generate new ideas. occurs in preliminary problem solving phase; sketches are dense and ambiguous.

• Vertical transformation	▪ Vertical movement: conceptual movement from one idea to more detail and specific version of same idea; use to develop one idea; are more specific and contain more detail. ▪ Sketches can be viewed computationally and from embodiment. ▪ Consider semantics and syntactics to make inferences about cognitive phases and conceptual themes.

Considering directional transformation in thought processes from utterances allowed me to detect instances of adaptive behaviour where participants reversed the direction of transformation from client/brief to designers, to one of designer to client/brief. By analysing sketches, I could identify processes containing participants' lateral transformation of their thoughts as well as vertical transformations. The computational approach meant that I had to individuate moments when sketches were started and identify what their source was. By carefully studying the sequential order in which sketches and verbal utterances occurred in the protocols, I could establish whether a sketch was syntactically and semantically new, or whether it originated from a previous sketch or utterance. By considering the embodiment principles relevant to my study, I considered what perceiving the text in a brief, or perceiving and contemplating their own sketches while making them or in retrospect, meant for the participants.

Computationally viewed, consideration of the source of a sketch was important. If a sketch was syntactically new, it indicated the generation of a new idea, usually implying lateral movement. To me, the typical density and ambiguity of this type of sketches indicated non-commitment, which could then be correlated to the preliminary problem solving phase. Drawings originating from previous drawings usually indicated vertical movement, meaning that participants were developing a previous idea by adding detail. From a syntactic point of view, the notion of transformations visible in sketches resonated with the embodiment view of perception. The semantics embedded in the different types of sketches were also embodied in such sketches. This means that I could derive the meanings of the sketches, embodied in their shapes and positions, and relate this to the different types of knowledge the participants implicitly used to either generate a new idea or develop an existing one. Using the directional typology of sketches to analyse and interpret the participants' sketches allowed me to draw inferences to the different psychological characteristics in the design problem solving space.

3.6 CONCLUSION

The aim of this chapter was to synthesise elements from different approaches organised around a hybrid conceptual framework consisting of units with three different approaches. In the first unit, Goel (1995) built on Goodman's theory of notationality and non-notationality (refer to Chapter 2) to conceptualise the notions of directional change of transformation and the syntactic correlation of symbols systems with particular states during the design process. This development of Goel allowed me to explore the role of perceived information and socio-technological knowledge stored in the LTM of participants, and how they interact with their representations. The second unit relates to Goel and Pirolli's (1992) characterisation of generic invariant characteristics of DTE and DPS founded in information processing theories. These theories are both embedded in the computational approach to researching design cognition. The way in which these authors adapted classic symbol systems theory to that of design problem solving situations allowed me to integrate this with the third unit, namely Gibson's (1977) affordance principles rooted in embodiment theories. These theories are embedded in the ecological psychological approach.

Viewing design tasks in this way vindicates my belief that studying design behaviour should include consideration of the environment as a whole, in which design problems are solved (Goel & Pirolli, 1992). In analysing, selecting and discussing existing literature, I was directed by the foci of my study as determined by the research questions and the aims of the study. In addition, I focused on possible subfields in which my study could potentially contribute to the existing knowledge base of design cognition. In the next chapter, I describe the empirical study I undertook.

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CHAPTER FOUR

Research Methodology:
Design and Implementation

4.1   INTRODUCTION

In Chapters 2 and 3 I provided theoretical background and a conceptual framework for my study. The fundamental background provided in these chapters served as a basis for the way I planned and conducted an empirical study. This basis enabled me to firstly explore and describe the manner in which expert designers access internal and external information and how they adapt their behaviour through information processing in the early phases of the design process. Secondly, it allowed me to explain how a modified methodological approach to conventional protocol studies based on computational assumptions might contribute to existing theory on research methodology in design contexts.

Research Purpose	• To explain and describe interrelations between expert designers' use of situational information and internal knowledge and cognitive processes • To expand on the theory of design problem solving space and design task environment in terms of intentional states • To explain an innovative methodological manner to conventional protocol studies based on computational assumptions
Epistemology	• Critical Realism

Approach	• Mixed methods: parallel QUAL-quan implying:
	  • Quantitative data and qualitative data
	  • Parallel data analyses
	  • Deductive and inductive reasoning
	  • Integration of data interpretation

Research Design	• Case study design using protocol studies (TAPS)
Participants	• Members from the community of expert designers
Strategies	• Informal interviews • Modified concurrent think-aloud problem solving (TAPS) protocol study, including concurrent protocol study, including production of sketches • Observation • Research dairy
Considerations	• Ethical principles
Outcomes	• Findings that are valid, credible, trustworthy, reliable and typological

Figure 4.1:   Overview of research methodology

In this chapter, I argue the methodological choices that I made in terms of the research questions and purpose of this study. As an introduction, I summarise the main research components (Figure 4.1). I then explain my selected paradigms, describe the research design I implemented and explain the process of data collection, analysis and interpretation. I conclude the chapter with discussions on the rigour of the study, the challenges I faced based on the choices I made, and the ethical guidelines I adhered to.

4.2   PARADIGMATIC APPROACH

Paradigms serve as foundational sets of premises that enable researchers to make knowledge claims about what knowledge is. Research frameworks are assumed to be rooted in a particular worldview serving as the lens through which meaning is made of what the researcher perceives and understands as the truth (Creswell, 2003; Denzin & Lincoln, 2008).

I support the view of research paradigms upheld by Danermark et al. (2002) that there should be congruence between the purpose of a study, the ontological assumptions about society and reality, and the epistemological conceptions of how knowledge is possible when selecting a research methodology. I was guided by my ontological and epistemological positions in selecting a research field from a computational point of view combined with an ecological point of view (Clark, 2006). Computational theories guided my understanding of the structure of the thought processes of expert designers, while ecological theories contributed to my understanding of the way in which designers learn and access external situational knowledge (Schuh & Barab, 2007). Therefore, I adopted a critical realist approach for this study.

4.2.1   CRITICAL REALISM AS EPISTEMOLOGICAL PARADIGM

Critical realism is an anti-positivist movement in the social sciences using the term 'critical' to refer to a transcendental realism that rejects methodological individualism and universal claims to truth (Denzin & Lincoln, 2008). Over the years, mixed approaches lead to mixing qualitative and quantitative research methods (see Tashakkori & Teddlie, 2003; Johnson & Onwuegbuzie, 2004). As this study mixes approaches and research methods (Tashakkori & Teddlie, 2003), I combined seemingly opposing approaches. I explain subjective interpretations (of cognitive behaviour including embodiment) by drawing causal links (relying on theory) (Danermark et al., 2006). Table 4.1 summarises the main components of critical realism which I employed in my study.

Table 4.1: **Critical realism** (Adapted from Denzin & Lincoln, 2008)

CRITICAL REALISM	
Methods	**Quantitative and Qualitative**
Logic	Deductive and Inductive Use theory to analyse
Epistemology	Modified dualism, findings probably objectively true
Ontology	Critical or transcendental realism
Axiology	Inquiry involves values but they may be controlled
Causal links	There are some lawful, reasonably stable relationships among social phenomena, these may be known imperfectly and causes are identifiable in a probabilistic sense that changes over time

By taking a critical realist stance, I was able to create a conceptual framework guiding the formulation and answering of my research questions. I thus embarked on this study striving for objectivity and neutrality. However, I acknowledge my own social situatedness underlying the theories, the set of ideas and concepts, values and methods determining my specific view on how reality (of design cognition) should be understood and studied (Denzin & Lincoln, 2008; Patton, 2008). I therefore challenged the dichotomous and polarising view that a researcher should necessarily select only one particular view in opposition to another. I assume that one does not necessarily need a unified view of the world in order to conduct successful research, and support the view that mixed method researchers do not all share the same epistemological assumptions (Denzin & Lincoln, 2005; Maxwell & Mittapalli, 2010). Critical realism is currently described as a philosophical perspective that validates and supports fundamental aspects of both quantitative and qualitative approaches while identifying some specific limitations of each (Maxwell & Mittapalli, 2010). Lakoff (1987, p.xv) lists critical realism's distinctive characteristics as: a commitment to the existence of a 'real' world; recognition that reality places constraints on concepts; a conception of truth that goes beyond mere internal coherence, and a commitment to the existence of stable knowledge of the world.

Critical realism differs from scientific objectivity (Cohen et al., 2007; Denzin & Lincoln, 2008; Goel, 1995) by assuming that the world is the way it is, while acknowledging that there can be more than one scientifically correct way of understanding reality in terms of conceptual schemes with different objects and categories of objects (Lakoff, 1987, p.265). This means that critical realism retains an ontological realism while accepting a form of epistemological relativism or constructivism.

The contribution of critical realism to mixed methods research has been widely recognised (Maxwell & Mittapalli, 2010; Pawson, 2006). The particular contribution of critical realism in

this study is embedded firstly in the way in which causal descriptions are made (which is different from typical positivist causal explanations), resulting from social experimental studies. Secondly, the study's contribution relies on critical realism's approach to mind as part of reality, and thirdly, it relies on the particular stance towards validity and inference quality, as well as in diversity as a real phenomenon, as explained by Maxwell and Mittapalli (2010) (also refer to section 4.3.7).

The pursuit of a critical realist stance implies that, even though I participated as a researcher, I acknowledged that diverse components in my study were co-created by the reasoning and problem solving abilities of expert designers from engineering, architecture and industrial design interacting with the physical environment in which non-routine design problems were situated. I considered this particular reality as one consisting of typical experiences of the participants' internal and external worlds, existing independently from my participation. As researcher, I aimed to reflect on the mechanisms resulting in expert designers' problem structuring and problem solving activities (Ericsson, 2006) as objectively as possible. At the same time, I allowed for relativism (Maxwell & Mittapalli, 2010). In an attempt to achieve this, I include various external representations by participants in my discussion of predetermined themes (derived from my 'toolkit' of diverse conceptual frames) in Chapter 5. Therefore, in following a critical realism stance, I attempted to keep a critical objective distance between myself and the co-created reality that I researched, as well as the experimental experience of the participants, thereby bridging the conventional divide between laboratory experiments and naturalistic design situations. I conceptualised design problems for participants to solve and consequently acted as 'client' during their design protocols in the attempt to co-create an insider view (emic perspective) (Cohen et al., 2007; Denzin & Lincoln, 2008; Tashakkori & Teddlie, 2009).

In line with this critical realist stance, my axiological assumption was that my research was both theory laden and value laden, and partly biased. I acknowledge the fact that, despite my endeavours to base my study on the theory of design cognition, and my attempts to authentically report on the reasoning and problem solving of the participants making use of theory, my interpretations cannot be regarded as completely free from my subjective voice. This might be ascribed to the fact that my background differs from those of the participants. I appreciated the fact that the participants are experts who had been solving design problems in their individual disciplines for more than fifteen years, winning several awards in design competitions locally and being regarded as experts internationally. In terms of my rhetorical assumption, I decided to use a dominantly neutral writing style in this study in an attempt to convey my attempt at obtaining critical objectivity.

4.2.2 RATIONALE FOR TAKING A CRITICAL REALIST STANCE

My first reason for taking a critical realist stance in this study is based on the process approach to causality which is viewed as fundamentally referring to the actual causal mechanisms and processes that are involved in particular events and situations. This approach enabled me to exhibit the ways in which the ecological mechanism of intention-attention involved in the design process bridged the internal worlds of the participants (their design problem solving space) and their external situations of the design task environment. By analysing the underlying cognitive mechanisms involved in design cognition captured during design experiments, it was possible for me to identify and explain the events and processes by which some events may influence others (Maxwell & Mittapalli, 2010). Critical realism is emphasised by the context dependence of mechanistic description, which allowed me to draw complex relationships between causal mechanisms and their effects that are not fixed, but contingent. This fundamentally means that such a relationship depends on the context within which the mechanism operates.

The second reason for my choice of a critical realist stance relates to Maxwell and Mittapali's (2010) argument that critical realism treats mental entities as equally real to physical ones when making sense of the world. Understanding the notion of making sense of the world further implies that critical realists are compatible with the idea that different valid perspectives on the world exist. For this study, such understanding entailed that the perspectives I held, as the researcher, are part of the world that I wanted to understand, and that such an understanding of perspectives could be more or less correct. In this study I thus recognised the reality and importance of meaning, as well as of physical and behavioural phenomena, as having explanatory significance (Maxwell & Mittapalli, 2010). In considering both individuals' perspectives and their situations as real phenomena, critical realism however sees these as separate phenomena that causally interact with one another. One advantage of a critical realist stance to this study was therefore that it enabled me to provide a framework that would allow a better understanding of the mental entities involved in the relationship between participants' perspectives on design problem solving processes and the actual design problems they were given to solve experimentally.

The third reason for using a critical realist stance relates to the critical realist position towards validity and inference quality, which differs from the typical procedure-based approaches of quantitative and qualitative approaches to validity. Both these approaches focus on providing evidence of the procedures used in collecting data and drawing inferences from. In contrast, validity, from a critical realist point of view, is not a matter of procedures, but of the relationship between the claim and phenomena that the claim is about.

A critical realist approach to validity in my study did not entail concepts, theories or claims reflected or correspondent to reality. It rather meant that the workability of the claims I made depended on their relationship to a reality independent of human constructions. It therefore seemed to be important for me to test claims against the evidence relevant to the claims. The claims testing process involved differentiating between different types of claims, each requiring its own type of evidence (Maxwell & Mittapalli, 2010). I differentiated between claims about meanings and perspectives which fall under interpretive claims, claims about behaviour, and claims about the relationships between variables. I provide descriptions, explanations and interpretations in later chapters, supported by evidence, while also aiming to address plausible alternatives about the claims I make.

The fourth reason for selecting a critical realist point of view is its assumption that diversity is a real and significant phenomenon. Where quantitative research often aggregates data across individuals and settings, it ignores individual and group diversity that cannot be subsumed into a general explanation. By emphasising general descriptions and causal theories, quantitative research tends to impose or generate wide-ranging, but simplistic models that do not account for individual variation and unique contextual influences. Similarly, qualitative research is inclined to neglect diversity in the emphasis on uniformity and shared values and perspectives in communities. This tendency is often seen in the sampling methods of participants being so purposefully selective that it fails to identify and characterise the actual diversity existing in a studied population in order to make some generalisations (Maxwell & Mittapalli, 2010).

The quantitative parts of this study provided me with tools that focus on particular phenomena and processes, and their unique contexts. Similarly, qualitative methods provided me with the tools to provide systematic evidence for diversity and helped to correct a tendency to ignore complexity and to focus on typical characteristics and shared concepts and themes. In this study, critical realism thus enabled me to integrate the two approaches coherently with the aim to increase the usefulness of the two approaches (Cohen et al., 2007). In addition, critical realism allowed me to mix different approaches to design cognition, namely the computational approach (representing post positivism) and the embodiment approach (representing constructivism).

Ultimately, an advantage of taking a critical realist stance to design cognition was that it contributed to my acquirement of an overall picture as well as the description of some detail (Maxwell & Mittapalli, 2010) about embodiment principles associated with mental states and information processing involved in the early phases of the design process. When the perspectives of the participants were interpreted, I preferred to use the term 'personal' instead of 'subjective', because of the latter's value-laden association with bias and unreliable outcomes or results based on the perception that 'all is in the eye of the beholder' (Rose, 2001; Van Leeuwen & Jewitt, 2010).

In this study I aimed to obtain a deep understanding of the internal mental states of the participants during the early phases of their design processes. I aimed to grasp these mental states, which can be associated with interactive perception of an external environment. This entailed a consideration of the actions and experiences of selected expert designers, which encompassed various design domains, and how these mental states changed during the course of the early phases of the design process through interaction with their external design environments. I aimed to describe combined reconstructions of pairs and teams participating, and acknowledge the possibility of using existing theory as building blocks, adding to the knowledge of generic design behaviour with the primacy of practical knowing resulting from my participatory role of observer.

The qualitative component of this study implied that I brought my own personality and history to the study. Being a Fine Arts and Social Sciences female, white graduate, implies the possibility of bias and subjectivity (Tashakkori & Teddlie, 2009). As such, I had 'no clear window into the inner lives' (N.K. Denzin & Lincoln, 2008, p.9) of the participants I observed. I believe that my gazing into participants' lives was filtered through the lens of my own personal design experience and ideas around design problem solving. I aimed at keeping my own voice as neutral as possible throughout my study. I aimed to identify some of the 'truths' in the reality of design cognition as closely as possible. Where objective interpretation was not a possibility, I provided participants with sufficient opportunities to clarify issues. I thus searched for confirmability (Guba & Lincoln, 2008). In addition to my own multiple readings and re-readings of participants' representations, I requested several knowledgeable people and peers to scrutinise my coding and interpretation.

4.2.3   MIXED METHODS APPROACH AS METHODOLOGICAL PARADIGM

I selected a mixed method approach and made use of a mixture of multiple and diverse tools which showed congruence with a critical realist stance. I thus mixed quantitative and qualitative methods to study the data I collected on the cognitive processes of three groups of expert designers in three successive phases over a period of one year. I believe that the application of a mixed methods approach was best suited to answer my research questions, which required data analytical techniques that could accommodate complex sets of *a priori* qualitative categories and themes statistically as well as qualitatively. A mixed methods approach provided me the opportunity to count incidents, map the distribution of co-occurrences on a timeline in terms of themes and sub-themes, and determine sequences of events. I followed the theoretical stance of Janice Morse (2010) towards the procedures and practice of a mixed methods design because of the clarity of her explanations and its relevance to this study in terms of maintaining control,

rigour and complexity. The study falls under the category QUAL-quan, which implies the dominance of the qualitative elements of the study.

Because the research questions focus on explanations of instances, exploring relationships, co-occurrences and sequencing implied questions about mechanisms, my study is primarily deductive with a qualitative theoretical drive, indicated by 'QUAL' (Creswell, 2003; Morse, 2010). I support my qualitative explorations and explanations through the presentation of quantitative findings in the form of temporal identifications of instances and tracking of distributions and sequences of events and their contexts. The current study can thus be described as complex and multi-layered. I used Tashakkori and Teddlie's (2010) frame regarding characterisation of multi method research designs, I summarise the salient features of this study in a reflective manner in Table 4.2.

Table 4.2: **Salient features of this study characterised in terms of Tashakkori and Teddlie's (2010) framing of a mixed methods study**

• Methodological eclecticism	I integrated appropriate techniques from multiple QUAL + quan mixed methods. There is one core data set for each participating expert design group, namely verbal utterances mapped temporally with design sketches. I qualitatively analysed and interpreted the data, supported by quantitative counts, sequences, distributions and associations.
• Paradigm pluralism	I observed that a variety of paradigms may serve as the underlying philosophy for the use of mixed methods. I adopted a position of critical realism.
• Emphasis on diversity at all levels of the research enterprise	I addressed a diverse range of confirmatory and explanatory questions, resulting in divergent conclusions and inferences. The observations, verbal protocols and visual material data sources yielded complex multi-layered information. From this I made conclusions about the socio-technological knowledge expert designers accessed and processed by interacting with the physical environment. I also made divergent inferences about the mechanisms involved in the design process in order to solve design problems.
• Emphasis on integration rather than a set of dichotomies	I considered a range of paradigms in terms of integration. This resulted in a multivariate model for my research methodology which included naturalistic inquiry, ecological psychology, and interactive perception, semiotics and transformation, and knowledge.
• An iterative, cyclical approach to research	My research cycle moved from grounded results (counts and temporal measurements of occurrences in the design protocols) through inductive logic to general inferences (abstract descriptions of typical characteristics in the design problem solving space). From these general inferences about the 'process', I moved through deductive logic to tentative hypotheses about the mechanical role of the physical environment on the behaviour of designers.

• Focus on the research question in determining the methods employed	My research question was central to all methodological choices. This allowed for congruence between the ontological, epistemological and methodological issues relevant to my study which determined the way in which I analysed, interpreted, applied quality measures and reported on my research.
• 'Signature' research designs and analytical processes commonly agreed upon	The QUAL + quan sections of my research occurred as independent, simultaneous strands. I rigorously collected verbal and visual data. I attempted to provide a trail of evidence so as to ensure validity as part of the inferences I made. I also addressed plausible alternative descriptions, explanations and interpretations of designers' behaviour.
• Implicit tendency towards balance and compromise	I did not seek confrontation between opposing paradigms or approaches (QUAL + quan), but rather looked for a way to create productive and negotiated dialogue between the two.
• Reliance on visual representations	My analysis of the data lent itself to visual representations such as diagrammes, tables and graphs that simplified the complex interrelationships among QUAL and quan elements. I made use of a notation system that allowed me to communicate in a convenient and shorthand manner.

4.3   RESEARCH DESIGN AND METHODOLOGY

In this study, I focused on a small group of expert designers in a semi-controlled environment, which resonated with my critical realist stance and mixed methods approach. This study is a case study which describes the cognitive processes represented in the think-aloud protocols (TAPS) of three groups of expert designers from different domains involved in the early phases of their design processes. I employed parallel qualitative and quantitative strategies, based on concurrent TAPS protocol studies. I captured the moment to moment thought processes of the participants (Crandall et al., 2006) together with the production of concurrent sketches involved in the early phases of their design processes.

4.3.1   RESEARCH DESIGN

I selected a case study design using concurrent TAPS protocol studies, and applied critical realism principles. The concept 'protocol study' is grounded in Campbell's philosophy of critical realism (Blessing & Chakrabarti, 2009) and is used in social research situations where it is not possible to employ true experiments.

This case study approximates true experiments in the sense that I had control over 'the who and to whom' of measurement, but lack of control over 'the when and to whom of exposure' (Cohen et al., 2007). In order to conduct true experiments in this study, it would require artificial settings which would make it impossible to elicit the naturalistic behaviour from participants

necessary for answering my research questions. I therefore modified the conventional experimental research design using a case study design with selective control.

In this study I had control over the selection of participants that constituted the 'who and to whom of measurement' (Cohen et al., 2007). I selected a homogenous group of expert designers from the broader community of designers. In addition, I controlled the design tasks that participants were required to solve and parts of the setting in which the experiments took place. However, parts of the protocols took place in environments of participants' choice, such as the particular design studio's they preferred to work in. I further controlled the context in which design tasks were situated (see section 4.3.4.3, Excerpt 1), but did not have control over when participants preferred to interact with their contexts. I also did not control the 'when and to whom' exposure as participants determined their own dates to partake in the experiments. Participants furthermore selected their own 'thinking partners' over which I had no control. In order for me to answer my research questions from a critical realist point of view, I relied on the application of several theories embedded in the conceptual framework that I presented in Chapter 2 and 3. I summarise this research process in Figure 4.2.

Phase 1	Preliminary Survey of the Field		
Instruments	**Approach**	**Purpose**	**Rigour**
Pilot study	QUAL +	Test conceptual framework	Validity
Informal interviews	quan	Test methodology	Credibility
Reflective diary		Affirm the rationale	Reflection of legitimate inquiry and warrantable knowledge
Literature survey		Conceptualise study	
		Establish relevance and fit	Multiple instruments
			Ensuring fit
			Reflexivity
Phase 2	**Sampling**		
Type		**Purpose**	**Rigour**
Purposeful sampling		Elicit knowledge from human specialists representing all design fields	Honesty: requirements and expectations
			Consent: benefits, risks
			Transferability
			Representativeness

Phase 3	**Concurrent Data Gathering and Capturing**		
Instruments	**Approach**	**Purpose**	**Rigour**
Concurrent TAPS	QUAL + quan	Cross referencing	Validity
Data: Verbal protocols	parallel model	Counting occurrences	Multiple appropriate instruments
Visual: Hard copy of hand sketches		Measuring units of time	Trustworthiness
			Triangulation
			Controlled observations

Phase 4	**Structuring Data**		
Instruments	**Approach**	**Purpose**	**Rigour**
Constructs	QUAL	Establish correlation between semantics of symbol systems and relevant constructs	Limit researcher bias
Criteria	Quan		Maximise objectivity
		Renders concepts embedded in theoretical schemes observable and manipulable	Theoretical validity:
			Explaining phenomena sufficiently
			Construct validity ensuring external validity

Phase 5	**Data Analysis**		
Instruments	**Approach**	**Purpose**	**Rigour**
Constructs	QUAL +	Establish correlation between semantics of symbol systems and relevant constructs	Limit researcher bias
A priori criteria	Quan		Maximise objectivity
Categories		Renders concepts embedded in theoretical schemes observable and manipulable	Theoretical validity:
Time measurement and numbers			Explaining phenomena sufficiently
Cross-Impact analysis			Construct validity ensuring external validity
Reflective			

Phase 6	**Reporting and Dissemination**		
Integrated parallel model	**Approach**	**Purpose**	**Rigour**
Multivariate	QUAL +	Integrating QUAL + quan findings	Triangulation
	Quan	Correlation and cross referencing	Interpretive validity
	Narrative	Classifying, grouping and pattern recognition	External validity
	Tables and diagrammes	Patterns	Sum of standardisation
		Renders	Mean unit durations
			Member checking

Figure 4.2:   Phases of the research process

4.3.2   SELECTION OF PARTICIPANTS

For the sake of diversity and identifying generic behavioural patterns, I identified one expert designer each from architecture, mechanical engineering and industrial designing. I selected the

field of architecture as architects are known as designers of socio-cultural artifacts in which the knowledge of semiotics and aesthetics play an important role (Lawson, 2006; Suwa & Tversky, 1996) and mechanical engineering because they are acknowledged designers of technical artifacts which demands technical and theoretical knowledge that involves movement and mechanical advantage (Vincenti, 1990). I selected industrial design as a discipline as it represents a group of designers that specialise in both technical and social knowledge to ensure effective people-object interaction (Eastman, 2001; Krippendorff, 2006).

Relating patterns in this way did not mean that I underemphasised the importance of the participants' domain specific knowledge. It rather meant that I used their discipline specific knowledge to explain the context and specific detail of generic design characteristics (Goel, 1995). This decision could confirm existing research findings and shed additional light on understanding generic expert design behaviour. I took care to ensure similar levels of expertise amongst the three identified designers (Ericsson & Charness, 1999), using the criterion of expertise to select the participants. I was guided by expertise studies carried out by cognitive psychologists towards the identification selection criteria for the participants in my study (Ericsson, 1999, 2003, 2006; Ericsson & Charness, 1999; Ericsson et al., 2009). I namely matched the participants on the grounds of their generic expertise in design instead of similar domain specific knowledge. Table 4.3 provides the selection criteria that I employed (Crandall et al., 2006; Ericsson, 2006).

Table 4.3: **Criteria for expertise** (Adapted from Crandall et al. [2006], Ericsson [2006] and Hoffman [1992])

Superior declarative and procedural knowledge of domain
Rich mental models enabling them to understand a wide range of causal connections that govern how things work
Exceptional ability to apply mental models fluidly and flexibly as events change
Exceptional perceptual skills that enable them to notice subtle cues and patterns
Superior memory of previous design cases
Exceptional memory performance in general for arbitrary detail
Superior retrieval of appropriate ideas that they have stored in memory during past experiences
Superior encoding of essential information
Superior ability to integrate new information into effective solutions
Possess exceptionally varied set of routines that enables them to find some way of approaching problems
Superior outcomes of solving problems
Exceptional ability to generate better ideas
Superior ability to recognize patterns and experiences into prototypes

| Exceptional ability to judge when dealing with a typical event and when faced by something that needs attention |
| Superior ability to encode and manipulate internal representations |
| Exceptional ability to discover potential threats very soon |
| Superior ability to develop new solutions |

Expertise in any domain requires individuals to have engaged in at least ten years of intensive training and experience (Ericsson & Charness, 1999). After my initial selection of design disciplines, I identified and accessed particular experts in the relevant discipline based on this criterion first. Thereafter, I approached professional and academic institutions that I know through personal association with design associations and through my work as fulltime lecturer in design methodology and TE at the University of Pretoria. Continual networking with academics involved in design education, engineering courses, researchers and leaders in the design fraternity in other parts of South Africa, the United Kingdom, The Netherlands and France further afforded me the opportunity to expand my study and select additional experts from different design disciplines.

The process of accessing and involving experts in design experiments is often problematic due to the competitive and demanding real world environment in which they work (Blessing & Chakrabarti, 2009). However, in this study, accessing suitable candidates in architecture and mechanical engineering did not pose problems. I contacted participants and secured introductory interviews with both groups without difficulty. Contrary to this positive experience, accessing a suitable participant in the industrial design field proved difficult, primarily due to the scarcity of industrial designers in South Africa who qualified through recognised academic universities or universities of technology. Eventually, I accessed an industrial designer through a colleague at a design faculty. After introductory telephone conversations and the provision of information about the research, I explained the envisaged experimental procedures via email to each identified expert designer. I also arranged personal meetings and informal interviews which served to establish mutual trust between me as the researcher and the participants, familiarising them with the intended procedures, the time and setting involved as well as their TAPS protocols. The purpose of these interviews was to ensure representation and quality matching of participants in terms of my selection criteria (see Table 4.3, p.118). I particularly aimed to ascertain the importance of interactive perception in their thinking processes (Ericsson & Charness, 1999). During the interviews, I was open to any suggestions from the participants' side to keep the experiments as natural as possible. Participants responded differently to these discussions, but everyone demonstrated his awareness of what would elicit his own natural expert abilities and what would inhibit it (Ericsson, 2006; Ericsson & Lehmann, 1996).

On the participants' request, I fulfilled the role of the 'client' in this study, who could interact, give information as well as ask questions in order to keep the experimental situation as natural as possible. Agreeing to participate in the protocols as client, researcher and generator of the design brief, and being involved in their process of structuring the design problems subsequently had methodological implications. While I intended this participation to enhance the naturalistic approach to the experiments, I could not become involved in the problem solving phase of the design problem or interfere with the natural directional transformation changes during their reasoning processes when solving the design problems. I decided to adapt the conventional concurrent TAPS protocol studies which resulted in 'snowball sampling' (Cohen et al., 2007), as the participants all selected thinking partners that they considered as equally expert as themselves. The architect and engineer chose to work with one partner each, while the industrial designer preferred to work with two team members to solve their design tasks. All participants agreed to work until they had arrived at an appropriate conceptual solution for the problem, allowing for a maximum of three hours. This meant that the problem could not be too complex. These interviews subsequently served as clarifying the detail of the data collection phase which resulted in the procurement of informed consent.

4.3.3   DATA COLLECTION AND DOCUMENTATION

Johnson and Turner (2003) recommend that in mixed methods research, methods should be mixed in such a way that it has complementary strengths and no overlapping weaknesses. In adopting a mixed methods approach, I collected data that could yield both objective quantitative information such as counts and temporal measurements, and personal qualitatively derived information, which resonated with my critical realist stance (Maxwell & Mittapalli, 2010).

4.3.3.1   Overview of data collection process

I decided to conduct the primary data collection in three phases, with each phase entailing a separate concurrent TAPS protocol study for the three selected teams of expert participants. This required participants to produce design sketches concurrently. I implemented these phases over a period of one year, from June 2010 to May 2011, as illustrated in Figure 4.3.
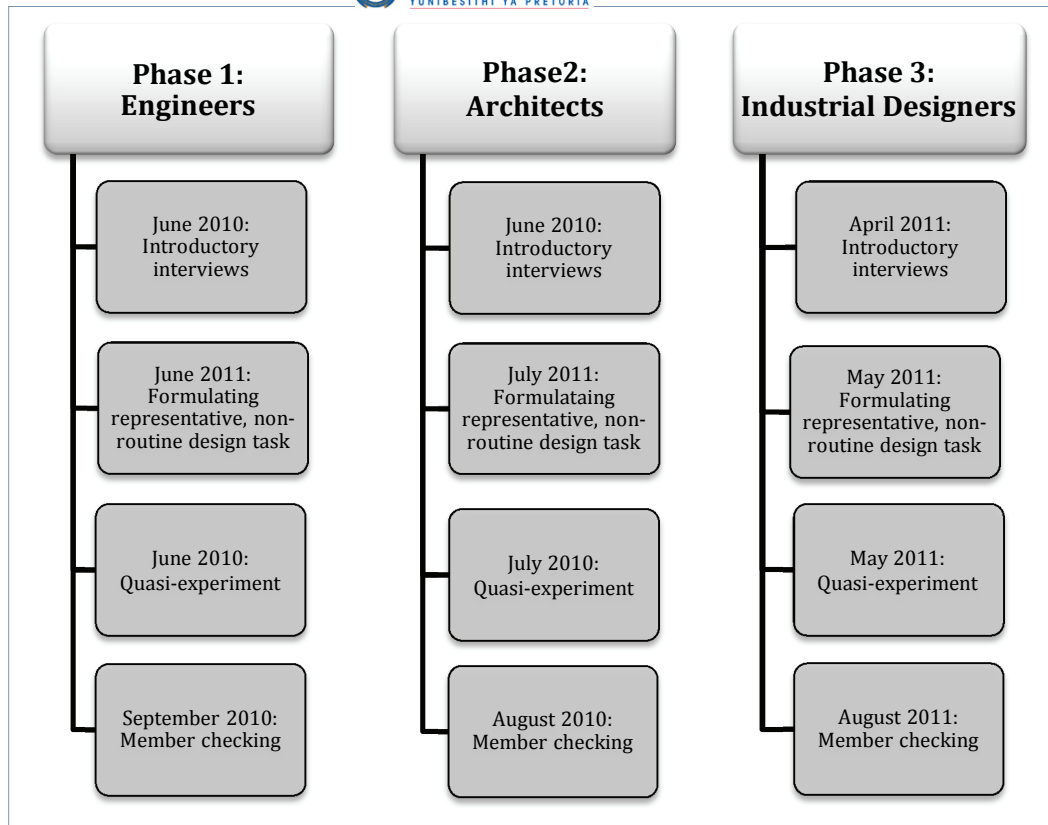
Figure 4.3: **Phases of data collection**

The moment-to-moment verbalisation and visualisation of thoughts (core data in this study), were primarily qualitative. However, the manner in which I collected this data yielded temporal measurements of duration of particular cognitive activities. By using a conceptual framework that determined lists of categorised variables as basis for analysis, I was able to quantify the data in terms of instances of occurrence of particular cognitive activities, which allowed me to count, objectify and support qualitative data. I considered the verbal reports as evidence for the existence of certain cognitive structures and processes. Evidence from the structural properties and semantic information of the concurrent sketches participants made supported the verbal evidence. I used such evidence (Ericsson & Simon, 1993) in order to gain substantiation of possible abstracting towards typical expert design behaviour (Goel & Pirolli, 1989) away from domain specific behaviour. Data collection, data analysis and data processing formed an integrated unity that could only be separated in theory. This means that the point of interface (see Figure 4.2, p.115) between the quantitative and qualitative types of data was at the data collection stage and therefore will be discussed integratively. Concurrency in the protocol studies implied the simultaneous production of verbal data seen in the speech acts and writing of participants and the sketches that they produced during the protocols. From the concurrent protocol method it was possible to infer cognitive processes underlying the actual concurrent sequences of thought (Ericsson & Simon, 1993). Participants' representations and actions

allowed me to gain direct access to their thoughts which accounted for moment-to-moment information processing.

Participants' TAPS protocols provided primarily verbal data which were video recorded by a specialist and transcribed by myself. Thinking aloud is a data collection strategy where participants are asked to talk aloud while solving a problem. The theory behind classical verbal protocol analysis is that, by asking an individual designer to simultaneously perform a representative design task and 'think' aloud, one can gain access to that person's thoughts and hence the patterns and sequences of the thoughts required for the task. In terms of CTM theory, TAPS protocols are claimed to vocally represent the successive states of heeded information (Ericsson & Simon, 1993). Experienced researchers in the field of design studies regard TAPS protocol studies as the most direct, and therefore reliable way of making 'visible' design thinking.

The conventional manner in which protocols are conducted is further characterised by isolating individuals in laboratory conditions in order to free them from the necessity to communicate (Lloyd et al., 1995). However, I agree with others such as Van Someren et al. (1994), who argue that such isolation is artificial and does not reflect the naturalistic way in which contemporary design work takes place. All participants confirmed this unnatural practice during the introductory interviews, which is why thinking aloud in my study was enhanced through dialogue between team members.

The data collected informed me of the interaction between participants' reactions to external situational stimuli provided by the task environment and internal mental processes (Kirsh, 2009). I considered the data as evidence of the way in which perception was instrumental in the evocation and use of socio-technological knowledge by designers in the early phases of the design process. The overall advantage of this data collection strategy was that I could trace detailed generic ways of processing information in order to conclude on the mechanisms at work when experts solve design problems. The large amounts of data being generated encompassed a wide range of cognitive activity (L. T.M. Blessing & Chakrabarti, 2009; Goel & Pirolli, 1989; Suwa & Tversky, 1996). I planned the process of collecting verbal (and visual) data during the protocols by following the same sequence of steps recommended by protocol literature (Ericsson, 2006; Ericsson & Simon, 1993; Goel & Pirolli, 1992; Van Someren et al., 1994).

Step 1: Preparing the design tasks
Step one involved preparation of the design briefs for each group of designers. The overarching experimental principle of consistency (Ericsson & Simon, 1993) guided this step. In addition, I kept in mind that the design task environment should be representative of the domain discipline

of selected participants yet non-routine; that design problems should comply with the requirements of ill-structured design problems (see Chapter 3); and that design problems should be sufficiently challenging. Each of the design tasks that I formulated represented a complex 'real world' design problem in that it had most of the features specified in Chapter 3 (refer to Addendum 4.1).

However, these problems differed in two respects from real world design problems. Firstly, as in all experimental design problem solving protocols, there was no substantive penalty for being incorrect or proposing a weak solution, as there would be in the real world of design (Goel, 1995). Secondly, the design tasks given to the participants would in real life be required on the order of days to weeks to reach completion of specifications. For the purposes of this study, I asked participants to restrict their sessions to approximately three hours, during which time I requested them to develop preliminary solutions only until they reached consensus on a satisfactory solution.

Step 2: Preparing the setting

I decided on a setting that would make participants feel at ease to ensure an atmosphere that lent itself to effective thinking, namely a quiet room with comfortable furniture, stationery, sufficient water and a laptop with Internet connection at hand. I provided light meals in the form of sandwiches, coffee and tea. Any interference were controlled and kept to a minimum in order to avoid influencing the course of the thought process as far as possible (Ericsson & Simon, 1993). During the settling down period, which lasted approximately ten minutes in each case, I again explained the purpose of the research, the procedure we would follow and protection of the data. I introduced the video recording technician, who participated in the discussion about the procedure. Excerpt 4.1 illustrates the way in which the procedures were structured and the venues in which the participants preferred to work. All three protocol studies consisted of three distinguishable practical phases, namely receiving instructions and studying the design brief in studio; exploring the environment, and developing a solution in studio.

| 1 | | ENGINEERS | 2 | | 3 |

Receive instructions in studio provided by researcher → Study brief in studio provided by researcher → Exploring the terrain in which problem is situated → Engaging in vocalisation and visual protocols in studio provided by researcher
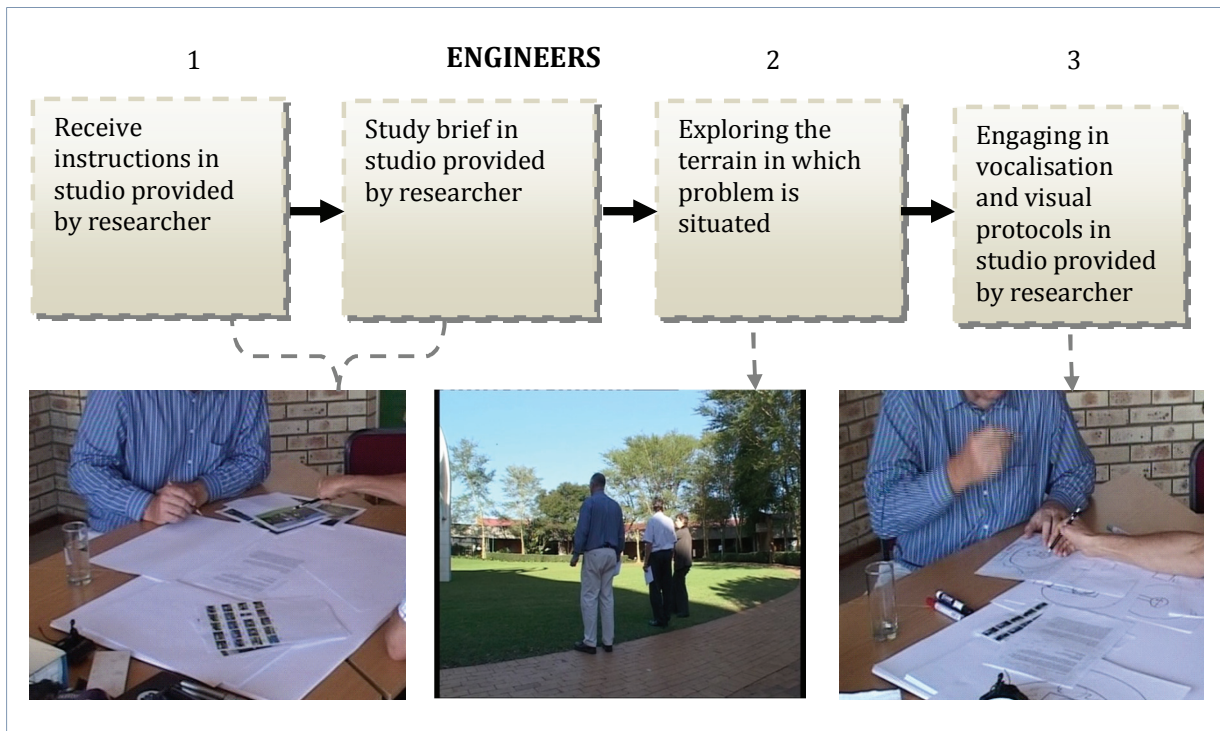
Photograph 4.1:   Practical phases of the engineering protocol

The engineer pair conducted their protocols in the studio provided by the researcher during phase one and two[20]. In phase three, they went outside to inspect the relevant terrain and then went back to the studio, completing phase four. The architect pair followed the same procedure and protocol as described for the engineers, except for an additional phase, when we all travelled together to their own studio between phases four and five. It took us fifteen minutes to travel from the relevant terrain to their studio and to set up, although no recording was made during the travelling. During the drive their conversation was general and concerned observations about the terrain. The industrial designer pair followed the same routine as the engineering pair. However, they did not need to leave the studio in order to inspect a physical terrain. Instead, they perceptually and physically examined Lego™ parts that they were required to design a managing device for. The studio in which they were conducting the protocols was typical of the environment in which their design task was situated. Table 4.4 summarises the time each group spent in each practical part of the protocols.

Table 4.4:   Time participants spent in each practical phase

	Architects	Engineers	Industrial designers
Part one: in studio (including warming up and settling down)	50 minutes	30 minutes	60 minutes

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[20] Practical phases of the implementation of the protocols should not be confused with the mental or cognitive phases of problem structuring and problem solving.

Part two: physical exploration of environment	25 minutes	10 minutes	20 minutes
Part three: in studio	45 minutes	80 minutes	115 minutes
TOTAL	**120 minutes**	**120 minutes**	**195 minutes**

Step 3: Giving instructions

The essence of an instruction in protocol studies is to 'perform the task and say out loud what comes to your mind' (Ericsson & Simon, 1993). In this study, the instruction was extended to include the request to make sketches and any other marks (e.g. words or formula) the participants felt were necessary. Participants were encouraged to avoid interpretations or explanations of what they were doing or thinking and to focus on the task (Ericsson & Simon, 1993; Van Someren et al., 1994) in order to enhance the natural flow of thoughts (Appendix B).

The standard instruction to all participants was:

> *In a moment you will receive a design task. You are requested to read the brief and perform this task in the way you usually go about a commission in your daily practice. Please say aloud everything that you think or do in your customary way when designing. The camera will focus on capturing your words as well as any marks you would be making on paper. When outside or handling any objects, the camera will follow your movements in order to capture your vocal and visual reactions to the environment or elements thereof.[21]*

Step 4: Conducting the concurrent protocols

I asked the participants if they would like to practice the concept first, although they declined this option. Traditionally, the role of the researcher is that of a restrained outsider (Lloyd et al., 1995), only prompting the participants to keep on talking when needed. As the participants in this study solved their particular problems in small teams, the natural dialogue between team members enhanced the flow of their thoughts. These dialogues were treated as data regarding the process as a whole and were not used to analyse dialogues of individual participants (Van Someren et al., 1994). It was sometimes necessary to repeat the request to think aloud when it seemed that participants were so immersed in 'thinking' while sketching, or during pauses, that they forgot to think aloud (Van Someren et al., 1994).

4.3.3.2 Collecting and documenting visual data: concurrent sketches

Making sketches while thinking about design problems and their solutions seems to be a natural and necessary activity for designers in the early phases of the design process (Goel & Pirolli,

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[21] Refer to appendix C for the full instructions to the various participants

1992). The cognitive importance of sketches for this study was situated in the ability to show me how ideas are transformed through manipulation of sketches. Because of the close connection between ideas verbalised and sketches visualising such ideas, I focused on capturing the relationship between the verbal and visual data. Participants were allowed to use pencils, pens and paper, making manual sketches so that they would not be affected by the properties of mediums and tools, such as in the case of computer drafting systems (Goel, 1995). Participants seemed to sketch naturally and it was not necessary to prompt any of them to do so.

4.3.3.3 Recording the TAPS protocols

I recorded each protocol on video camera with a video technician who captured the voice data, general movements and gestures, sketching and writing of participants. When participants were walking and moving outside on the terrain, they had a microphone that recorded voice data. The technician followed the participants in order not to miss any concurrent or sequential writing or sketching. Although I was able to clear most of the background noise during editing, the recordings' audibility was affected at certain stages in the protocols. During reflection on my own research processes, I came to the conclusion that using only one camera limited the viewpoints from which participants' activities were recorded. Having two cameras at the same time could have provided me with more angles and focused on more than one object at a time. However, I could infer some missing visual information from the spoken words or sketches during data analysis. The video recording process was the first point of interface between the quantitative and qualitative data, as the recording process captured moment to moment qualitative activities while simultaneously capturing the temporal measurement digitally.

4.3.4 DATA ANALYSIS STRATEGIES

I used concurrent mixed methods analysis which enabled me to generate and validate interpretations, formulate inferences and draw conclusions. For qualitative data, namely the verbal transcriptions of the TAPS protocol studies and the sketches produced by the participants, I relied on qualitative semantic and syntactic analyses. I quantised qualitative data through binary methods and subsequently analysed it by means of descriptive statistics and reliability analysis.

I grounded my data analyses in various supporting activities and studied general descriptions of the core characteristics of each of the selected design domains (Crandall et al., 2006). I explored multiple case studies conducted in each domain and supported my mental preparation by inspection of design sketches and story boards, as well as visiting exhibitions and presentations of related artifacts. These grounding activities contributed to the general quality of my study and informed my decision on a data analysis strategy.

I adopted Goel's methodology as described in his work *Sketches of Thought* and combined it with some methodological ideas of Suwa and Tversky (1997) for three reasons. First, his descriptions are rich and make the application of the theories of symbol systems and non-notational theories transparent. Second, his methodology provided me with guidelines for legitimate inferences related to the multiple interrelated factors involved in characterising the design problem spaces from an information processing point of view. Third, his methodology allowed me to (a) test the integration of a set of factors not covered by his study, namely the principles of embodiment (Anderson, 2003), and (b) build an explanatory model in which 'intention' has the potential power of bridging internal and external mental processes and elements when solving design problems. Figure 4.4 provides an overview of the switch between verbal and visual data and between the QUAL and quan analysis procedures that I employed.
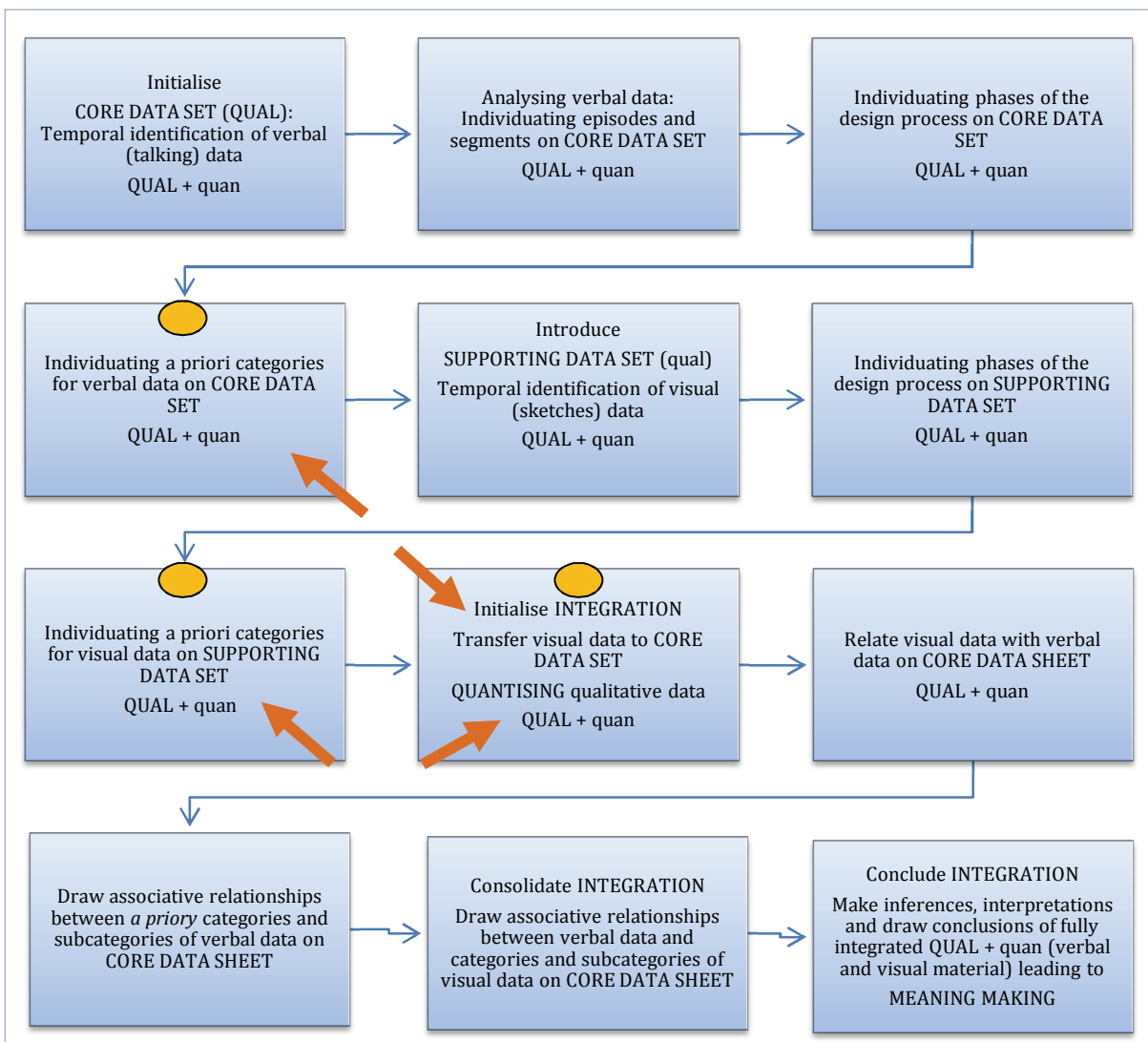
Figure 4.4:   Overview of data analysis procedure

The verbal and visual material that I gathered simultaneously during the concurrent protocols produced QUAL + quan data that I analysed in parallel. The QUAL components consisted of the vocal utterances and sketches produced through a series of three concurrent TAPS protocols.

The quan element involved temporal measurement, counts of occurrences separately and combined, and calculations of separate and combined means for *a priori* categories identified in both verbal and visual data relevant to the purpose of this study.

I transcribed the video recorded TAPS protocols of the participants and imported them into EXCEL, after which I completed thematic analysis. I employed both inductive and deductive reasoning for this analysis. I followed a deductive approach because the structure of the protocols which I used, in terms of cognitive phases, was used as an overarching physical framework. I used an inductive approach in identifying cognitive activities guided by the theoretical categories of the conceptual framework of my study.

Themes that I coded in the verbal data generally referred to embodiment principles (implying psychological activities) that were applied and socio-technological knowledge denoted in words and represented in sketches. However, the individual and intercepting relationship of these two categories with the psychological characteristics of design problem spaces also had to be established. My initial study centred on the identification of these characteristics, including personal stopping rules, memory retrieval, transformation and control structures. Themes that I coded in visual data generally also referred to either the structure of the sketches and the types of artifacts represented by sketches, or parts of sketches. As my study progressed, it became evident that these characteristics did not provide explanatory apparatus to bridge the internal socio-technological knowledge and external situational information facets of design cognition. Instead, I found the key to such explanations to be embedded in the concept of 'intention' as explained in Chapter 6.

4.3.4.1 Qualitative analysis

Qualitative data analysis concerned the data in which information was organised, compressed, and assembled by means of graphs, charts, networks and models (Crandall et al., 2006). The final stage of the analysis entailed drawing conclusions and verifying these. Figure 4.5 illustrates the key components of the analysis process that I followed.
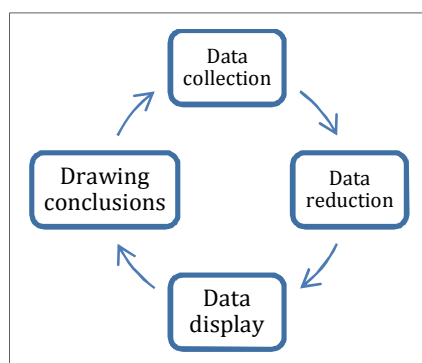
Figure 4.5: **Components of the qualitative data analysis process** (Adapted from Punch, 1995)

Step 1:   ***Structuring data***

In the analysis of both verbal and visual data sets, extensive data structuring took place. This included organising data so that emerging themes or patterns could be identified (Crandall et al., 2006) and that the data could be reduced to manageable chunks without loss of complexity (Tashakkori & Teddlie, 2009). The process of data structuring was not separate from the analysis, but was inherently part of the analysis. First, it involved editing, segmenting and summarising and second, it involved coding, notations (remarking on codes and themes), and developing themes. The research questions and theory implied in this study provided focus to the data structuring process. In the light of my central research questions, I catalogued *a priori* themes and sub-themes from the theory which I used with the aim of testing these in design practice. My intentions were twofold.

▪   General: Finding out in which ways the coexistence of some external situational aspects of cognition and some internal processes might contribute to explaining the complex and dynamic practice of experts solving design problems.

▪   Theoretical: Testing whether an embodiment theory of cognition might be integrated with existing information processing theories of problem solving space by focusing on intentions as mechanism to form a mental bridge between internal and external processes.

I treated each protocol according to a stringent and consistent strategy of structuring and analysing the data. I structured the three data sets individually. This was also the case for the visual data, consisting of three sets of sketches made by participants during the protocols. The process of structuring these data sets was part of the preliminary steps in the data analysis process. The process entailed working with the qualitative data within the structure provided by the temporal identification of participants' verbal utterances. I structured the data prior to analysing it in terms of the *a priori* theoretical categories, which enabled me to find effective ways to decompose the texts (verbal data) into discrete segments that could help me examine the content and context of the situation of the texts.

Due to the cognitive connection between the various 'modes of output', namely verbalising and visualising thoughts, it was important for me to capture the structural connection of the design process in each protocol study. The subsequent sections describe the processes involved in structuring the verbal data (words) and visual data (sketches) separately. The reason for analysing these outputs separately was to ensure reliable coding by systematically applying the two different sets of theory underlying my study. Due to the fact that I structured the data, this meant that I first had to individuate instances of cognitive activity and secondly, I had to ensure consistency in the inferences I made (explained in section 4.3.7.2). I structured the data in

several layers, of which the first layer entailed the identification of three primary categories, summarised in Figure 4.6.
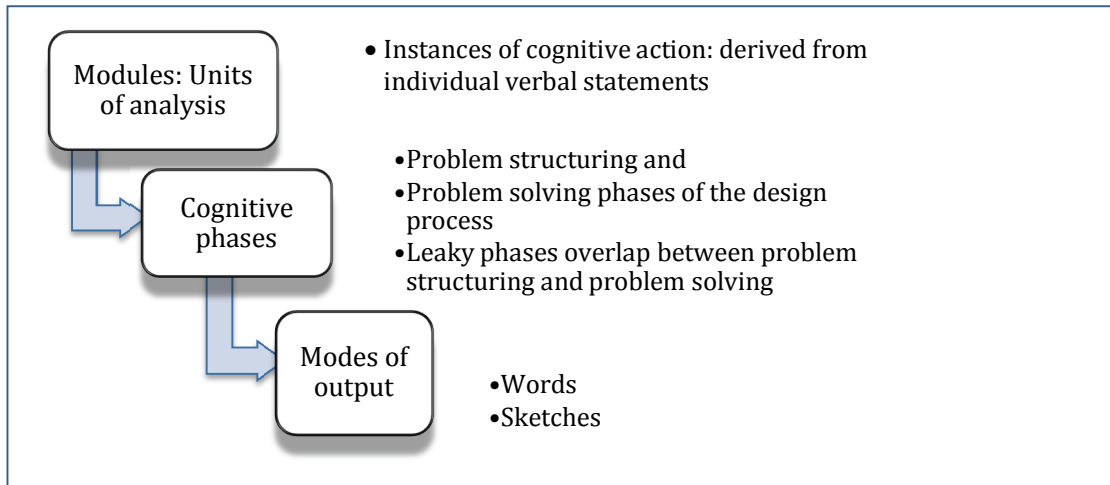
Figure 4.6:   **Coding tree for primary steps in the qualitative data structuring process for verbal and visual data**

The identification process of 'modules' and 'modes of output' had no connection with the theories underlying my study but was a practical measure to break up the data in manageable chunks. The identification process of cognitive phases, however, was the first step in applying Goel and Pirolli's (1992) procedure for analysis of design problem spaces.

Step 2: Structuring verbal data

As suggested earlier, the first task of the data structuring process entailed a parallel QUAL and quan process of the verbal data only. I commenced by identifying the exact points in time (quan) to which particular text (QUAL) related to. The structure of verbal data in the levels illustrated in Figure 4.7 served both methodological and theoretical purposes. All categories contributed to both my methodology and exploration of theory. The methodological purpose of structuring the verbal data was to systemise my investigation and to enable me to quantisise occurrences and co-occurrences of the various categories and sub-categories.
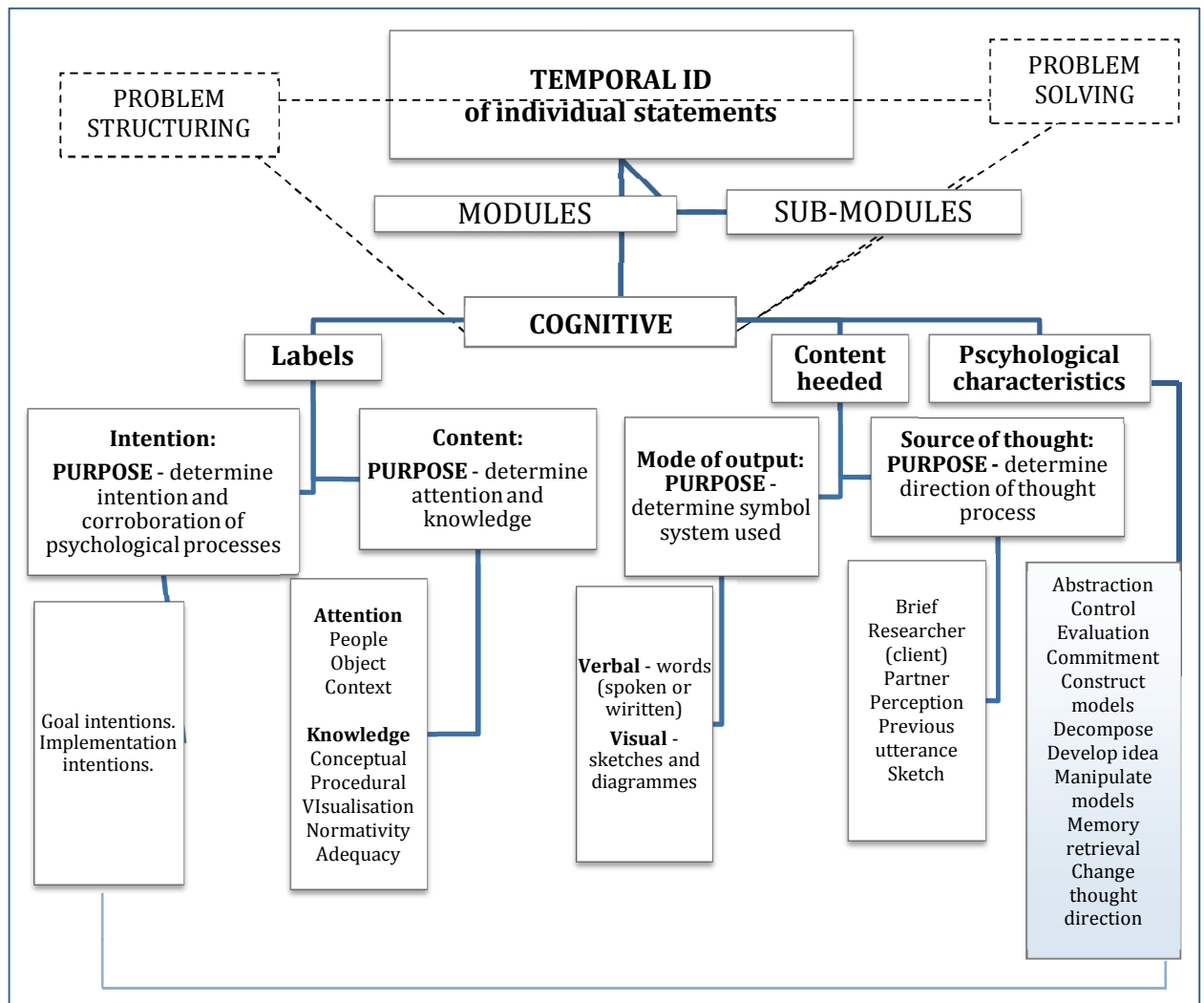
Figure 4.7: Coding tree for structuring analysis of verbal data

Due to the central role the notion of intentions played in this study, I encoded instances within modules that I individuated as intention-attention behaviour (Appendix F). From my analysis I was able to count the number of intention-attention instances and determine their distribution across the whole protocol of all the participants. I looked for possible interactive explanations of the way in which the participants transformed their ideas and made commitments. I considered each fraction of a design related thought as the smallest unit of a design process and called such fragments a 'module'. I considered a set of adjoining modules that were conceptually related to each other as a 'dependency chunk'. Suwa and Tversky (1997, p.2) call such modules 'segments'. They explain that if module 'A' is not related to any modules in the conceptually related sequence that immediately precedes module A, then the set of previous modules are grouped into a dependency chunk, and module 'A' is treated as a 'focus-shift'.

Step 3: Structuring visual data

Sketches are qualitative representations that visualise some parts of designers' thought processes. Sketches played an important role in investigating the theory of design cognition in this study. The visual data in my study required its own supplementary structuring process. Therefore, I created my own coding system as illustrated in the coding tree in Figure 4.8, which also flowed methodologically from the primary coding process as illustrated in Figure 4.7 (see p.129).
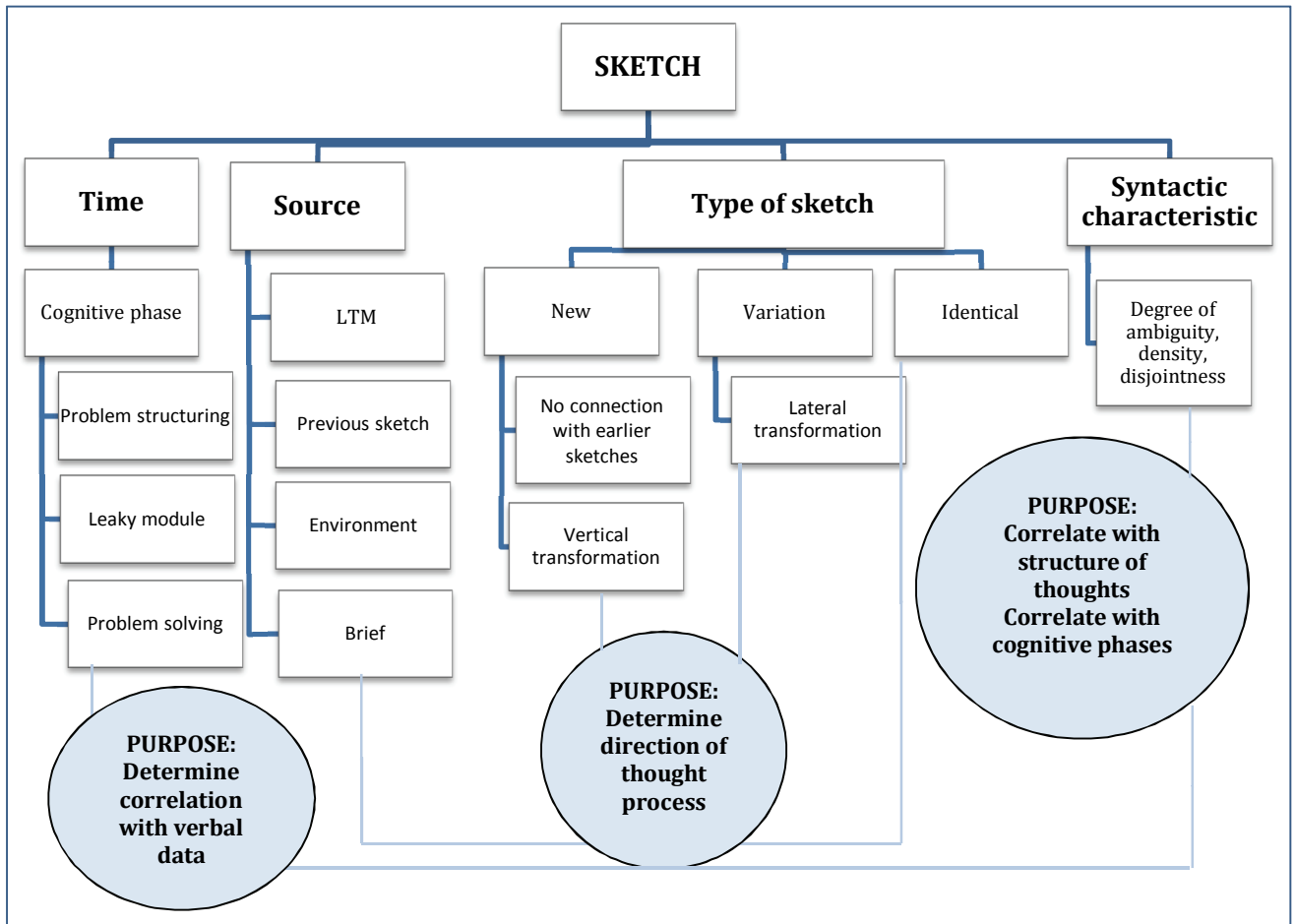
Figure 4.8:   Coding tree for structuring analysis of visual data

I semantically examined pieces and parts of the sketches (see Photograph 4.2) to establish detail that points to changes in the direction of thought processes. I individuated sketches and their various parts and layers. Some sketches were one dimensional and simple to analyse. However, some sketches were complex and needed a systematic process in order to decode them. By using colour coding, I labelled structural characteristics and themes. The participants' were identified by coding them as P-A (architects), P-E (engineers), and P-I (industrial designers).
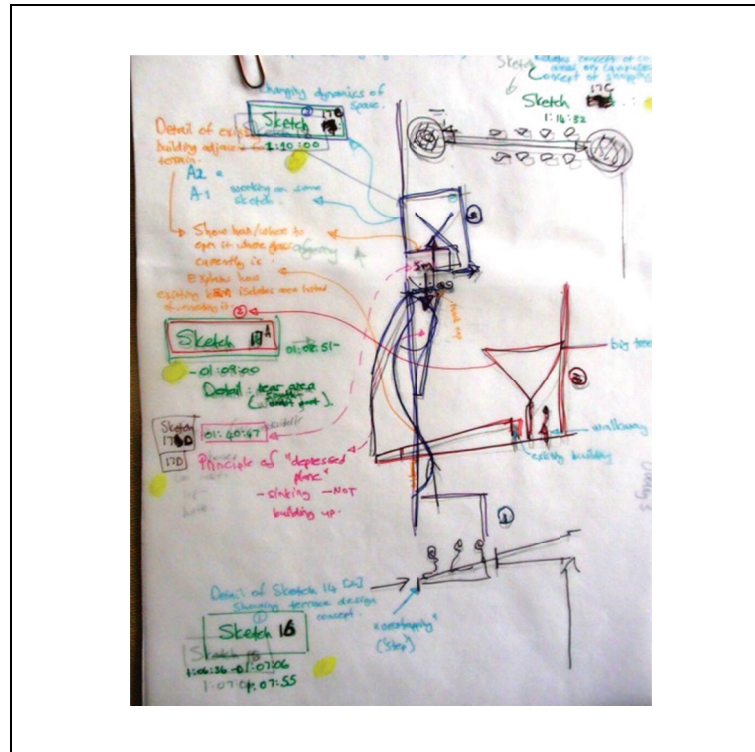
Photograph 4.2:   **Examples of examining pieces and parts of sketches of Participants P-A**

By closely watching video recordings, I retraced the different syntactic structures in the order in which the particular participant was sketching and coded these by a simple numbering system. I counted any periods of sketching activity between the start and completion of sketches as part of an episode. This temporal individuation allowed me to make unique maps between verbal and visual modes of output, which resulted in calculations of the number of sketches or episodes across these two modes. In all protocols, I revisited the video recording several times to determine when the participants initiated each point of a sketch and transformations represented in the sketches. Data analyses in this study went through iterative and cyclical processes, moving backwards and forwards between QUAL and quan processes.

Applying Goel's (1995) modelling of the characteristics of design sketching, sketch information was quantified by the identification of two primary categories. The first was *Source type,* which asks where the sketch originated; and the second was *transformation type,* which asks how it was generated. The syntactic source of a drawing was evidence of the origin of the sketch itself, whereas the semantic source traced the origin of the idea represented by the sketch. In previous studies of this nature, coincidence of the two components did not typically occur.

Possible sources of sketches in this study were long term memory and a previous idea or solution. Drawings that I identified as syntactically originating in the long term memory were considered as 'new' drawings which helped me classify these as a new idea, development or detailing sketch. Sketches that I classified as originating in previous ideas implied that they

related to existing drawings and were therefore part of the development phase of an idea. I further analysed them by exploring the distance in meaning and structure between them and the originating sketch. I detected syntactic variation between sketches by considering whether or not the marks of the drawing were closely related to, but distinct from the marks constituting one or more previous drawings. Semantic variation meant that the idea or content represented by the drawing was similar, but not identical, to the concept or contents of previous drawings. Both sketches (a) and (b) in Photograph 4.3 semantically represent ideas for a sorting rack. From the shapes the marks represent, and the number of shelves involved, the variation of sketch 11 (b) is to be seen in the syntactics. It therefore follows that sketch 10 (a) represents a new idea, but not sketch 11 (b).

(a)　Sketch 10
Originated from LTM at 2:36:45

(b)　Sketch 11
Originated from Sketch 10.
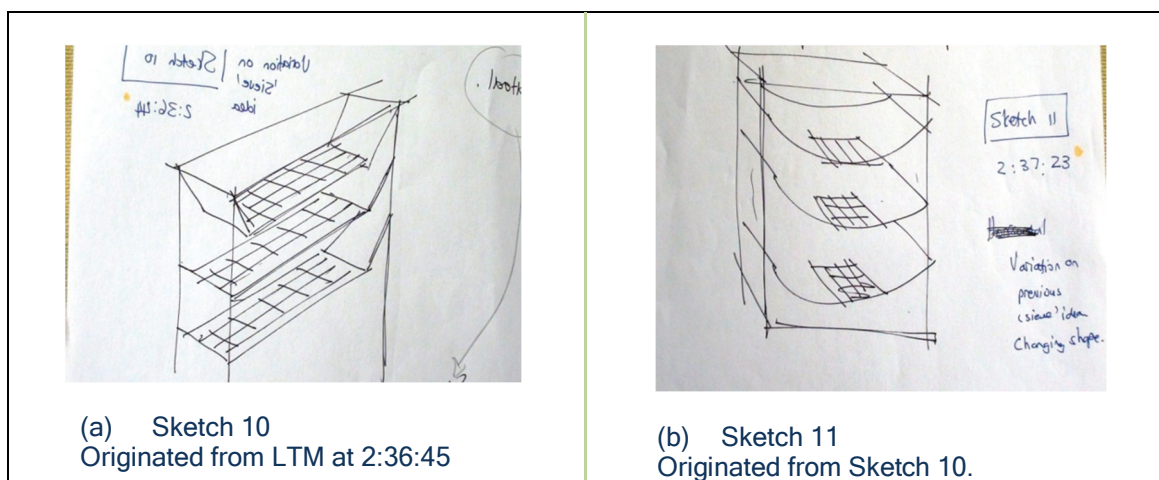
Photograph 4.3:　**Examples of variation type sketches indicating when a new idea was generated**

I identified transformation-type sketches, which was of importance to this study. Transformation drawings imply that a sketch in this class originated from a previous drawing and that I could measure the distance between the original and following sketch in a lateral, vertical or duplicate way. As previously explained, lateral transformation of an idea can be detected in a drawing which is a modification of a previous one. It is related, but distinctly different than a previous one. Vertical transformation can be identified in a sketch by the way it represents the same idea as a previous sketch, but gives more detail and specifics thereof. Lateral transformations in freehand sketching seem typical, whereas vertical transformations seem to be more scarce (Goel, 1995).

4.3.4.2　Quantitative analysis

I analysed the verbal and visual data in terms of descriptive statistics, including box plots as well as a variety of inferential statistical procedures through the use of descriptive analysis techniques. My preliminary steps for quantitative analyses were temporal indications of

utterances or sketching derived from the digital video material. I used SPSS software for binary identification of thematic analysis on EXCEL sheets. The analyses described below pertain to the main research question of how designers interact with the environment in the early phases of the design process. It also pertains to how embodiment principles manifest when expert designers structure design problems.

I decided to analyse the data manually as the cognitive processes underlying the vocal utterances and sketches were complex, multi-layered, iterative and at times consecutive. I chose a manual analysis system, using EXCEL, and considered its visual and spatial qualities, freedom it affords the researcher to create customised visualisation of data and ability to handle large amounts of data. Another advantage of EXCEL is that no formal training was required. It also allowed me to quantisise qualitative data in SPSS, and provided easy access to particular quotations, codes and memos. EXCEL's code-retrieve function supported theory building, enabled me to easily retrieve codes in order to facilitate higher order classifications and categories, provided me with a platform for the facilitation of cross-referencing of data and enabled me to develop associations.

I used descriptive statistics to summarise the data. Measurements of central tendency such as the mean, mode and median as well as measures of distribution, including temporal measurements, the ranges of counts, minimum, maximum and standard deviation were analysed in terms of individual categories (thematic identification of embodiment principles) (Coolican, 1999). In SPSS, I generated item and group outputs that included frequency measures, standard deviation, minimum and maximum temporal indications and range. The SPSS output consisted of graphic representations in the form of graphs, plots, and tables (Kinnear & Gray, 2008). The TAPS data consisted of categories and complex sub-categories, which meant that I assigned values to variables, generated values of a variable, and tested equations for variable *y* versus *x.* The assessment of inter-coder reliability of the protocol codings in this study was a key aspect in the quantitative analysis of the data.

Inter-coder reliability refers to the rate at which different coders of the same data sets reach consensus about designating codes. A rate of 85 per cent or higher between two coders was considered as the benchmark for typical cognitive task analyses (Crandall et al., 2006). An expert colleague helped me by independently coding the verbal statements and another expert colleague assisted me to code the sketches independently for statistical purposes. After each coding process, a percentage of agreement was calculated. In cases where this rate was not achieved, coding was revised by both coders in each case. Contributing to its validity, the increase in accuracy of subsequent interpretations ensured that the resulting theory is not based on haphazard observations that may vary over time (Ericsson, 2006). The overall re-coding consistency for all the transcriptions was 86,5 per cent. A re-coding consistency of 82 per cent

was achieved for the sketches, which was regarded as acceptable because the data was analysed in order to explain typical cognitive dynamics in expert design behaviour. The mean was calculated in terms of temporal measurement, namely seconds. I used the mean to statistically describe the distribution of the occurrence of instances of behaviour around a centre line. The standard deviation measured the spread or variability of occurrences, which indicates how closely variables measured were spread around the mean. In Table 4.5, I summarise the statistical descriptives used in this study.

Table 4.5:   **Example of statistical descriptives used to analyse cognitive structure of the protocols in terms of phases and leaky modules**

<div align="center">Descriptives</div>

	Phase		Statistic	Std. Error
Time period (seconds)	Problem structuring	Mean	64.79	22.204
		5% Trimmed Mean	44.69	
		Median	16.00	
		Std. Deviation	127.550	
		Minimum	1	
		Maximum	551	
		Range	550	
	Problem solving	Mean	39.77	9.122
		5% Trimmed Mean	33.92	
		Median	14.00	
		Std. Deviation	50.788	
		Minimum	2	
		Maximum	201	
		Range	199	
	Leaky module	Mean	100.67	17.639
		5% Trimmed Mean	97.24	
		Median	75.50	
		Variance	3733.515	
		Std. Deviation	61.102	
		Minimum	37	
		Maximum	226	
		Range	189	

a. Design group = Architects

I used bivariate and multivariate methods of profiling combinations of variables (Hair, Black, Babin, Anderson & Tatham, 2006; Kreft & de Leeuw, 2000). I was able to represent the temporal distribution of problem structuring and problem solving activities in the total time it took participants to complete their design task in this study. The box plot type graph used in Figure

4.9 illustrates how I used the statistical information in Table 4.5 to visualise particular bivariate characteristics (time and cognitive phase) of one group of participants in this study.
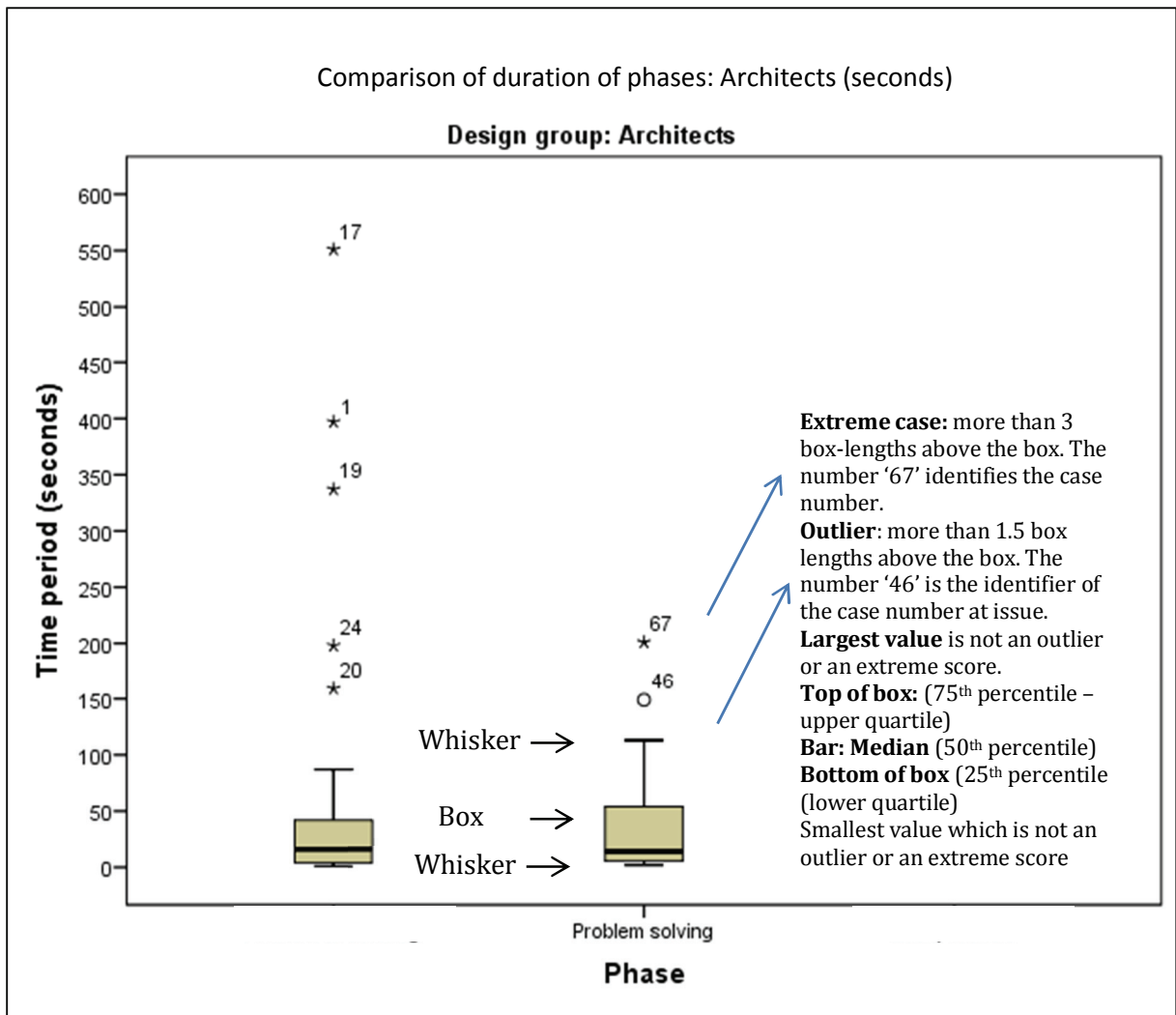
Figure 4.9:   **Bivariate profiling of the proportionate time Participants P-A spent on the cognitive phases in the design process, including leaky modules (**Adapted from Kinnear & Gray, 2008)

Figure 4.9 illustrates how I used box plots as a graphical method that pictorially represented the data distribution of a metric (quantitative) variable (time) for each category of a non-metric (qualitative) variable. The top part of the box (above the horizontal bar) represents the upper quartile, while the bottom part of the box represents the lower quartiles of the data distribution. The box length represents the distance between the 25th and the 75th percentile. The box itself includes the middle 50 per cent of the values. The larger the box is, the greater the spread (e.g. standard deviation) of the observations. The lines extending from the box are called 'whiskers' which are found at the top and bottom of the box and represent the distance between the smallest and the largest observations that are less than one quartile range from the box. Outliers, depicted by '*' represent the observations that range between 1.0 and 1.5 quartiles away from the box. Extreme values, depicted by "° ' represent observations greater than 1.5 quartile away

from the end of the box. Both outliers and extremes are depicted by symbols outside the whiskers (Hair et al., 2006). I explored the qualitative themes and categories in the text and visual data, and quantitatively linked the statistical data in order to identify moments of design behaviour objectively within the structure of the participants' thoughts. The quantitative analysis assisted me in confirming themes in the verbal data indicated by patterns in the *a priori* categories that count occurences of themes (variables). I determined locations within networks of interrelated themes. Through all these methods, I was able to build a model consisting of variables contributing to defining the internal and external circumstances under which the problem solving space of this study was shaped.

I quantisised the participants' sketches and applied the theory of non-notational symbol systems theory (Goel, 1995). By counting the number of times they sketched, I inferred how important the external act of sketching was in internal processes. Quantitative analysis of data yielded by the sketches also entailed the measurement of grades of vagueness, ambiguity and coarseness of sketches, the characterisation of sketches based on syntactic analysis. I used a grading scale from 1 to 5 as a guide to ensure that marks that represent information relevant to the intentions of the participants and client were covered. Grading marks in this manner relied on qualitative judgements that were not at all times easy to quantify, and needed verification from an expert colleague. Based on the methodological mixing, which required an inductive-deductive research cycle (Tashakkori & Teddlie, 2009), I aimed to ensure quality by also mixing relevant criteria appropriately. This means that I attempted to achieve a logical and appropriate integration of rigorous and systematic qualitative and quantitative research strategies. With regard to the TAPS protocol data used in this research, validity was inferred on the grounds of evidence that is construct-related, since the core purpose of this study was to examine design cognition as described by Goel (1995), embodiment as described by Anderson (2003), and knowledge as described by De Vries (2006). I measured all supplementary criteria against the central phenomenon of psychological characteristics of the design problem solving space.

4.3.5   QUALITY OF THE STUDY

Quality assurance in research relates to verification measures being taken to ensure that data is legitimate (Maxwell, 2004; Onwuegbuzie & Teddlie, 2003). In quantitative studies, data verification allows a study to be repeated in exactly the same way, yielding the same results. However, in qualitative studies replication is not possible, as repeating the same research will not yield the same results, due to the non-static nature of humans (Merriam, 1998). Validity and reliability in research signifies the extent to which the interpretations of quantitative results are appropriate, adequate and legitimate. Validation involves a process whereby validity evidence is collected. Given the importance of theory in my study, quality resided in construct-related

validity and inter-coder reliability. With the aim of expanding on theory and testing hypotheses, this study required validity measures appropriate to TAPS. Such measures refer to attaining internal and external validity (Denzin & Lincoln, 2008).

4.3.5.1 QUAL measures

In terms of qualitative measures, what I regarded as truth was determined by how I viewed the trustworthiness. Continuously scrutinising how one's view of truth influences the research process and is known as reflexivity (Pyett, 2012). Rigour in qualitative research is described in terms of the trustworthiness, indicated by credibility, transferability, dependability, confirmability and authenticity of the research (Denzin & Lincoln, 1994).

Participating in TAPS included considering and checking my methodology, comparing it with academic literature on the subject of design cognition, protocol studies and expertise studies as well as with the population (expert designers) that I researched. I did this by consulting with expert colleagues in the field of design studies and with my supervisors. In an attempt to achieve maximum credibility, I attempted to provide sufficient contextualised detail in reporting on my research methods to enable the reader to critique my findings in a meaningful way (Pyett, 2012). Confirmable encoding and the interpretation of the data in the theoretical structure provided by my study's conceptual framework, which reflected reflexive validity of the encoding process, resulted in credible inferences.

As an additional measure, I conducted separate follow-up interviews with all groups for member-checking purposes, ensuring confirmability and dependability. During these sessions, I aimed to develop insight into the manner in which designers interacted with the physical environment or elements thereof when accessing information as well as with their sketches when solving problems. I also gained insight into the changes in direction in their reasoning process as a result of the afore-mentioned interaction. Throughout, I aimed to understand the authentic world of the participants from the inside out and subsequently attempted to produce descriptions that are as faithful as possible of participants' behaviour and words. I followed this up by attempting to take the descriptions produced and organise, systemise and correlate this in terms of my conceptual framework, with the aim of attaining self-understanding in an etic manner (Patton, 2008).

Reflexivity has been described as encompassing "continual evaluation of subjective responses, inter-subjective dynamics, and the research process itself" (Finlay, 2002, p.352). In my data analysis, reflexivity was important, given the complexity of the conceptual framework that I used. The credibility of the inferences I made was directly dependent on rigorously revisiting the data while constantly testing my interpretations and the role of my own constructions of

meaning of the participants (Finlay, 2002) in terms of the theory upon which this study is structured (Ericsson & Simon, 1993).

Credibility in qualitative studies refers to the concept of internal validity (Lincoln & Guba, 1985), which means that the quality of the research is dependent on the ability of the researcher to make interpretations of data which are compatible with the constructed realities of participants, putting the researcher at the centre of quality requirements (Patton, 2008). I used triangulation to ascertain the credibility of my interpretations (Cohen et al., 2007). An advantage of triangulation is that it reduces the risk of chance associations and eliminates bias. It can furthermore assist the researcher to formulate better explanations of behaviour (Maxwell, 1996). In this research I considered the verbal protocols of participants as one method of data collection in combination with the visualisations or sketches of participants as triangulation strategy. The aim of triangulation was thus to explain the complexity of design cognition in the early phases of the design process, therefore I studied this from a computational perspective and integrated embodiment elements of an ecology perspective to ascertain the role perception plays in shaping the DPS. Both verbal and visual data were used to confirm cross-validating and corroborating findings about the thoughts of the participants (Creswell, 2003).

I also strived to ensure dependability of the results. Dependability suggests the presentation of evidence that, if the inquiry was repeated in exactly the same manner, the findings would be the same. However, in using TAPS, it is acknowledged that the data provided do not speak for themselves, and observations made cannot be exactly replicated (Ericsson & Simon, 1993). Compensating for this limitation of protocol studies, I attempted to provide a clear audit trail. This means that it is possible for an 'auditor' to examine documentation on which my research findings were based in order to confirm the results. The audit trail of this study includes (Lincoln & Guba, 1985):

- Transcripts of the TAPS protocols (Appendix D) as well as the original sketches of the participants (Appendix G).
- Data reduction and analysis products, which include theoretical notes compiled from literature as well as the coding system used (see section 4.3.4.4).
- Data reconstruction and synthesis products that comprise of the categories of themes and relationships as well as the conclusions drawn (Appendix D).
- Instrument development information, including the design tasks for each group of participants (Appendix C).

4.3.5.2 Quan measures

Validity involves the adequacy of the researcher to understand as well as represent participants' meanings. Validity therefore becomes the quality of the knower's relation to the data, enhancing different perspectives and forms of knowing (Onwuegbuzie & Teddlie, 2003).

a)   Validity of the design tasks

Internal consistency is achieved when a number of items are formulated to measure if a certain construct produces a high degree of similarity among them (Maree & Van der Westhuizen, 2009). This characteristic is called internal reliability. I aimed to achieve internal reliability among the three design tasks formulated. Internal reliability was used in validating the design tasks the participants were required to complete (Ericsson & Simon, 1993; Goel, 1995). Validity of the design tasks as conceptualised for this study refers to the compliance of the design tasks to the requirements of ill-structured problems. Of importance was the extent to which the design tasks were representative of real world design tasks the participants are involved in during their real life work situations.

b)   Face validity

Face validity refers to the extent to which an instrument 'looks' valid. This type of validity cannot be measured or tested but when scrutinised by experts in the field, they should find a high degree of face validity (Maree & Van der Westhuizen, 2009). In this study, the design tasks were scrutinised by expert colleagues in the field who agreed to their face validity.

c)   Content validity

Content validity signifies the extent to which the instrument encompasses the complete content of the particular construct that it intends to measure (Cohen et al., 2007). My intention was to determine the structure and content of the participants' thought processes during the early phases of the design process. By conducting concurrent TAPS protocol studies, I aimed to explore their cognitive processes. Ericsson and Simon (1993), primary researchers in the field of protocol studies, state that the central assumption of protocol analysis is that it is possible to instruct participants to verbalise their thoughts in a manner that does not alter the sequence of thoughts mediated during the completion of a task, and can therefore be accepted as valid data on thinking. I based the premise of this study on these authors' argument that the closest connection between thinking and verbal reports is found when participants verbalise thoughts generated during task completion.

d) Construct validity and criterion validity

Construct validity relates to how well the constructs covered by the instrument are measured by different groups of related items (Pieterson & Maree, 2010). My data collection procedures primarily comprised of inter-construct validity applying criteria from the conceptual framework of the study, which was closely related to criterion validity. Criterion validity refers to the correlation between scores on an existing instrument (the criterion) and the instrument used in the current study. For this purpose, I aimed at adhering to three internal quality conditions. The first was relevance, which refers to the relevance of verbalisations to the given design task (Ericsson & Simon, 1993). The underlying theory of this condition is that observed verbalisations, such as free association or day-dreaming with no relevance to the task, cannot be considered pertinent or valid data. Very few such instances occurred in this study, and when they did, I did not consider them as pertinent to the problem solving process. I applied the same relevance condition to the sketches that the participants made.

The second condition is consistency (Ericsson & Simon, 1993), which refers to the logistical consistency of verbalisation with the verbalisations that just precede them. This means that items in a sequence of verbalisations that are not related to each other could not be considered as internally consistent with goal-directed, cumulative or intentional processes. I found no evidence of logically inconsistent verbalisation or visualisation in the participants' protocols, which allowed me to identify higher-level control functions applied by the participants. The third condition ensuring internal consistence is memory (Ericsson & Simon, 1993), relating to the notion that a subset of the information that participants heed in their protocols will be remembered. This means that when participants are thinking aloud, much of the information that comes to conscious attention will be remembered and available for subsequent retrieval. I considered information remembered and retrieved as internally part of the same mechanism which allowed the participants to process information and solve the problem. As such, construct validity served a unitary and standardizing purpose.

4.3.6 CHALLENGES IMPLIED BY THE METHODOLOGICAL CHOICES I MADE

My interpretation of protocol results assumes that the tasks to be performed by participants had to be properly prepared and administered (Ericsson, 2006). Finding experts that fit the criteria of expertise whose professional practices would allow them to participate in the study challenged me greatly. My sampling methods had to ensure that the selected participants were representative of the general group of design experts in the real world. However, it was not possible to eliminate personal design strategies, preferences and habits (Goel, 1995), which resulted from domain specific training.

I created a non-threatening, 'safe' environment that represented the 'real world of work' elements as closely as possible while conducting the design experiments, which was challenging as experiments are considered as artificial. However, as the participants were experts, they did not seem intimidated by the video camera recording, the outcome of the process, or my presence as researcher. One group, however, commented that they found the 'thinking-aloud' aspect challenging. I assumed that the participants were truthful to their habitual ways of solving real design problems in the way that they approached the design experiments due to the fact that they would have nothing to gain by not being honest. Ericsson and Simon (1993) confirm that the reliability of research results of design cognition studies does not depend on the trustworthiness of participants' behaviour. Therefore, through the assumption that participants acted true to the habitual way of designing, I assumed verbalisation as being pertinent to the cognitive processes this study aimed to scrutinise.

Another challenge in this study was maintaining control. I made minor variations in the implementation of true experimental protocol requirements which included the setting and the number of team members in order to enhance naturalistic task environments. I managed to control the structure of the protocols, ensuring that all three protocols were consistent as far as the characteristics of the design tasks (Van Someren et al., 1994) were concerned. I also controlled the requirements of the output of the different design processes, namely verbal and visual representation, from problem structuring to the moment when a satisfactory solution was generated (Goel, 1995).

Some critics of the usability of verbal reports for general theory development argue that they are idiosyncratic, meaning that such reporting may reflect the unique experiences of individual subjects and hence not be usable (Van Someren et al., 1994). However, Ericsson (1993) points to the fact that the difficulty does not lie in verbal reporting as such, but in the existence of individual differences, a variable that cannot be concealed or solved by using other research methods. The challenge involved in sampling units of analyses from the data representative of expert design cognition, at the same time ensuring internal as well as external validity, necessitated creativity yet parsimony. I addressed this challenge through the combination of seemingly opposing theories and approaches, combining visual analysis with verbal analysis, yet staying close to the theories from which my coding constructs were derived. I aimed to ensure validity of the design tasks by using typical criteria for ill-structured design problems.

The process of ensuring representation through formulating appropriately challenging design tasks that would produce expert design behaviour was also a challenge. Design tasks therefore had to be representative as well as consistent in terms of their characteristics. Expert judgement was brought to bear upon the formulation of design tasks that I used for this research by involving senior members of the architecture department, engineering department and

industrial design department of a university close by. These experts served in an advisory capacity in both the design of the design tasks and the analysis of results.

Due to the fact that I followed a mixed methods approach, I faced the risk of reducing the complexity of the study through simplified quantitative processes. Through the combination and integration of quantitative and qualitative processes, I attempted to successfully represent the complexity of design cognition. The use of mixed methods and integratively reporting on findings further contributed to achieving the confirmatory and expansion goals of the study. I could constantly correlate the quantitative and qualitative parts of the data with one another, providing richness, depth and confirmation of the findings and interpretation thereof. In the case of the visual data, my decision to manually analyse and process the sketches was based on the complexity of the analytical process. Because the sketches had their own unique coding scheme, it was not possible to process them in the same way as the text data. Manual data analysis had the advantage of allowing multiple readings and layers of interpretations. Despite maintaining complexity of the psychological nature of designing, the density of the knowledge and acquired skills of the participants made it virtually impossible to describe the complete structure of the cognitive processes involved in this study (Ericsson et al., 2009).

Obtaining both verbal and visual data in this study differs from previous studies in the design cognition I accessed thus far. Past studies either focus on verbal data or visual data only. It was therefore important, through the analysis and interpretation of the data for this study, to keep in mind that the particular structure of each group of participants' particular problem space was a function of their particular design task environment. Expanding theories as dense as those provided by computational approaches provided challenges of their own. Combining it with ecological theories required a critical, yet flexible stance. Because the physical environment to which a particular design task environment pertains plays such an important role during the early phases of the design process, it seemed appropriate to consider the role of interactive perception on the invariant psychological features of the design task space of each, which is also not considered by Goel (Goel, 1995; Goel & Pirolli, 1992).

4.4   ROLE OF THE RESEARCHER

During the introductory interviews, participants indicated that they could produce the most naturalistic data when I, as the researcher, participated in the experiment. This changed my proposed role to that of modified dualist/objectivist (Guba & Lincoln, 2008). I did not aim to understand socially and experientially constructed realities of participants, but rather aimed to identify the truth as closely as possible from a critical realism point of view. The critical community was thus used as an external custodian of objectivity (Guba & Lincoln, 2008). I

adapted the classic form of design protocols through my participation in the protocol and acted as the 'client'. This resulted in a change in my role as researcher from outsider to insider, or participating researcher. All participants agreed that it would be quite unnatural for them not to involve me acting as client and providing the design task (brief) and additional information. This resulted in participation during the problem structuring phase of the design process when participants required particular information that would help them to understand the context of the problem (Goel, 1995). My involvement in this manner did not constitute unnatural interruption, but rather contributed to keeping the natural flow of the participants' thoughts as close as possible to their customary way of thinking.

My participation phased out as the participants came closer to the end of the problem structuring phase, after which I restrained myself from becoming involved in any way during instances of the problem solving phase. This implies that I had to constantly remain sensitive to any suggestions, subtle or obvious, of participants engaging in thinking about possible solutions and not about understanding and structuring the problem. During problem solving instances, I was able to take on a critical realist position through my observation of the way in which participants engaged in design sketches, consulted one another, reasoned by processing information, as well as the way they used sources and instruments as was customary to them. Because the participants are experts in their domains, I was focused on the way they reasoned rather than on wanting to interrupt them with my opinion on their thoughts.

4.5   ETHICAL CONSIDERATIONS

As all participants are independent professionals in their own private companies, I did not require permission from any organisation or institution to conduct the research. After gaining access to the participants, I conducted introductory interviews during which I explained the intentions and planned procedures of my study. I followed these discussions up with written letters in which I confirmed the information and requested written voluntary informed consent from the participants. I also assured them that they could withdraw at any time of the study. All participants provided informed consent by returning signed letters. No participants withdrew from the study at any stage (Cohen et al., 2007; Creswell, 2003).

I assured participants that I would control possible challenges to confidentiality, anonymity and respect for privacy in not sharing data with others during the course of the research process. I do not include any identifying information with respect to their professional identities, personal information or the setting of their studios. I ensured anonymity by modifying identifying information in the transcripts of the protocols and notes about sketches. I omitted or changed the names in raw data and have ensured that my research diary, DVD's, transcripts and other data are kept in a secure environment. My relationship with the participants might have

positively impacted on the participants decision to allow me into their professional physical and mental space (Cohen et al., 2007; Denzin & Lincoln, 1994; Gero & McNeil, 1998). I invited the participants to ask questions or pose requests for more information whenever they needed to do so. This ethical principle was part of the protocol studies and contributed to the validity of the protocols (Ericsson, 2006). I also assured the participants that, if necessary, I could arrange a complete debriefing session on their thought processes during the protocols. I explained the potential outcome and benefits of the entire process at the beginning of the study. These benefits included that participation could enable participants to reflect on their own design process in their everyday working lives. During the research process, participants had the opportunity to reflect on their own thinking processes and consolidate their design practices (Ericsson, 1999).

In my interactions with the participants, I protected their general and psychological well-being by respecting them as individuals as well as professional experts. This was achieved by creating a setting as naturalistic as possible to ensure participants' natural and optimal design behaviour as experts (Hoffman, 1992). Prior to the protocol studies, I allowed participants' expression of self-purpose and execution of self-determination by modifying the experiments at their request, as explained earlier. I did not expose any participant to physical risks or harm other than those faced during a normal working day. During the introductory interviews, I established as much trust as possible (Van Someren et al., 1994). Through the explanation of my intentions and exposing my personal as well as academic interest in the work done by expert designers, participants learnt to trust my motives and research abilities. Participants thus became aware of the social as well as academic benefits that the study implied for educational as well as professional purposes. They expressed their enthusiasm about learning more about their own thinking processes through their participation, but also about the possible contribution their participation could make in improving design education, and a possible contribution to the expansion of design theory.

I did not withhold any information from participants relevant to the study; neither did I mislead them in any way. Through the use of critical realist principles, I implemented a neutral and objective approach during the entire process (Cohen et al., 2007; Van Someren et al., 1994), while at the same time, I engaged in the protocols with enthusiasm and participation as 'client'. Lastly, I considered the principle of accuracy when reporting on and including data. I did not falsify or fabricate any data in my data reports; neither did I omit any data obtained. I continually guarded against manipulating the data and reflected truthfully on the inherent challenges of the study. I believe that, by being a trained designer and design researcher, I was able to conduct the study in a professional and competent manner. As such, I knew how to create design settings, including design problem tasks that would simulate real world design settings. I knew when to participate during the protocols and when to hold back – based on my own design

experience but also from theoretical information gained through the literature review for the study (Blessing & Chakrabarti, 2009; Liikkanen, 2010; Lloyd et al, 1995; Visser, 2004).

4.6 CONCLUSION

Based on the literature survey and conceptual framework discussed in Chapters 2 and 3, I planned and conducted an empirical study consisting of three TAPS of design experts in architecture, mechanical engineering and industrial designing. The purpose of the study was threefold. First, I aimed to explain and describe the coincidence of expert designers' use of external situational information and internal knowledge. Second, I aimed to expand on Goel and Pirolli's theory of design problem solving space and design task theory. Third, I aimed to discuss an innovative methodological manner to conduct conventional TAPS based on computational assumptions. I subsequently also explored the potential of intentional states to serve as mechanism bridging external and internal processes.

This chapter focused on a detailed description of the research process that I employed. I described and justified my research methodology in terms of my research questions and the purpose of my study. I also considered the strengths of my mixed methodology as well as its resulting challenges. I reported on the way I attempted to address the challenges I faced. Furthermore, I described my role as participating researcher during the study as well as the way in which I persistently attempted to obtain trustworthiness, validity and reliability, and the manner in which I addressed the ethical issues of the study. In Chapter 5, I discuss the results of the study, focusing on the overall structure of the participants' thought processes against the background of existing literature. Thereafter, I discuss and interpret the mechanistic role of intentions in the internal and external processing of information in Chapter 6 against the background of existing literature.

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CHAPTER FIVE

Findings of the study:
Overview of quantitative results

Data Analysis and Interpretation

Require
considering the

| Context | Task environments | Problem solving space |

Which are
characterised by

| *Distinct and overlapping cognitive phases* | *Interactive use of external resources* | *Interaction between internal and external processes and resources* |

Influencing the

| Role of conduct controlling attitudes | Role of intentions | Relation between various intentions | Internal-external synergy |

5.1 INTRODUCTION

In Chapter 4, I described the empirical part of my study. I justified my selected research design as well as other methodological choices, in terms of the research questions and the purpose of my study, as formulated in Chapter 1. In this chapter, I present and discuss some of the salient results of the three different protocol studies during which three design teams from three different design domains, each had a different design problem to solve. I interpreted the results I obtained computationally by closely coupling the inside (problem solving space) and outside (material objects in the physical environment) (Kirsh, 2009). The aim of this chapter is to account for the mechanisms involved in these couplings, to explain the role that the physical task environments played in the participants' search for structure in their individual design tasks and exploration of the most suitable solution to their problems. This is followed by a discussion of the qualitative results of my study in Chapter 6.

I commence the chapter by describing how participants elicited situational information cues with existing personal and domain specific knowledge to generate advancement towards a general theory that may explain how designers exploit the physical environment to help them reason and solve problems. In order to arrive at a general theory of problem solving, sufficient resemblance was required between the actions of the different groups of participants. I used only three different groups which, as a small sample, therefore limits generalisation. However, the results discussed in this chapter, which link these to existing studies reported in the literature, might serve as pointers to develop large scale projects in support of further theory development.

5.2 DATA ANALYSIS AND INTERPRETATION

Based on the theories of symbol systems discussed in Chapter 2, design problem solving, embodiment and socio-technological knowledge, which I deliberated in Chapter 3, I now discuss some significant invariants (psychological characteristics) in the problem solving space in my study reported on by Goel and Pirolli (1992) as a way of confirming their theory. In the case of each invariant I asked: *What is the phenomenon? Why did it occur? What is the supporting data?* In order to extend their theory, I asked the following additional questions: *What embodiment principle(s) played a role in each of the invariants as a result of external resources available? What internal resources in the form of personal and domain specific knowledge did the participants access and use? How did the access and use of internal and external resources interact with each other?*

In line with the mixed method approach and the dominance of the QUAL elements of the study, the theoretical drive of the interpretation processes was deductive. As was explained in Chapter

4, I constantly had to consider the fact that the invariants which characterise a design problem space could be explained by appealing to the structure of the symbols system. When the meaning of words and sketches were found, it implied semantics which resulted in qualitative discussions and meaning making. As such, interpreting the data sensitised me to the role that syntactics and semantics played in representing cognitive processes in this study. These sensitivities begged the following questions:

- What do syntactics, analysed in this way, tell me about the theoretical and thematic categories relevant to my study?
- What are the theoretical implications of understanding the distribution of particular categories and the number of instances?

The particular units I established to analyse (symbols clustered in meaningful modules used in verbal as well as visual systems) counted as syntactics. Parallel qualitative and quantitative processes implied that if a unit could be qualitatively distinguished, it could be classified, quantified by counting and plotting distribution, and interpreted by considering its contextual sequencing. Counting occurrences implied syntactics from which I inferred density of ideas, whereas temporal measurements implied syntactics from which I inferred duration of cognitive instances. My interpretations were filtered through the lens of the close coupling of computational and situational principles. This means that I looked for rich information about the internal (existing knowledge and procedures) and external (situational information and objects) resources used by the participants in a particular instance. In the following section, I contextualise the three groups of participants' task environments, against which background all interpretations should be considered.

5.2.1 CONTEXTUALISING THE PROTOCOLS

I collected three protocols within a maximum duration of three hours each, as well as the sketches made concurrently by experts in the disciplines of architecture and mechanical engineering working in pairs, and industrial design who worked in a team of three members. Each group's dialogue was considered as an individual protocol. When I discuss the findings, I report on groups as units and not as individuals, although their dialogues were transcribed by using pseudonyms for each individual participant in order to make sense of the flow of the dialogues. Although the focus of this study was not on co-design and distributed cognition as aspects of ecological cognition (Blessing, 2000; Temple 1994), I did at times distinguish between participants making sketches or talking when it was a meaningful factor in the interaction between internal and external resources and processes. This aspect could be studied in more detail in a separate follow-up study.

5.2.2   DESIGN TASK ENVIRONMENTS: AN OVERVIEW

I managed to control some aspects of the design task environments. The design task environments for each of the participating groups were similar in some aspects and different in others. The types of artifacts the participants were required to design differed from one another (relevant to their particular domains), but were chosen because the complexity involved in them as independent objects envisaged and intended by the client (me, the researcher), was equal. Similarities could further be found in the insufficiency of input information which was determined by the deliberate formulation of design tasks which provided little information in the design briefs. The reason for providing little information was to give the participants unrestricted opportunities to search and access information internally as well as externally. Supporting external information and resources from the client/researcher and the physical settings of each design task was equally available to all groups. As such, I actively participated in the provision of information when needed.

I furthermore considered the levels of expertise as equal, which implied that the extent of knowledge internally available to them was assumed to be similar, although the details of the content were different. Existing research on the early phases of design processes indicate that the knowledge used is primarily domain specific (Kilgour, 2006; Kirsh, 2009; McCormick, 1997). Yet, I focused on the domain-independent processes in these early stages, including the knowledge that the participants accessed and transformed (Goel & Pirolli, 1989; Liikkanen, 2009; Popovic & Kraal, 2010). I assumed that these generic processes are intertwined with domain specific conceptual and procedural metacognition (Gollwitzer & Schaal, 1998; Kilgour, 2006).

However, the participants' tendency to determine their own interpretation of the scope and complexity of the artifacts could not be controlled. I did not specify how the participants should use and transform internal and external resources (except for the requirement to use hand sketches only, and no computer generated drawings). This aspect was therefore prone to the possible effects of individual personality and stylistic preferences, biased values and belief systems which could not be controlled (Ericsson, 2006; Goel, 1995). This lack of experimental control weakened the study in terms of generalisability, but strengthened the situational arguments that individual contexts can play an important role in the way design processes take place.

5.2.2.1   Architecture task environment

The architects' task involved the design of an open-air theatre in the garden of the University of Pretoria, Groenkloof campus (where an existing concrete sculpture of considerable size is

standing). As external resources, Participants P-A were given two documents: an outline of the experiment procedures and a design brief that motivated the need for the theatre and specified the client's needs and requirements (Appendix C). They visited the site, took photographs and used colour aerial photographs of the site which they downloaded from Google Earth once in their own studio. At their own request, the experiment was concluded at a distant site, in the studio of one of the participants where they had access to the Internet and reference books. Participants P-A further had pens, pencils, paper and transparencies at their disposal.

5.2.2.2 Mechanical engineering task environment

The mechanical engineers' task involved the design of a rotating stage for the theatre described above. However, Participants P-E did not have the architects' specifications. Therefore, the engineers' task was to design a multi-purpose stage system irrespective of the size and shape the architects would commit to. This implied that even less specific information was available than what is typically expected in mechanical engineering problems (Vincenti, 1990). This feature of their design task opened the opportunity for the participants to interpret the need of the client in multiple ways. Participants P-E received two documents: an outline of the experiment procedures and a design brief that motivated the need for the theatre's rotating platform and specified the client's needs and requirements (Appendix C). They visited the site, made site drawings and the experiment was conducted in a venue within walking distance from the site. They had access to drawing paper, pens, pencils, reference books, the Internet and photographs of the site.

5.2.2.3 Industrial designing task environment

The industrial designers' task involved the design of a device or system that could assist technology education staff in managing the use and storage of Lego™ parts on and off the campus of the University of Pretoria. Participants P-I received two documents as external resources: an outline of the experiment procedures and a design brief that motivated the need for the device and specified the client's needs and requirements (Appendix C). Participants P-I further had access to a variety of examples of the said Lego™. The experiment was conducted in a venue similar to sites where Lego™ is typically used. They also had access to the Internet, drawing paper, pens and pencils.

In the following section, I give an overview of the salient elements of the participating teams' problem solving spaces in this study. I provide descriptive statistics for each group's two primary cognitive phases of the protocols, problem structuring and problem solving as well as a section on leaky phases (section 5.5). With a sample of seven expert designers from three different domains, the purpose of the statistical measures in this study was not to make

comparisons across the cognitive processes of the various participants. Instead, I examined statistically significant patterns within participants (Goel, 1995; Suwa & Tversky, 1997). I present these patterns and qualitatively explain the findings involving some similarities suggestive of generalities across participants' processes. In Chapter 6 I present a detailed qualitative discussion of some of the salient psychological phenomena relevant to my research questions.

5.2.3   DESIGN PROBLEM SPACES: AN OVERVIEW

I considered the problem solving space of each of the participating groups of design domains as unique in detail, but similar in the general aspects involving their task environments.

5.2.3.1   Architecture problem space

The architecture pair, Andrew and Jonathan[22], constructed their problem space by first reading through the design brief in an indoors setting close to the site involved, and asking the client/researcher questions to help get a preliminary hold on the core of the problem. They also attempted to understand the requirements for the type of artifact required. The only item in their brief which they attended to externally at this stage was that of the required size of theatre. By making diagrammatical sketches (Photograph 5.1), Jonathan explained to Andrew what was meant by 'diameter' in the brief.
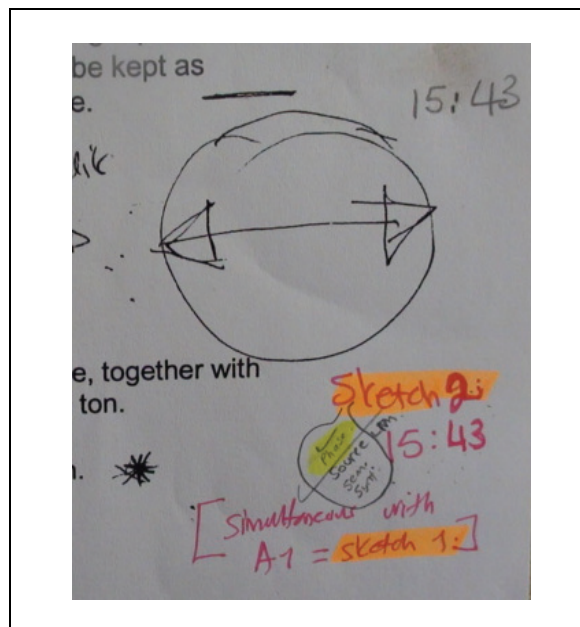
Photograph 5.1:   Diagrammatical sketch made by architects while structuring their design problem (Sketch 2 00:15:43)

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[22] Pseudonyms assigned to all participants

In their discussion and questioning of the client, Participants P-A related to similar projects that they had previously been involved in or experienced by observing similar artifacts. Andrew, was immersed in a case through recall of a theatre he considered as unconventional because of the way it functioned, as well as its aesthetics. Andrew revisited this particular case and the philosophy behind its design, including its aesthetics. His insight represented the way in which he interpreted the problem.

Throughout the protocol, this interpretation became a decisive theme in the development of the architects' ideas. Through the use of his internal resource, namely a long term memory of a personally experienced space, and drawing the domain specific architectural principles behind its design into the experimental situation, Andrew demonstrated the dynamic interaction between internal and external resources and environments (Appendix G).

After this episode of recall, the architects decided to go outside to explore the physical site while talking about what they were seeing. They observed the surrounding buildings as the broader landscape surrounding the site at issue by walking through areas and commenting on aspects in the architecture as well as landscape design that they regarded as relevant. While they were exploring the environment, one of the participants made a rough sketch of the site specified in the brief as the intended location for the artifact (theatre) they were asked to design. They took particular note of the style of the surrounding buildings, how the buildings were joined and the properties of the material of the buildings, which related to architecture specific notions of aesthetics and design principles of spatial relationships.

When they were satisfied that they understood the physical layout of the site and the area surrounding it, they continued with the development of their design in one of the participants' studio close to the campus area involved. Working in a familiar studio space, with its own culture, rituals and habits behind it, the participants had access to and made use of many cultural artifacts (Kirsh, 2009). They immediately acquired an aerial photograph from Google Earth™ which they used as basis for all their subsequent thinking and sketching. The details of their process of working with the aerial photograph (Photograph 5.2) as an object which aided their thinking and ability to develop a solution, is described in more detail further on.

Photograph 5.2: **Architects using an aerial photograph as external support** (Sketch 14 01:02:35)

In addition to the aerial photograph, I offered to provide Participants P-A with a set of photographs of the site, which they declined. Instead, they used two reference books illustrating architectural design principles that they prefer to apply in many of their professional projects. I inferred that the explanation or external demonstration of the effect of their ideas, aesthetic or functional, was a habitual behaviour and not an arbitrary action or a forced and artificial behaviour for the sake of the protocol experiment. I determined this from the fact that they repeatedly engaged in immersing themselves in scenarios of similar cases, either by recalling them or by showing them in the books when taking a decision.

The architects' process of developing the theatre that they were required to design was systematic and incremental. However, they generated ideas far beyond the requirements and yet ignored others. In this process, they managed to find a creative solution in dealing with the constraint of an existing sculpture by repositioning it and yet incorporating it as part of the direct surroundings of their theatre concept. By making several layers of sketches when working in their studio, the architects generated many ideas and developed them. They layered their sketches through the use of transparencies being placed on top of the aerial photograph, assisting them to orientate themselves in the space of the site. In addition, this strategy seemed to relieve them from the burden of calculating the scale of the theatre and other additions to their design. The architects' final product produced as a transparent overlay of the aerial photograph is presented in Photograph 5.3.
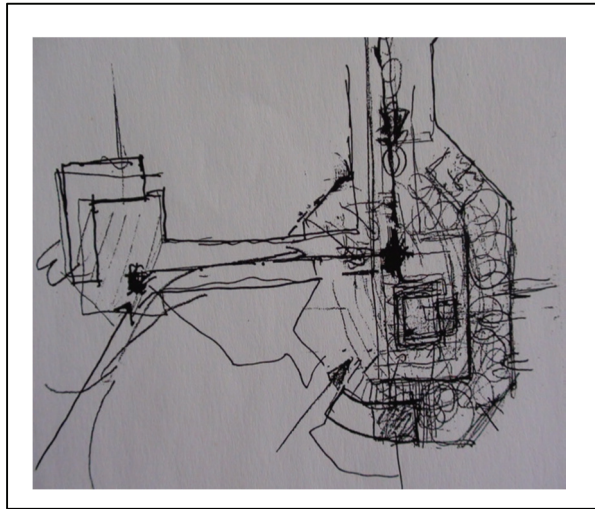
Photograph 5.3: **Final product of Participants P-A in plan view** (Sketch 14 01:02:35-01:59:00)

5.2.3.2 Mechanical engineering problem pace

In contrast, Edward and Eugene (Participants P-E) spent much time reading and discussing the brief in an indoors studio on the premises where the site at issue was located. The primary issue for them, in order to determine what was expected of them, was the specified size of the artifact that they were required to design (a rotating platform for an open air theatre). From the start, they were concerned about the necessity to have a stage of the size specified in their brief. They started measuring the size of the studio they were sitting in to orientate themselves in space judging the required size of their artifact. This concern seemingly resulted from the fact that they did not have a specification from the architects which would indicate the total space of the theatre itself, and they had to design an all-purpose, generic rotating object that could fit in any size within the parameters stipulated in their brief. The engineers' quarrel with the size became one of the themes during their exploration of the site; as they considered possible solutions and searched for information and a possible solution.

During their general discussion about the requirements in their brief, the participants started making sketches that outlined possible shapes for theatres, relating this to recreational spaces such as sports' arenas and other theatres (Appendix G) that they had encountered in their personal lives. A set of photographs that I provided of the site aided the engineers at this stage. It depicted the primary constraint of the setting that was specified in the brief, namely a concrete sculpture which should not form part of the theatre-idea. While making general exploratory sketches, they started generating broad concepts for different types of rotational systems. The basic shapes and concepts that they generated (Photograph 5.4) in these early sketches later proved to be the 'seeds' planted for their solution that was developed later.
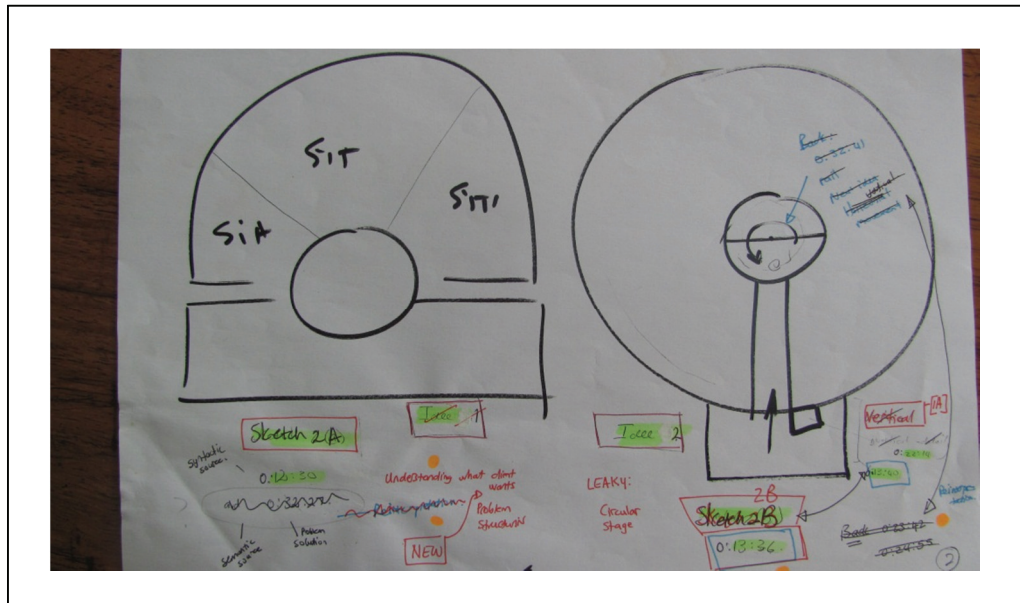
Photograph 5.4: **Participants P-E's early conceptualisation of theatres based on their recall of previously experienced theatres** (Sketch 2A 00:12:30 and 2B 00:13:36)

After satisfying themselves that they understood what was expected of them, they went outside to explore the physical site. While inspecting the site, the engineers focused on measuring the size by using their bodies. They roughly measured the whole area by pacing it off using the length of a pace as an instrument of measurement. They further observed details in the surrounding area such as entrance pathways, parking space and the general shape of the site. Their perception of the existing sculpture that they were required to disregard as part of their solution, however, played an interesting role in their thinking process. They seemed to be visually and intellectually stimulated by the presence of the object. For a relative large chunk of the time that they spent outside, they generated ideas in which they considered to fit the rotating platform inside the structure, despite the fact that the client/researcher reminded them of the brief's constraint in this regard and the foreseen impracticality of such an idea.

The engineers used their bodies to visualize and represent ideas. By means of gesturing, they simulated shapes, functions and positions of objects. Steered by their domain specific understanding that they were crossing over in the domain of the architects, they changed the direction of their thoughts and stopped considering the sculpture as part of their solution. I discuss this event in detail further on. One of the participants made a rough sketch of the shape of the site and its structural and proportionate relation to surrounding buildings and objects. This sketch (Photograph 5.5) later on assisted them to orientate their ideas both on the site and their subsequent continuation of thinking back in the studio. In the studio, they started with their sketches, plotting out the ideas suggested on the site, adding technical mechanical (Photograph 5.6) and structural detail and they generated a specification list. Intermittently though, they engaged in metacognition representing strategic procedural knowledge, by

drawing diagrams of the sequence of design procedures in which they were trained as mechanical and systems engineers, and which they habitually practice in their professional lives. At the end of the process one of the participants wrote a list with specifications.
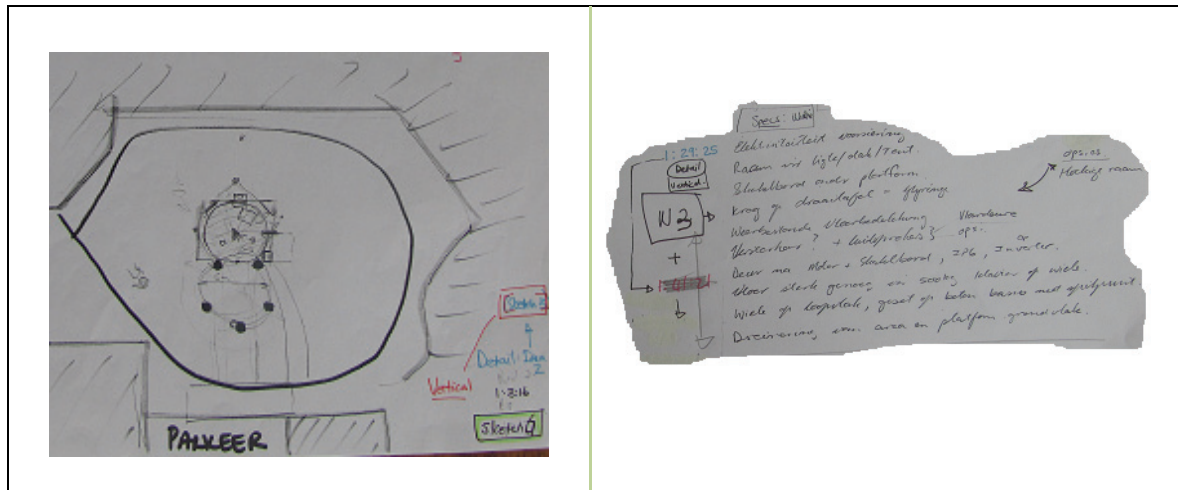
Photograph 5.5:
Engineer's final product of the platform in plan view (Sketch 6 01:30:16)

Photograph 5.6:
Engineers' written specification list (Writing 3 01:48:32)

5.2.3.3   Industrial designing problem space

The thinking process of the industrial design team, which consisted of Adrian, Brian and Clint was initiated, as with the other groups, by their interaction with the design brief inside a studio that simulated a typical classroom. This setting represented the site in which the required artifact (counting and managing device or system for large quantities of Lego™ used for educational purposes) would be used by the client. Samples of the Lego™ were present in the setting. The participants did not leave this setting during the whole process. After reading the brief, two of the participants started exploring the Lego™, while one participant started sketching. Simultaneously, the participants took turns questioning the client/researcher about the current procedures surrounding the actual use of the Lego™ that contextualized the need for the required artifact. They persistently and systematically engaged in asking a series of questions and responses regarding the procedures, sequencing and technical details, extending the information provided in their design brief. This line of questioning and listening to situational information provided by the client/researcher seemingly became the drive behind the suggestion and incremental development of their solution. In contrast with the other two groups, who tended to work on a particular concept as a team and worked on each other's drawings by adding detail, the three industrial design participants each worked independently on their own series of sketches, all generating different versions of the core concepts under discussion (Appendix G). At the end of their process, they consolidated their choices and

decisions with the leader[23] of the group making a final set of drawings (Photograph 5.7) with written specifications.
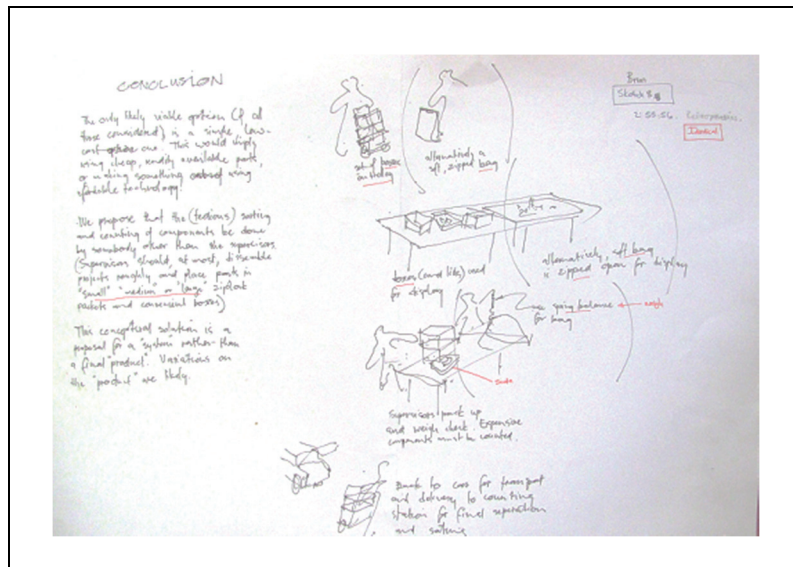
Photograph 5.7:   **Participants P-I's final product** (Brian Sketch 8 02:55:56)

The following section provides a holistic picture of two primary cognitive phases subsuming 'leaky phases' and how the use of existing knowledge and situational information was distributed throughout the protocol encompassing the three groups of participants.

5.3   DISTINCT AND OVERLAPPING COGNITIVE PHASES IN THE EARLY PART OF THE THREE DESIGN PROCESSES

In Chapters 2 and 3, I elaborated on the nature and role of problem structuring and problem solving phases. I also discussed the fact that these two phases sometimes overlap and that it is not always clear where the one phase ends and the other starts. I call this overlap a 'leaky phase' (after Goel and Pirolli's (1992) notion of a 'leaky module').

Unambiguous problem structuring instances were characterised by the process involved when the participants read their design briefs, asking questions that flowed from reading and figure implications of the requirements of their tasks. An example of such structuring is evident from Excerpt 5.1 (architecture participants' protocol).

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[23] The 'leader' was Brian, the primary participant I accessed at the outset of this project (Chapter 4, section 4.3.2).

Excerpt 5.1[24]

> ANDREW 00:50:04
> So that we can just get a feel for … on the time ….
> The look and feel should convey the concept of creativity, growth and playfulness'. So this should already be out of the box, you know – how this thing will work … but can we question this?
>
> JONATHAN 00:53:34
> Textual constraint'…That's why I asked if this was people or what? 'Audience not being exposed to looking in the sun while watching the performance.' That's why I asked if this refer to people or what? So this thing should face south.

From the detail of the protocols in my study as illustrated in Excerpt 5.1, I could deduce that the instances that the participants spent on structuring their design problems could be linked to explicit decomposition methods, as there was a clear indication of their efforts to structure the problem space. This inference of mine is supported by studies which suggest that experts rely on a 'dual-mode' of decomposition (Ho, 2001; Liikkanen, 2009). This means that they use the explicit decomposition strategies at the beginning of their process as can be seen in Excerpt 5.2.

Excerpt 5.2

> BRIAN 00:04:28
> OK, what you have given us here … would this be sort of an average would you say, like, uhm...
> BRIAN 00:04:39
> In other words, I see one green bottle, but I see quite a lot of red...
> BRIAN 00:05:09
> Individually? Or in sets?
>
> CLINT 00:05:21
> These teaching sessions, that are conducted by the relevant lecturers… Uhm, are they specific to the subject? In other words they will take a Lego set which is physics orientated or take a Lego set which is mechanically engineering orientated.
> BRIAN 00:06:17
> OK, so let's just go over this again.

I also found explicit strategies in the participants' problem solving phases and, as sub-goals emerged, that they used explicit and implicit methods of decomposition as seen in Excerpt 5.3 (engineering protocol).

Excerpt 5.3

> EDWARD 01:35:50
> Then you have here … this is the inside … the stage goes that way, say to there. And here you have a whole rotating axis … Okay. Sure.
> Question is then about maintainability'.
>
> EUGENE 01:36:07
> That's easy – easy to maintain.
>
> EUGENE 01:36:41

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[24] Even though many conversations transpired in Afrikaans, I include translated versions of these conversations for the sake of an international audience. The original Afrikaans version of the conversations is included in Appendix D.

You've got a motor – there – where ever that motor sits …. You put it … on the platform … you make a handle for it … You can put it any place.
EUGENE 01:36:20

Yes … and … you can put your wheels …. It depends … at this moment that thing is not much higher – I don't know what the incline is – it cannot be much more than 200-300 mm. So, it is relatively flat. So you can easily – if you open the platform, you can reach it to change the wheels, or whatever.
Put the motor anywhere. Put it there – with access from there. Open the door and put the motor there. You can access it – you let the wheels go round – at the back – it doesn't matter.
EUGENE 01:36:54

And underneath this platform you will have an electric box which you can open. Then you can have all your electricity … because you will have some kind of other wiring to the platform in order to have power on the platform.

In contrast, 'leaky phases' contained elements of problem structuring and problem solving in the same modules. Leaky instances often occurred as a result of the emergence of sub-problems and the generation of conceptual solutions. The participants partly solved some of the sub-goals at the point of emergence, while others were solved at different times during the explicit problem solving phases, whereas a number of sub-goals were ignored. Excerpt 5.4 illustrates how the engineers in the same module were making a decision as they raised a question to further structure their problem, suggested an approach, questioned their suggestion and delayed making a decision.

Excerpt 5.4

EUGENE 01:27:15
Our engineering therefore only functions as far as the rotating platform. Up and down?
EUGENE 01:31:36
I don't think you want to go much higher than what is level with the highest point of the ground.
EDWARD 01:31:41
I mean in terms of the hole – to lift the whole floor up and down like a shaft. I wonder if it makes any sense for this purpose. It is too 'fancy. I don't know – you can say. It is too fancy, keep it simple.

Goel and Pirolli (1992) concur with this finding and ascribe designers' tendency to delay solving sub-problems to the fact that there are few or no logical connections among modules but only contingent ones. In Excerpt 5.4 Participants P-E seemingly delayed their decision taking and were only able to make a decision once they articulated the necessity to keep the design 'simple'. This means that their decision depended on their norm for success, namely 'simplicity'.

5.4 MAPPING THE STRUCTURE AND CONTENT OF PARTICIPANTS' DESIGN PROCESSES

In the following sections I discuss my understanding of the three participating groups' structuring of their problem spaces revealing their intentions and subsequent dependency patterns embedded in the sequences of their thinking. This implied that I attempted to interpret the behaviour of the participants and establish the plausible relationships between internal and external variables dependent on the context of each protocol.

I subsequently attempted to establish where problem structuring instances occurred. I therefore asked questions such as 'where in an entire protocol do I find evidence of the participants attempting to understand the nature of the problem, the scope of the problem? *What kinds of aspects, including the required behaviour of the intended artifact, required functional and physical properties of the intended artifact, did the participants consider?* To establish where problem solving instances occurred, I asked questions such as *when did the participants engage in generating ideas, develop ideas, and detail ideas? Where and how did a particular instance originate?* To identify leaky phases I asked questions such as *when did the participants, in one module (existing of a single statement or group of statements covering one theme) simultaneously attempted to understand the problem and generate, develop or detail ideas?* In order to link these broad mental processes with the use of internal and external resources, I asked questions such as *what was the distribution of occurrences of types of knowledge underlying the types of thoughts they heeded in each cognitive phase?, what was the distribution of the use of internal resources and the simultaneous occurrence of embodiment principles in one module?*

In order to obtain such an overview, I acquired statistical information. As I explained in Chapter 4 (Section 4.3.4.2) I used particular operators[25], as suggested by Goel (1995) to indicate when and how the participants' cognitive processes moved between problem structuring, problem solving and leaky phases. I carefully coded the verbal data in terms of the theoretical characterisation of each of the three cognitive phases as explained in Chapter 3. Photograph 5.8 captures an example of my coding process.

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[25] The verbal operators included 'commenting', 'qualifying', 'elaborating', 'justifying', 'evaluating', 'proposing' 'commenting' and 'repeating'.
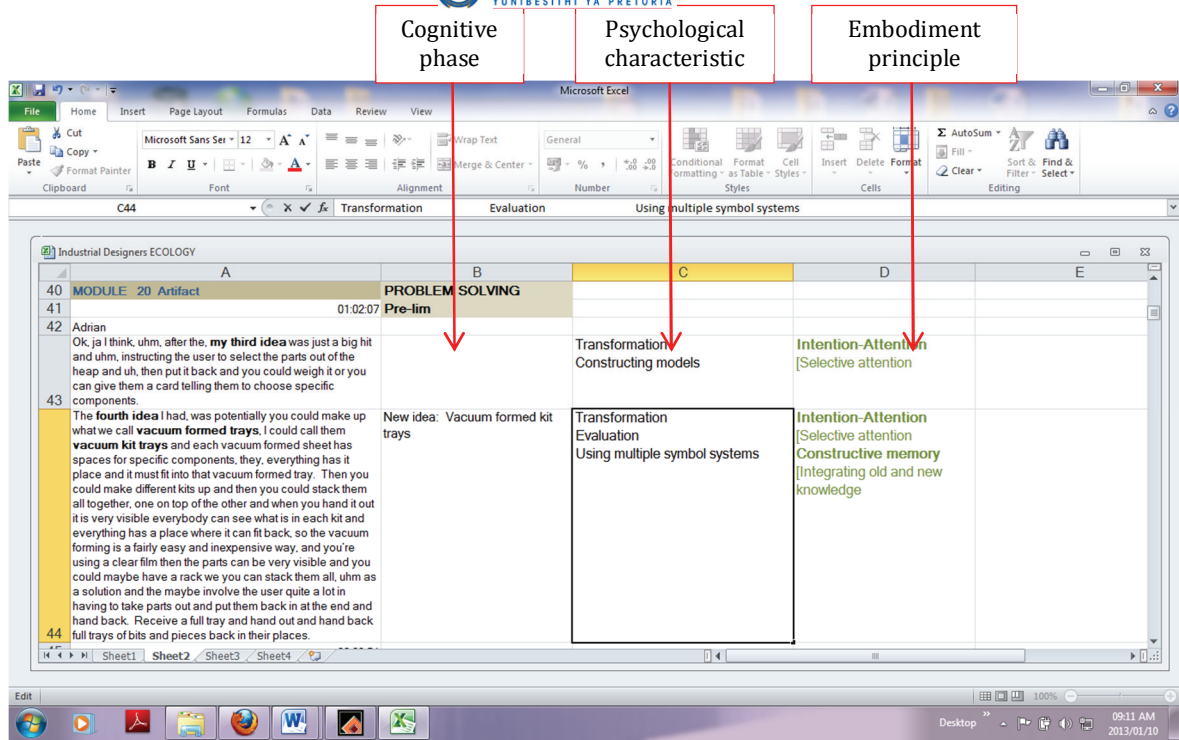
Photograph 5.8: Example of the qualitative coding process from the industrial designers' dialogue

The qualitative coding was subsequently transferred by the statistician into a binary coding system. During this process I checked the accuracy of the binary coding system (Appendix E) several times, which was complex and labour intensive, but provided the necessary counts, distributions and co-occurrences of events with relative accuracy. Applying SPSS software to the coded transcripts, I was able to visualise the distribution of instances across the entire protocols of each of the participating design teams in the boxplot in Figure 5.1.
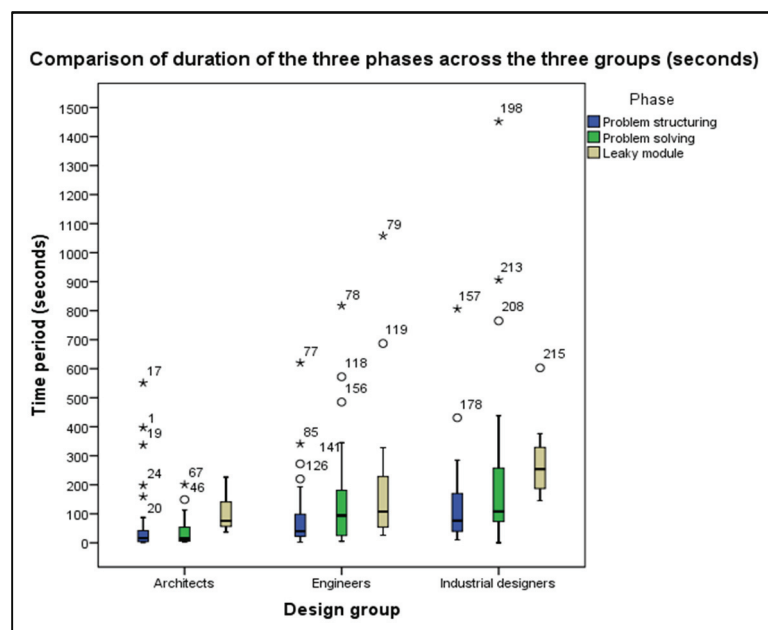
Figure 5.1: Distribution of instances across the protocols of each of the participating design pairs/teams

Figure 5.1 indicates that each group went through both phases and that there were clear indications of instances of leaky phases. The statistics namely indicated that all groups spent more or less the same proportion of time solving their problems, but that there were considerable variability in problem structuring and leaky phases. The significance of outliers, indicated by 'ᵒ' cases (instances) and extremes indicated by '*' cases in the problem structuring phase is that they demonstrate the wide spread occurrences of the participants explicitly and implicitly trying to get a mental hold on all the given and emerging aspects of the problem throughout their protocol. The frequency calculations of instances indicate which proportion of time each groups spent on each of the phases calculated from the time (per seconds) proportionate to each group's total time used to complete their tasks, as summarised in Table 5.1.

Table 5.1: Summary percentage of overall temporal structure of the cognitive phases found in the TAPS across participants

Design group	PHASE		
	Problem structuring %	Problem solving %	Leaky phases %
Participants P-A (Architects)	33	31	12
Participants P-E (Mechanical engineers)	31	33	16
Participants P-I (Industrial designers)	23	28	10

(*Proportion (%) Time period (seconds))

Table 5.1 suggests broad patterns in the behaviour of the participants on a macro level. However, on a micro level, which is described and explained in more detail in Chapter 6, I found that each of the groups had different ways and sequences of activities in decomposing their problems. The architects (Participants P-A) spent 33% of their time explicitly decomposing their problem by linking it with old problems (Liikkanen, 2009). This was evident from the number of times they immersed themselves in case scenarios (Appendix E-Statistics). These case immersions suggest that Participants P-A recognized their 'new' problem type and could make relevant associations with stored domain specific knowledge (Kirsh, 2009) early in the structuring phase, which seemed to have resulted in relatively little time, 12%, spent in leaky phases as opposed to the 31% spent on problem solving. Although it was relatively simple to detect the occurrence of case-immersion during the first part of Participants P-A's protocol, it was not easy to determine the precise cognitive function of the recalled cases, due to the seemingly isolated nature of some of the recalled cases, which resulted from what appeared to be free association (Lichtenstein, 1965).

Cognitive functionality only became clear after several iterations of the whole process and close connection between the semantics and syntactics of accompanying sketches with verbalized and visualised decisions that Participants P-A took during the latter part of their protocol. Photograph 5.9 presents the sketches the participants made while relating to other cases. It was in particular the structural properties and semantic information of the case-sketches the participants made, that provided information of their relevance to a particular cognitive phase. By closely attending to the video material, and close coupling of sketches with the psychological behaviour of evaluation functions, abstraction hierarchies, and its subsequent links with knowledge type efficiency and normativity, I was able to link case immersion to particular cognitive phases, and determine which sketches (and related verbalisation) served as evaluation functions, showing when a particular design would not be functional and efficient in their design problem space, and which one's contributed to the solutions of their design task.

The importance of context was particularly relevant in the interpretation of the cognitive function of the case. The coding and interpretation of the visual data in particular, assisted me in inferring cognitive function of case immersion. Photograph 5.9 captures an example of the coding of Participants P-A, which was closely coupled with the verbal data and time indications on the video material.
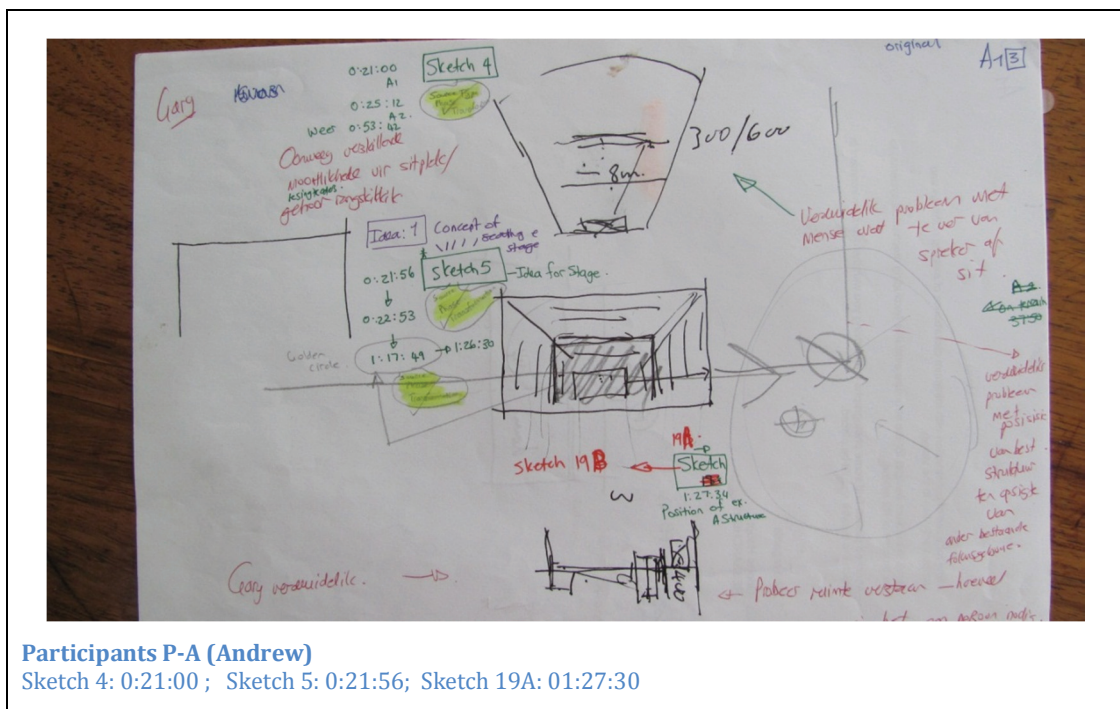
Participants P-A (Andrew)
Sketch 4: 0:21:00 ;   Sketch 5: 0:21:56;   Sketch 19A: 01:27:30

Photograph 5.9:   **Example of coding of visual data with explanatory contextual notes with regard to spatial organization principles in particular cases that Participants P-A immersed themselves in**

The engineers (Participants P-E) spent 31% of their time on problem structuring, 33% on problem solving and 16% in leaky phases. I found that they spent relative much time in leaky

phases. In spite of their initial apparent confidence in what they would be focusing on, their leaky phases demonstrated that they were easily distracted when being visually stimulated. This tendency of the participants to react on perceivable information complicated the classification of their verbal utterances, as their application of perceived information were constantly diffused by confusing references of possible use of perceived objects and the intentions of their design brief, as demonstrated by Excerpt 5.5.

Excerpt 5.5

EUGENE 00:01:36

Now this – does it stay here, or does it become the stage?

EDWARD 00:01:40

This is a good question. What I understood of the client (researcher) … mmm … was that this element is an architectural element and should stay part of the whole set-up. But, if it should stay there in its current position, is an open question. We will have to figure that out. The question is what she wants to do with this thing. Because, if it is going to be an obstruction – then you won't be able have a forty meter stage – how big will it be? 5 meters?

As a result, Participants P-E engaged in relatively long modules during which Participants P-E attended to sub-problems that emerged as a consequence of their observation of the site, which was in actual fact not specified as part of their design brief (Appendix C), but rather explicitly and repeatedly excluded (Appendix D). Intertwined with their attention to the possibilities afforded by the 'irrelevant' sculpture, was the engineers' constant switches of attention between what was required by the brief, and what they perceived as do-able, although not required. Suwa and Tversky's (1997) situated account of designers constantly shifting their attention corroborates this observation. Goel (1995) also observed that the mode of output implies commitment.

In order to interpret the cognitive significance of the length of time the participants spent on considering seemingly unnecessary elements including the sculpture (refer to Chapter 6 the number of references to a particular object to prolonged attention as suggested by Suwa and Tversky's (1997). As such, I connected duration with the total number of instances when they referred to the sculpture (Appendix D), including the sketches (Photograph 5.3, p.155) and Appendix G) related to the sculpture. From this connection I inferred that Participants P-E considered including the sculpture as an alternative solution, and therefore represented problem solving and not problem structuring thoughts.

In turn, classifying the behaviour of the industrial designers as problem structuring or problem solving posed its own challenges. Their distinct tendency to make sketches, appearing as generation of ideas, while reading and interpreting their design brief, made it difficult to decide when the sketches signified a generated idea, a recalled case representing a previous solution, or

a way of understanding the problem. I inferred case immersion from the participants' psychological behaviour of forming abstraction hierarchies. Deriving accurate inferences in this regard was not simple due to the fact that Participants P-I assumed typical types of artifacts as cases, instead of referring to specific contexts (cases) in which such artifacts were previously designed, as was the case with the architects.

Therefore, instead of assisting me to map the structure of their thoughts, the sketches that Participants P-I made during the first part of their protocol confused me. Photograph 5.10 captures one instance when Adrian made three sketches without explicitly indicating whether he recalled the ideas represented in them from previous cases, or whether he generated them as original ideas.

Participants P-I: Adrian
Sketches 1, 2 and 3 00:15:02 – 00:18:00
Implicit cases adapted for new situation?

Photograph 5.10:   Ambiguity of cognitive function of sketches made by Participants P-I

Not knowing whether particular sketches belonged to case immersion or to generating ideas, was significant for classifying them accurately. If they belonged to case immersion, it could be argued, based on previous studies by Goel (1995), and my findings regarding the architects and engineers, that these sketches served as tools to visualize LTM, which typically occur during the problem structuring phase. In contrast, if the sketches served as tools to generate ideas, they could be classified as part of the problem solving phase. Member checking confirmed that these sketches were based on cases Adrian recalled, but adapted as part of his understanding of how storing and sorting Lego™ could work. I therefore conceded interpreting these sketches as problem structuring.

Contributing to this confusion was the fact that Participants P-I consisted of three members and not only two. The implication was that, while two particular participants were talking to one

another, the third member might be engaged on his own, thinking about things non-related to the current conversation between the other two members. However, by closely listening to the line of thought derived from their dialogue, and reviewing all the sketches made by all the participants during their entire protocol, I could connect the semantics and syntactics of the sketches with the psychological characteristics.

After several iterations of coding and recoding, in attempting to untangle the cognitive functions of the sketches made during the first part of their protocol, I inferred that Participants P-I needed less time than the other participants to structure their given problem. They reportedly spent 23% of their total time structuring the problem and 28% on problem solving thoughts. This tendency could be explained by their explicit and uninterrupted trail of questioning and interpreting the problem while constantly perceiving the objects (Lego™) at issue. Participants P-I spent only 10% of their time in leaky phases, which implies that they decomposed their problem into sub-goals primarily during their problem structuring phase, with a few sub-goals emerging during the rest of their protocol (Appendix D-Psychology). I surmised from these different patterns in the sequences of the three protocols that it was the participants' generic experience as experts that they executed their own individually and combined known strategies, clarified the requirements of the client, interpreted the various design problems and weaved their own intentions in their solutions in terms of the aspectual, functional and implementation goals, that resulted in the solving of their problems (Gollwitzer & Schaal, 1998).

In the following section I present evidence of the different modes of output that the participants used to represent their knowledge, what they thought about and how this interacted with external resources. I interpreted the knowledge to know when to use a particular mode of output as a scaffold, derived from domain specific strategic knowledge intertwined with generic expert or procedural knowledge (Kilgour, 2006; Popovic, 2004) and visualisation knowledge.

5.5 INTERACTIVE USE OF EXTERNAL RESOURCES

As I followed the mapping of the cognitive structures of the participants' protocols, I extended Goel and Pirolli's (1992) framework. I did this through examination of which external resources the participants used as scaffolds in their thinking processes to broaden the general understanding of what happened during the early phases of the participants' design processes. To this end, I considered various situational objects, including the design briefs, the site, objects in the site, representations of the site and other relevant aspects. Interaction with external resources such as their sketches, physical objects such as Lego™ pieces, aerial photographs that represent the real theatre site, references books and real objects in the theatre site, such as the problematic sculpture, all contributed to the participants understanding of their design problem

and sub-problems as well as to their generating and committing to ideas. Photographs 5.11, 5.12 and 5.13 capture some external resources the participants had access to.

Photograph 5.11:   External resources used by Participants P-I
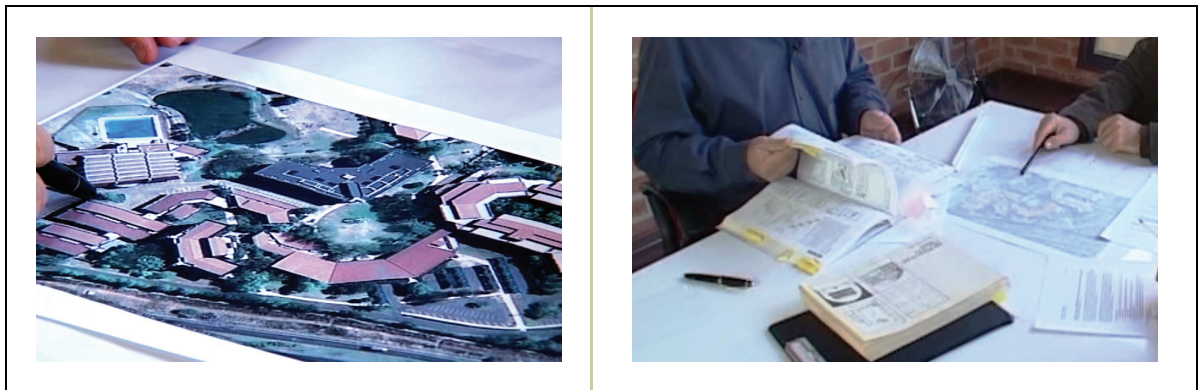
Photograph 5.12:   External resources used by Participants P-A
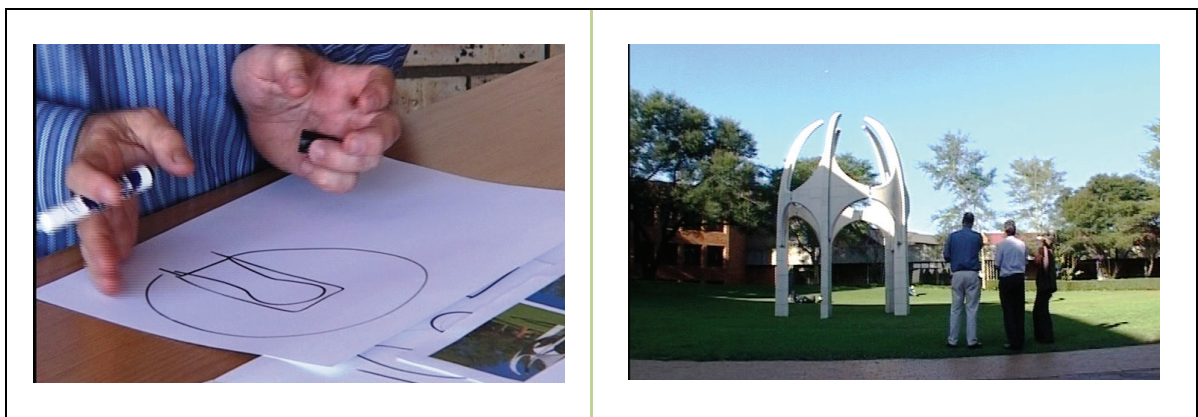
Photograph 5.13:   External resources used by Participants P-E

These types of activities the participants resorted to imply an intentional and systemic in-the-moment interactivity between the internal search and problem space and the external world affording perceptual cues and environmental anchors (Kilgour, 2006; Smith, 2005). I considered

people, including partners and client/researcher as well as activities, such as talking, writing, sketching and gesturing as external resources involved in the participants' thinking strategies. I individuated the instances in which I observed the participants interacting with external resources when a verbal or visual reaction followed. Through close observation of what was happening during each verbal utterance recorded on video, I could distinguish when the participants' actions were triggered by their design briefs or information provided by the client (researcher). I could also determine when partners in the various groups made sketches (refer to Chapter 6, Section 6.5 for detailed analysis of all the groups' use of internal and external resources). Coding such sources was relatively uncomplicated as I could perceive the relevant external resources.

I was therefor able to count instances when the participants used external resources available to them. I was furthermore able to observe and count instances when the participants interacted with other external resources, such as photos, books, and site-related objects such as Lego ™ (in the case of Participants P-I), or buildings in the environment (in the case of Participants P-A and P-E). However, what was not possible to observe, was the complexity of internal processing involved in the participants' encounters with external resources. The purpose of the counts and distributions in this chapter serve as indication of the complexity of the multiple interactions of internal and external processes and resources. I extend current information processing theories by connecting cognitive activities with embodiment principles and external resources. The aim of the extension is thus to empirically connect internal and external processes and resources, providing observable evidence of interaction. In Chapter 6 I attempt to describe and explain some of the salient and interesting interactive instances through evidence of the context of particular complex instances and theoretical argumentation regarding the cognitive significance thereof.

I carefully observed the resources the participants used, and coupled these with co-occurrences with types of knowledge (Appendix D-Knowledge and E-Statistical data) (which I interpreted as recall and application of LTM) as captured in Photograph 5.14 and 5.15. This enabled me to infer perception-action cycles of cognitive behaviour, which in turn suggested instances of interaction. These instances implied systemic perception-action instances, in which affordance, specificity and intention-action were embedded.
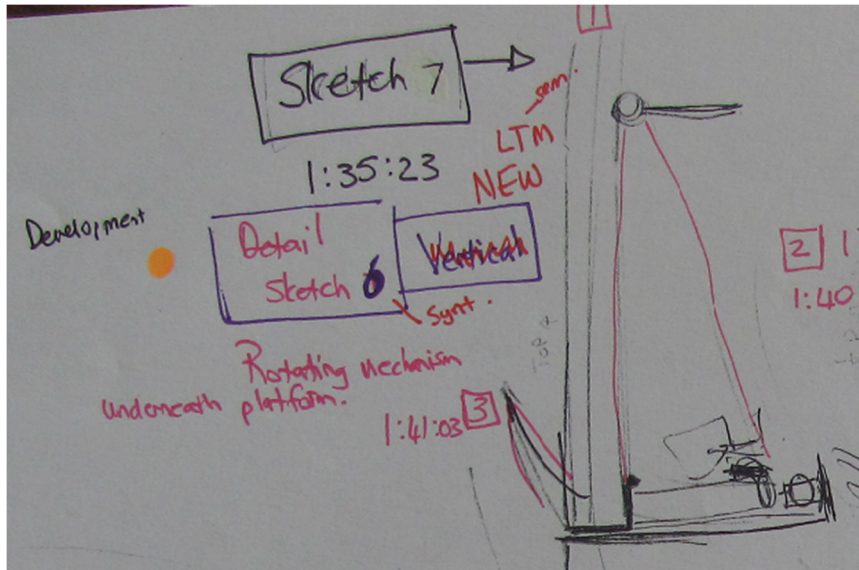
Participants P-E
Sketch 7 01:41:03
Sketches are considered as an external resources that
allow participants to represent their knowledge

External

External representation

Knowledge types   Abstraction   Resource

Internal

Photographs 5.14 (Sketches) and 5.15 (Spoken words):
Example of coding of resources used by the participants

It was important to consider the context of occurring instances relevant to this section. I closely watched the video material several times, to check which external resources the participants used that triggered a particular reaction and were externalised through a particular mode of output. From the video material I thus differentiated between verbal and visual output, or noted co-occurrences of talking and sketching. Photograph 5.16 and 5.17 capture an example of such differentiation extracted from the verbal data in the field notes that I made. I checked the coding
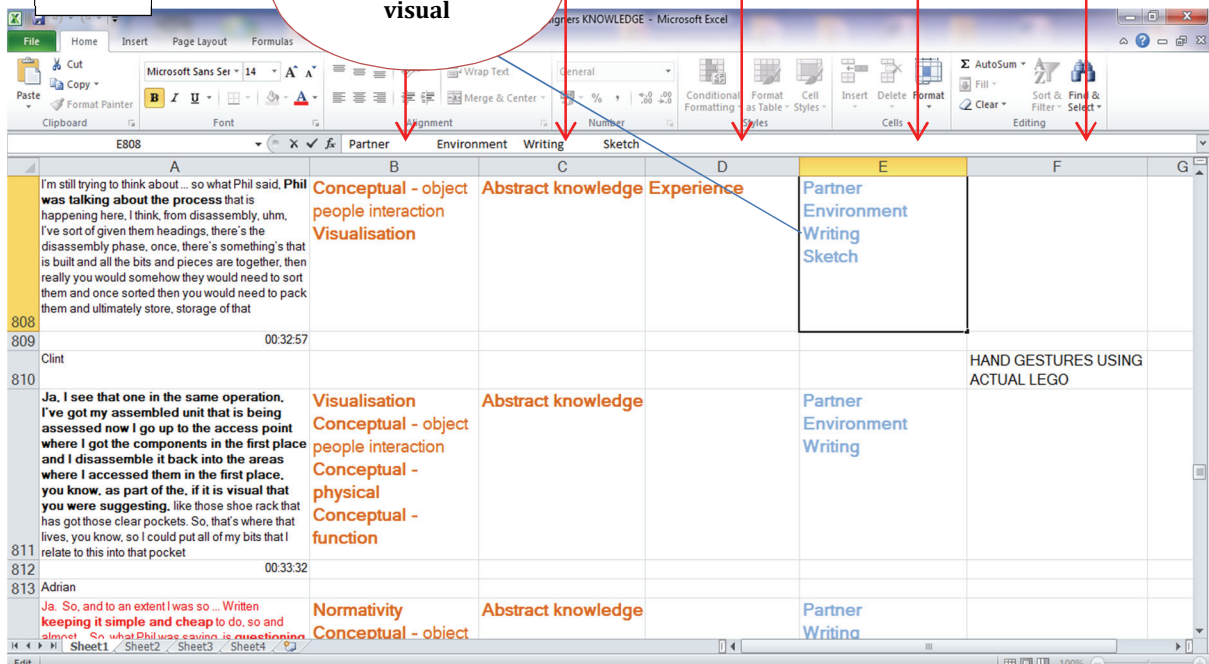
of the modes of output in multiple ways, including references to 'constructing/manipulating models' in the 'Psychological characteristics' category and references to visualisation in the Knowledge types' category coinciding with instances when the participants made graphic marks. In turn, I identified instances of writing, which counted as a verbal mode of output, from my observation notes while I watched the video recordings. Based on theory (Goel, 1995; Kirsh, 2009; Shani, 2012) I assumed that the mode of output implicitly served as extended resource that influence designers' behaviour.

Photograph 5.16 & 5.17:
Example of the coding of Participants P-I's modes of output coinciding with external resources

In Table 5.2 I summarise the total number of instances the architects used external resources, linked to instances of embodiment principles throughout their entire protocols. I derived this information from correlating the ecology category with my field notes and statistically merging

the binary coding for the various subcategories into statistical correlation between instances of occurrence (Appendix D and E).

Table 5.2: **Number of instances when Participants P-A's vocal utterances co-occurred with the use of external objects**

ARCHITECTS (PARTICIPANTS P-A)														
Resource	Brief			Partner			Client/ Researcher			Sketch			Other external aids*		
Embodi-ment principle	Specificity + Intention-attention			Specificity + Perception-action + Intention-attention			Specificity + Intention-attention			Affordance + Perception-action + Specificity + Intention-attention			Affordance + Perception-action + Specificity + Intention-attention		
Phase	PStr	PSv	LPh	PStr	PSv	LPh	PStr	PSv	LPh	PStr	PSv	LPh	PStr	PSv	LPh
Trend	6	8	1	8	53	2	16	16	10	6	95	2	0	70	23
Total no instances	15			63			42			103			93		

*Photographs, books, internet sources

The numerical information in Table 5.2 indicates that Participants P-A used more sketches as external aid in combination with all four relevant embodiment principles, than any of the other external aids. This could be explained by the fact that they made many sketches of cases that they were immersed in to visualise and explain their aspectual and functional intentions (refer to Chapter 6). In general, the number of times Participants P-A made explicit use of their brief was less than the other participants. They made use of the client/researcher to clarify issues and provide information instead. In contrast, their high usage of alternative external resources can be explained by the fact that they constantly used an aerial photograph to develop their ideas. They also made use of reference books, which aided their 'case' sketches and the choices they made in terms of spatial arrangements and visual functionality. Using the aerial photograph was cognitively beneficial to the architects in many ways due to the specificity of the visual information contained in it. This information included visual references to elements' size, shape, material and spatial arrangement. The fact that they relied on this information first saved them the effort to store the perceived information (gained from the physical site inspection) in their short term memories. Secondly it saved them time and mental effort to calculate the scale in order to draw their ideas proportionately. Thirdly, it served as visual cues reminding them of similar cases. Fourthly, the aerial photograph served as visual cues which afforded possibilities for integrating and transforming existing elements into their theatre design. Furthermore, Participants P-A made use of each other as aids (sounding boards) which can be explained by the longer duration of their single utterances (Appendix D). This means there were in general

I present a summary of the total number of instances that the engineers used external resources, linked with embodiment principles throughout their entire protocol.

Table 5.3: **Number of instances when Participants P-E's vocal utterances co-occurred with the use of external objects**

ENGINEERS (PARTICIPANTS P-E)														
Resource	Brief			Partner			Client/ Researcher			Sketch			Other external aids*		
Embodiment principle	Specificity + Intention-attention			Specificity + Perception-action + Intention-attention			Specificity + Intention-attention			Affordance + Perception-action + Specificity + Intention-attention			Affordance + Perception-action + Specificity + Intention-attention		
Phase	PStr	PSv	LPh	PStr	PSv	LPh	PStr	PSv	LPh	PStr	PSv	LPh	PStr	PSv	LPh
Trend	25	16	4	33	31	17	24	3	7	57	10	2	8	0	0
Total no instances	45			81			34			69			8		

* Photographs, books, internet sources

The numerical information observed in the frequency Table 5.3 indicate that Participants P-E used their brief considerably at the beginning, and very little towards the end. I attribute this trend to their personal strategy (and domain specific training) to explicitly clarify most of the requirements at the beginning of the process. Towards the end, Participants P-E used the brief to confirm their dealing with all the issues required by the client. Although they generally produced fewer sketches than other participants, the graphic marks that they used, had multiple meanings for them and kept on changing in content. In this manner, the ambiguity of the engineers' sketches contained multiple possible ideas. They also used very little alternative external aids. They used the photographs of the site provided by the client and the studio where they were working as other external aids. This means that they relied on their short term memories and site sketches to aid them with regard to the site.

Their little use of alternative external resources could perhaps be attributed to the fact that the physical environment only influenced the design of the mechanical system for the rotating platform in a limited way. The mechanical part of the platform could be considered as an isolated functional component of the theatre which, at a conceptual stage, was more dependent on the specifics of the theatre design than on the environment. This means that the type of artifact designed influenced their use of external resources. In addition, it seemed that Participants P-E stored much of the environmental information in their short term memories

through active interaction with what they perceived. This could be seen in the number of ideas (much of which were outside the scope of their design brief (Appendix C)), that they generated (and rejected later on) as response to the visual stimuli on the site (Chapter 6, Section 6.4). In Table 5.4, I summarise the number of instances when P-I's vocal utterances co-occurred with their use of external objects.

Table 5.4: **Number of instances when Participants P-I's vocal utterances co-occurred with the use of external objects**

INDUSTRIAL DESIGNERS (PARTICIPANTS P-I)														
Resource	**Brief**			**Partner**			**Client/ Researcher**			**Sketch**			**Other external aids***		
Embodiment principle	Specificity + Intention-attention			Specificity + Perception-action + Intention-attention			Specificity + Intention-attention			Affordance + Perception-action + Specificity + Intention-attention			Affordance + Perception-action + Specificity + Intention-attention		
Phase	PStr	PSv	LPh	PStr	PSv	LPh	PStr	PSv	LPh	PStr	PSv	LPh	PStr	PSv	LPh
Trend	39	8	21	36	53	49	31	7	2	15	34	28	34	23	37
Total no instances	68			138*			40			77			94		

*Photographs, books, internet sources

The statistical information observed in Table 5.4 indicate that there was a higher count for Participants P-I's use of partners, probably due to the fact that this team consisted of three team members and therefore together they produced more instances of dialogue change, which implies that the participants used each other as external resource most of the times. Participants P-I's protocol furthermore produced high combined counts for their use of the brief as well as the client. What was interesting was the extent to which Participants P-I used their sketches. In general, combined and on average, they used their sketches fewer times than the other participants. They produced much more writing which aided their sketches and decisions that they took. They furthermore made considerable use of the Lego™ provided by the client/researcher and constantly kept them on the tables for physical handling and inspection. The industrial designers were therefore consciously and subconsciously influenced by the specificity of the visual information afforded by the Lego™ and existing storage system (A4 boxes and plastic bags), with regard to the type of system used, and the shapes, sizes, variety and material of the Lego™ pieces. In retrospect I considered the constant presence of the existing system used by the client as a plausible explanation for the conceptual solution Participants P-I adopted as a solution to the client's problem. I deduced that the constant physical presence of

these elements served as visual and conceptual cues for their idea generation and evaluation functions. This insight confirmed the considerable influence of the external environment on these participants' choices and their reasoning strategies (also refer to Chapter 6).

While several previous studies emphasised the cognitive role of sketches and other external sources that may contribute to thinking strategies due to their role in cueing emerging information, (Gero & Yan, 1994; Oxman, 2002; Suwa et al., 1999), they did not explicitly explain their links with embodiment principles to internal information processing and the psychological characteristics of design problem solving. It is this limitation in existing literature that I aim to fill in the following section. In order to capitalise on my observation that the participants in this study had high incidences of intention-attention and specificity instances, I explored its potential significant associations with psychological characteristics and various types of knowledge, as discussed in the following section.

5.6   MAKING COMMITMENTS AND MODES OF OUTPUT

Through the analysis of the verbal utterances of the participants, I was able to detect when they committed themselves to simultaneously engage in verbal (vocal utterances) and visualisation (sketching) activities. In turn, considering the visual documentation of the protocols, I was able to find evidence of how the participants constantly moved between internal processes and external resources as part of their problem solving situations (Chapter 5). Goel (1995) argues that the more designers use different modes of output when thinking about design solutions, the more committed they seem to be to a particular idea. For this reason, I interpreted instances of simultaneous talking and sketching as a sign of commitment.

In making their commitments, designers typically use different modes of output, such as uttering suggestions, repeating them to themselves, to colleagues or to clients, writing things down, or making different kinds of sketches, drawings or diagrams to represent their commitments (Goel, 1995). In Table 5.5, I summarise the modes of output Participants P-A used to represent their commitment to ideas across the phases (problem structuring [PStr], problem solving [PSlv] and leaky phases [LPh]).

Table 5.5: **Modes of coinciding output confirming P–A's commitment to ideas throughout all their cognitive phases**

MODES OF OUTPUT ACROSS THE COGNITIVE PHASES																	
Talking									Writing			Sketching					
Commitment statements across the phases (repeat statements)			Generating development ideas across the phases			Reversing transformation direction across the phases			Across the phases			Constructing and manipulating models across the phases			Explicit scenario immersion instances		
PStr	PSl	LPh	PStr	PSl	LPh	PStr	PSl	LPh	PStr	PSl	LPh	PStr	PSl	LPh	PStr	PSl	LPh
6	8	7	13	28	17	11	6	5	0	0	0	16	23	9	8	5	0
21			58			22			0			48			13		

From the frequencies and distribution of their commitment behaviour, it became evident that Participants P-A generated more ideas than what they committed themselves to throughout their protocol. I inferred from Participants P-A's observable commitment behaviour that they did not use any writing except from their calculations included in the two diagrams they drew during their protocol. They constructed one diagram when they structured their design task problem and one when developing a solution. Both diagrams represented their thinking about the scale and size of seating required by the client. An interesting characteristic of Participants P-A's commitment behaviour was that they used multiple sketches when they immersed themselves in similar case scenarios from which they drew their implementation intentions. This indicated to me their dependence on their externalisation of the LTM to illustrate architectural principles, either to adapt in their current design task, or to justify and explain to the client the reason for their decisions. These sketches of Participants P-A were embedded in their long chunks of attention-intention instances discussed previously.

Similarly, the engineers' commitment behaviour was characterised by their various modes of output. The frequency of their ideas suggested that the developing of a solution was higher than their repeat statements, which indicated Participants P-I's commitment. They made use of writing only when they explained their domain specific procedural metacognition, which externalised the sequence of cognitive activities in their design process by drawing a diagram. They drew this diagram towards the end of their protocol as a way of checking their own thinking process thus far. They used the diagram to demonstrate their commitment to a particular way of thinking to the client. Two other instances of writing include when the one participant (Eugene) committed himself to the final decisions they took and listed them as specification at the end of their protocol. In Table 5.6, I present a summary of Participants P-E's commitment behaviour observed in the modes of output that they used.

Table 5.6: **Modes of coinciding output confirming Participants P– E's commitment to ideas across all their cognitive phases**

MODES OF OUTPUT ACROSS THE COGNITIVE PHASES																	
Talking						Writing						Sketching					
Commitment instances across the phases (repeat statements)			Generating development ideas Statements across the phases			Reversing transformation direction across the phases			Across the phases			Constructing and manipulating models across the phases			Explicit scenario immersion instances		
PStr	PSl	LPh	PStr	PSl	LPh	PStr	PSl	LPh	PStr	PSl	LPh	PStr	PSl	LPh	PStr	PSl	LPh
31	59	27	28	77	29	13	19	27	1	2	0	26	30	13	2	0	0
117			134			59			4			69			2		

In contrast to the other participants of my study, the industrial designers used much writing to support their thoughts. All three members of this team used their writing to explicitly formulate the advantages and disadvantages of each concept that they individually generated through preliminary sketches. They used these as discussion points in order to structure their dialogues and based their commitment to concepts on the content of their written outputs. In Table 5.7, I summarise the modes of output Participants P-I used to represent their commitment to ideas across the phases.

Table 5.7: **Modes of coinciding output confirming Participants P– I's commitment to ideas across all their cognitive phases**

MODES OF OUTPUT ACROSS THE COGNITIVE PHASES																	
Talking						Writing			Sketching*								
Commitment instances across the phases (repeat statements)			Generating development ideas across the phases			Reversing transformation direction across the phases			Across the phases			Constructing and manipulating models across the phases			Explicit scenario immersion instances		
PStr	PSl	L	PStr	PSl	L	PStr	PSl	L	PStr	PSl	L	PStr	PSl	L	PStr	PSl	L
16	81	26	0	24	13	17	73	30	5	24	13	5	24	13	0	0	0
123**			37			120			42			42			0		

*Combined score – taking ideas into account, and not number of sketches by each individual team member.
**Three team members, together with longer time used to solve their problem all contributing to total number of commitment instances, account for high frequency, compared to other two pairs, consisting of two members

5.7 INTERACTION BETWEEN INTENTIONS, APPLICATION OF CONTROL STRUCTURES, PERSONAL STOPPING RULES AND EVALUATION FUNCTIONS ON THE USE OF TYPES OF KNOWLEDGE

The aim of this section is to provide stepping stones towards the development of an account of the significance of intention in the process of designing technical and social artifacts. I discuss the salient trends and patterns observed in the statistical findings by calculating frequencies and establishing distributions of instances of interaction between internal and external resources with regard to individual participating teams as well as across the teams. The purpose of this section is thus to highlight the trends of the assumed interaction between internal and external resources with the focus on instances when the embodiment principle of intention-attention could be linked to internal use of knowledge. In the context of this study, goal intentions imply 'intentions as plans' (Kieran, 2011) for the functionality of artifacts. As such, I adopted the view of cognition of Bratman, cited by Kieran, (2011, n.p.), which encompasses discipline specific knowledge, who argues that

> *Intention is a distinctive practical attitude marked by its pivotal role in planning for the future. Intention involves desire, but even predominant desire is insufficient for intention, since it need not involve a commitment to act: intentions are 'conduct-controlling pro-attitudes, ones which we are disposed to retain without reconsideration, and which play a significant role as inputs to [means-end] reasoning.*

The focus of this section is therefore to provide the foundation for tracing the relationships between participants' goal intentions, their implementation intentions and their knowledge of the physical and functional nature of the artifacts that they designed, which is discussed in detail in Chapter 6. I base this foundation on evidence of the participants' application of their normative knowledge in the psychological characteristic behaviour of designing (Goel, 1995; Goel & Pirolli, 1992). I focus on control structures, personal stopping rules and evaluation functions while I assume that designers apply them as metacognitive procedural tools of action control (Gollwitzer & Schaal, 1998).

5.7.1 THE ROLE OF CONDUCT CONTROLLING ATTITUDES

Due to its strong relations with 'conduct-controlling' attitudes (Kieran, 2011), I link the notion of intentions, which I consider as situationally bound (Smith & Semin, 2004) to their particular design tasks. In this section, I use this 'intention conduct-controlling' argument to extend Goel's (1995) study to demonstrate what kinds of thoughts expert designers tend to heed in the different phases of the design process. To this end, I attempted to find evidence of dependency direction between the types of thought the participants paid attention to when they expressed their intentions to include planning of future action and future artifacts. The aim of the following sections is to trace the dynamic movement between internal and external sources when the

participants consciously or unconsciously applied control structures, personal stopping rules and evaluation functions (Goel, 1995; Goel & Pirolli, 1992). The reason for focusing on these psychological characteristics is based on the assumption that designers may apply them as metacognitive tools of action control (Gollwitzer & Schaal, 1998).

5.7.2   THE ROLE OF INTENTIONS

Previous studies indicate strong links between the design process and the particular type of artifact being technical, social or socio-technical in nature (Eastman, 2001; Ferguson, 1992; Love, 2002). Such kinds of studies emphasise the differences in the design processes with an apparent mistrust in the plausibility of covering different design domains in one study (Kroes, 2002). This study however aims to find similarities between the various domain specific design processes, without denying the existence and importance of these differences in order to find ways to inform basic design and TE. I focus on the similarities in the participants' processes of constant movement between their inner mental states and external elements that demanded participants' attention. I relate this to the participants' drive to achieve their goal intentions by using domain specific knowledge, as well as their expert knowledge of the physical and structural aspects of artifacts.

Kroes (2002) makes strong philosophical claims about the normative nature of the intentional behaviour of designers of technical objects. Although I support the general notion of the normative role that intentions play, I believe it is necessary to differentiate between different types of intentions in the context of design cognition, which can be found in cognition literature. In an attempt to extend Kroes' arguments, I found a potential way to explain the way in which people (expert designers) make explicit their various intentions to attain particular goals and the initiation of goal-directed responses through the use of Gollwitzer and Schaal's (1998) arguments. This is based on studies in the successful achievement of functionality goals for artifacts and systems that are dependent on the explicit articulation of implementation intentions and is automatized, which stems from a single act of will. I therefore seek to trace the cognitive links between explicated intentions based on experts' internal conceptual understanding of the physical and functional (Kroes & Meijers, 2002) nature of artifacts, and the automatic reactions of the participants on external information afforded by situational cues as observed in their sketches and in the environment (Chapter 6).

5.7.3   RELATION BETWEEN GOAL INTENTIONS, IMPLEMENTATION INTENTIONS AND KNOWLEDGE

From counts of instances where the use of conceptual knowledge, procedural knowledge, visualisation, normativity and efficiency were observed, I assumed access to and use of internal knowledge. From counts of embodiment principles that I observed, I deduced reaction on

situational cues, while counts of types of knowledge indicated the use of internal resources recalled from LTM. In this section, I discuss the occurrences of the intention-attention and its links with internal knowledge because of its logic relations with intentionality (Gollwitzer & Schaal, 1998; Kroes, 2002). I further relate these links to instances when the participants exercised their control strategies, personal stopping rules and evaluation function for the implied judgmental activities. I assumed these links based on logic of intentionality arguments and not empirical evidence. This means that I considered that intentionally selecting physical elements may lead to achieved planned functions of artifacts or activities (Dewitte et al., 2003).

The statistics (Appendix E-Statistics) indicate that there was no one general pattern across the three design domains in terms of sequence of concurrent intention-attention, knowledge use and control strategy, personal stopping rules and evaluation instances. Each participating team had explainable patterns in their individual protocols, that could be generalised on the basis of intentional goal attainment's dependence on the contexts of each protocol, some of which is discussed in Chapter 6 in detail. Context in this sense meant temporal identification as well as content classification within the modules and sub-modules of the protocols. In his study, Goel (1995) traced contexts by individuating design elements and explaining them in terms of control structures. Much research acknowledges the fact that we do not understand the higher order control structures linked to the use of domain specific knowledge (Goel, 1995; Kilgour, 2006; Kirsh, 2009) and driving forces of decisions taken (Suwa & Tversky, 1997). For these reasons, I extended Goel's (1995) explanations of context and individuated design elements in conjunction with the embodiment principle of intention-attention, and the psychological characteristics of control structures, personal stopping rules and evaluation functions.

5.7.4   INTERACTIVITY BETWEEN INTERNAL AND EXTERNAL PROCESSES

After I found the salient trends in interactivity of internal and external processes, I was guided by the following questions: *How often did the participants use knowledge? How often did they use external situational information? How often did they simultaneously use internal and external resources? What did the density and spread of the instances of such simultaneous use throughout an entire protocol tell me about the relationship between internal and external resources?* Towards answering these questions, I individuated the protocols into *a-priori* categories of 'knowledge' and 'embodiment'. The total number of possible combinations and relations were enumerable and therefor I highlight only the observations that yield notable patterns with regard to the role of intentions, knowledge and attention to external situational influences on the sequences of the participants' cognitive events.

I first individuated the embodiment principle instances, and isolated intention-attention. 'Intention' at this stage of the data analysis refers to what I call 'goal' intentions. This means that

I looked for instances when the participants explicitly or implicitly expressed an intended purpose of an artifact or activity. The differentiation between goal intentions and implementation intentions did not occur on the level of intentions, but rather on the level of knowledge. Within the category of conceptual knowledge, I identified instances when the participants referred to the physical properties and functional aspects of artifacts (see Chapter 3). This means that counts of conceptual knowledge provided an indication of the participants' goal intentions. In contrast, instances of their procedural knowledge indicated their consideration of how to achieve their goal intentions, which I interpreted as implementation intentions.

5.7.5 INTERNAL-EXTERNAL SYNERGY AS PSYCHOLOGICAL CHARACTERISTIC OF DESIGN COGNITION

I individuated modules within which the psychological characteristics (Goel & Pirolli, 1992) 'control structures', 'personal stopping rules', and 'evaluation functions' occurred simultaneously with observations of the use of types of knowledge. As such, relating intention-attention instances with types of knowledge could indicate which type of knowledge was most prominent in the selected psychological features observed. It is important to note that I did not differentiate between participants' references to the artifact that they were designing and references to other artifacts in the environment or stored in their memories when assigning values to their knowledge categories. I considered all statements in which the participants related to any artifact as equally indicative of socio-technological knowledge and therefore the direct or indirect influence on the decisions they took regarding the artifacts that they were designing. For the purpose of this discussion I processed the frequency counts and present graphs demonstrating which type of knowledge interacted with intention-action cycles proportionately (percentages) when the individual participating teams applied psychological strategies which included control structures, personal stopping rules and evaluation functions in their problem spaces in each of the cognitive phases.

5.7.5.1 Architecture participants

Table 5.8 summarises the number of knowledge types applied by Participants P-A in their problem structuring phase. Through the association of knowledge with their intention-attention instances while applying control strategies, personal stopping rules and evaluation functions, I gained insight into the dynamic interaction between their external and internal cognitive processes.

Table 5.8: **Knowledge types applied by Participants P-A in their problem structuring phase**

PSYCHOLOGICAL CHARACTERISTIC	EMBODIMENT PRINCIPLE	KNOWLEDGE TYPES				
	INTENTION-ATTENTION	Efficiency Series 1	Visualisation Series 2	Normativity Series 3	Procedural Series 4	Conceptual Series 5
Control strategy	% within Psychology	18.80%	0.00%	12.50%	12.50%	56.20%
	% within Knowledge	33.30%	0.00%	20.00%	50.00%	33.30%
Personal stopping rules	% within Psychology	16.70%	16.70%	33.30%	0.00%	33.30%
	% within Knowledge	11.10%	33.30%	20.00%	0.00%	7.40%
Evaluation functions	% within Psychology	12.50%	12.50%	37.50%	0.00%	37.50%
	% within Knowledge	11.10%	33.30%	30.00%	0.00%	11.10%

In Participants P-A's problem structuring phase, when they applied their knowledge in control strategies, they relied primarily on procedural knowledge, conceptual knowledge and efficiency knowledge. Their normative knowledge also featured proportionately high in their control strategies. What was interesting though was that at this stage of their process, Participants P-A did not generate any ideas through visualisation as control strategy but used their sketches to support their personal stopping rules and to illustrate the design principles they had applied when making professional normative judgements regarding the social and spatial effectiveness of objects in space in urban design. They achieved this through visualisation of these abstract ideas using external primary shapes and spatial relations of similar design scenarios. Figure 5.2 provides a visual summary of the data captured in the table above.

Figure 5.2: **Interaction between Participants P-A's knowledge types, external and internal processes in their problem structuring phase**

The process of solving their problem showed different patterns in the architects' simultaneous engagement in intention-attention, use of knowledge types and control strategies, personal stopping rules and evaluation functions, as is presented in Table 5.9.

Table 5.9:   Knowledge types applied by Participants P-A in their problem solving phase

PSYCHOLOGICAL CHARACTERISTIC	EMBODIMENT PRINCIPLES	KNOWLEDGE TYPES				
	INTENTION-ATTENTION	Efficiency Series 1	Visualisation Series 2	Normativity Series 3	Procedural Series 4	Conceptual Series 5
Control strategy	% within Psychology	15.40%	15.40%	15.40%	7.70%	46.20%
	% within Knowledge	40.00%	22.20%	13.30%	16.70%	33.30%
Personal stopping rules	% within Psychology	0.00%	0.00%	75.00%	0.00%	25.00%
	% within Knowledge	0.00%	0.00%	20.00%	0.00%	5.60%
Evaluation functions	% within Psychology	0.00%	0.00%	75.00%	0.00%	25.00%
	% within Knowledge	0.00%	0.00%	20.00%	0.00%	5.60%

When working on the solution to their design task, Participants P-A were involved in an increased number of efficiency instances when they applied their control strategies compared to their problem structuring phase. It seemed that these participants used their knowledge of efficiency during the problem solving phase primarily to guide their control strategies when they made their decisions. This implies that efficiency in their case did not play a significant role when they indicated their personal preferences and evaluated ideas normatively, but were rather elements that affected the atmosphere and general aesthetics of the theatre that they had to design. In Chapter 6, I elaborate on what their personal stopping rules were that affected their evaluation functions, other than efficiency judgments.

The use of external visualisation increased steeply in Participants P-A's problem solving phase. They primarily used visualisation as a means to represent their control strategies. They made a relatively large number of normative judgements when they applied control strategies; they thus expressed their personal stopping rules and made evaluation statements. Participants P-A furthermore used less of their procedural knowledge when they applied control strategies in order to solve their problem than when they were structuring their design task. I also did not observe overt instances of procedural knowledge used concurrently with instances of personal stopping rules and evaluation functions. In turn, when they developed their solution ideas, the architects constantly used their conceptual knowledge of architectural artifacts, their structural

and physical qualities, and their social and cultural functions in urban design situations in general, and specifically in university campus situations.

The co-occurrence of efficiency, visualisation, normative, procedural knowledge and conceptual knowledge when Participants P-A applied their control strategies, suggested that there was a complex layering of the knowledge types when they exercised control (refer to Chapter 6). The absence of efficiency references when they used their own personal stopping rules suggests that they used other norms in their evaluation functions than efficiency norms. The absence of visualisation as means to represent their personal stopping rules suggested to me that they used sketches to generate new ideas and not as a way of expressing their personal preferences. Figure 5.3 visually represents the salient trends in the architects' protocol of knowledge types co-occurring with intention-attention instances when applying control strategies, their personal stopping rules and evaluation functions when solving their design task.

Figure 5.3: **Interaction between Participants P-A's knowledge types, external and internal processes in their problem solving phase**

5.7.5.2 Mechanical engineering participants

The statistical data of Participants P-E's problem structuring phase is presented in Table 5.10, which indicates that they had a different strategy when they used various knowledge types during intention-attention instances compared to their problem solving phase.

Table 5.10: Knowledge types applied by Participants P-E in their problem structuring phase

PSYCHOLOGICAL CHARACTERISTIC	EMBODIMENT PRINCIPLES	KNOWLEDGE TYPES				
	INTENTION-ATTENTION	Efficiency Series 1	Visualisation Series 2	Normativity Series 3	Procedural Series 4	Conceptual Series 5
Control strategy	% within Psychology	20.00%	10.00%	5.00%	30.00%	35.00%
	% within Knowledge	14.80%	6.50%	6.70%	10.20%	8.30%
Personal stopping rules	% within Psychology	18.20%	13.60%	18.20%	13.60%	36.40%
	% within Knowledge	14.80%	9.70%	26.70%	5.10%	9.50%
Evaluation functions	% within Psychology	17.40%	13.00%	17.40%	17.40%	34.80%
	% within Knowledge	14.80%	9.70%	26.70%	6.80%	9.50%

During the problem structuring phase, the engineers' data indicated a correlation with that of the architects in their consistent use of efficiency knowledge when they applied control strategies, personal stopping rules and evaluation functions concurrently with intention-attention instances. Participants P-E furthermore used a relatively consistent, but low number of sketches to support the relevant psychological processes, as was the case with the architects. Their relative low counts of use of procedural and conceptual knowledge in the context of their surrounding cognitive activities suggested to me that they attempted to find information rather than apply their knowledge. However, Participants P-E made relatively high percentages (26.70%) of normative judgements, not when applying control strategies, but rather that was embedded in their personal stopping rules and evaluation judgements. This indicated to me that these participants, at this stage, did not use their knowledge to express intentions. From this I inferred that they had not fixated on any preconceived intentions at the time. This confirmed their openness to objective, critical consideration of information. Participants P-E also made use of moderately few sketches during their problem structuring phase and this had a seemingly low influence on their number of control strategies, personal stopping rules and evaluation functions, as represented in Figure 5.4.
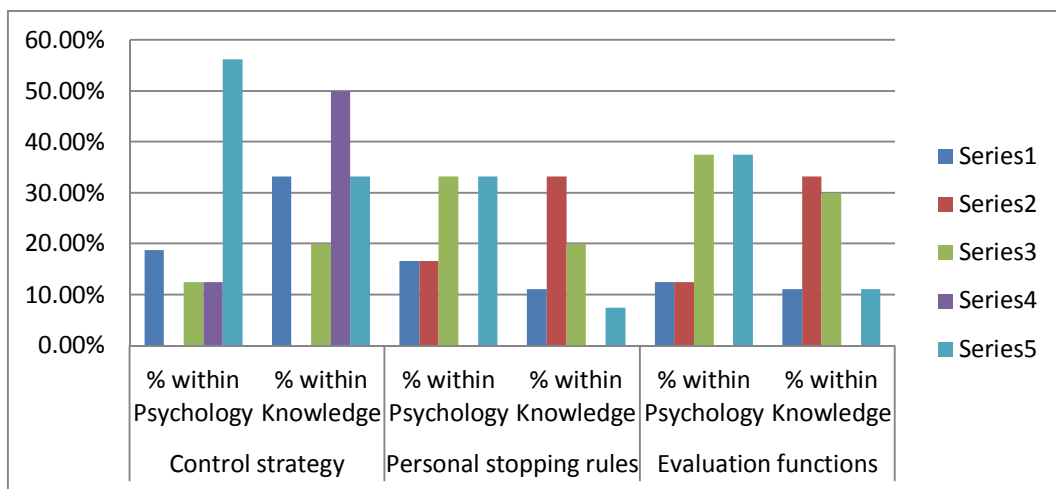
Figure 5.4: Interaction between Participants P-E's knowledge types, external and internal processes in their problem structuring phase

When I compared Participants P-E's problem solving activities with their problem structuring activities that I observed of control strategies, personal stopping rules and evaluation functions, the statistical data yielded the information presented in Table 5.11.

Table 5.11: Knowledge types applied by Participants P-E in their problem solving phase

PSYCHOLOGICAL CHARACTERISTIC	EMBODIMENT PRINCIPLES	KNOWLEDGE TYPES				
	INTENTION-ATTENTION	Efficiency Series 1	Visualisation Series 2	Normativity Series 3	Procedural Series 4	Conceptual Series 5
Control strategy	% within Psychology	25.70%	8.60%	11.40%	20.00%	34.30%
	% within Knowledge	13.00%	4.50%	10.80%	6.50%	8.30%
Personal stopping rules	% within Psychology	20.60%	16.20%	11.80%	20.60%	30.90%
	% within Knowledge	20.30%	16.70%	21.60%	13.00%	14.50%
Evaluation functions	% within Psychology	20.60%	16.20%	11.80%	20.60%	30.90%
	% within Knowledge	20.30%	16.70%	21.60%	13.00%	14.50%

I observed the consistent use of efficiency knowledge in Participants P-E's control strategy. There was an increase in their use of efficiency when they applied personal stopping rules and evaluation functions. From this I assumed that, on a personal level, they preferred to consider

efficiency issues when they applied personal stopping rules and evaluate artifacts, which could be attributed to the domain related habitual way in which they think about artifacts (Vincenti, 1990). There was also a consistent increase in their use of visualisation to express personal stopping rules and demonstrate the way they evaluated their choices when designing.

Participants P-E used normative knowledge slightly more when they controlled their choices during the process of developing their artifact design, but in the bigger picture the 10.8% is a relatively small proportion of their total cognitive activities. This implied that they were open to alternative ideas, and also confirms literature's widely acknowledged reports of the limited control strategies of expert designers (Cross, 2007a; Visser, 2004). Their relatively high coincidence of normative statements and efficiency knowledge in their personal stopping rules and evaluations function categories supported my conjecture that Participants P-E used efficiency as personal norm when they evaluated design quality. The fifty percent increase in Participants P-E's use of procedural knowledge, which coincides with their personal stopping rules and evaluation functions in the problem solving phase, in turn indicated to me that they were personally biased towards the implementation of particular procedures when they designed artifacts. The examination of the details of these procedures however, did not fall within the scope of this study. Figure 5.5 illustrates these patterns of intentionally involving the various types of knowledge when Participants P-E solved their design problem.
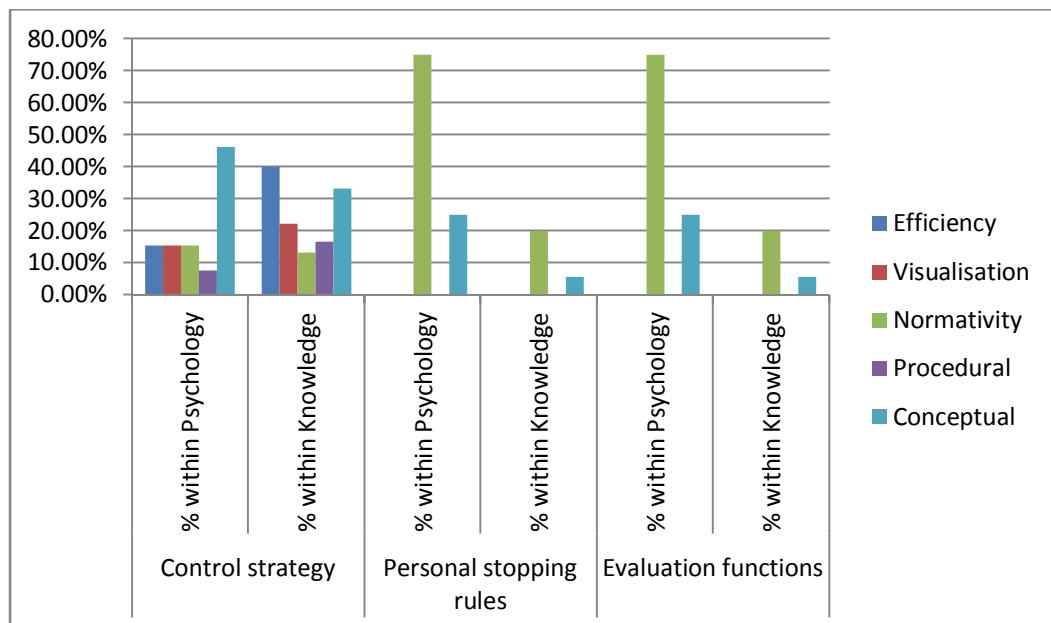

Figure 5.5: **Interaction between Participants P-E's knowledge types, external and internal processes in their problem solving phase**

5.7.5.3 Industrial designing participants

In Table 5.12, Participants P-I's statistical data indicates a strong, one sided use of knowledge. This trend primarily supports their evaluation functions which did not feature as support of

their control strategies and personal stopping rules when they structured their design task. It is evident that they did not make any normative judgments at this stage and did not commit themselves to any procedural knowledge. They did, however, make relatively extensive use of their visualisation knowledge, as seen in the numerous sketches that they made. Interestingly, their visualisations primarily coincided with their evaluation functions, which accounted for 40% of the intention-attention instances coinciding with Participants P-I's evaluation functions. Against the background of the industrial designers' systematic break down of their interpretation of the design problem during the problem structuring phase, I reason that the industrial designers used their visualisation knowledge at that stage primarily to externally support testing of their conceptual knowledge of the physical properties and potential uses of alternative artifacts. This assumption is supported by the lack of external visualisation activities that coincided with control strategies and personal stopping rules. In addition, the extensive written documentation of their evaluation of advantages and disadvantages of ideas discussed in Chapter 6, seemed to function as additional external support of Participants P-I's visualisations. The trends discussed here are reflected in Table 5.12.

Table 5.12:   Knowledge types applied by Participants P-I in their problem structuring phase

PSYCHOLOGICAL CHARACTERISTIC	EMBODIMENT PRINCIPLES	KNOWLEDGE TYPES				
	INTENTION-ATTENTION	Efficiency Series 1	Visualisation Series 2	Normativity Series 3	Procedural Series 4	Conceptual Series 5
Control strategy	% within Psychology	0.00%	0.00%	0.00%	100.00%	0.00%
	% within Knowledge	0.00%	0.00%	0.00%	5.90%	0.00%
Personal stopping rules	% within Psychology	0.00%	0.00%	0.00%	100.00%	0.00%
	% within Knowledge	0.00%	0.00%	0.00%	5.90%	0.00%
Evaluation functions	% within Psychology	14.30%	28.60%	0.00%	0.00%	57.10%
	% within Knowledge	33.30%	40.00%	0.00%	0.00%	25.00%

During their problem structuring phase, I observed no overt use of normative judgements, although Participants P-I formulated strong norm driven intentions (refer to Chapter 6). Their relatively high counts of using conceptual and efficiency knowledge when they evaluated ideas implies that Participants P-I were open to considering alternative concepts with regard to artifacts and efficiency when they evaluated ideas while interpreting their design task. The graph in Figure 5.6 represents the statistical data in Table 5.12.
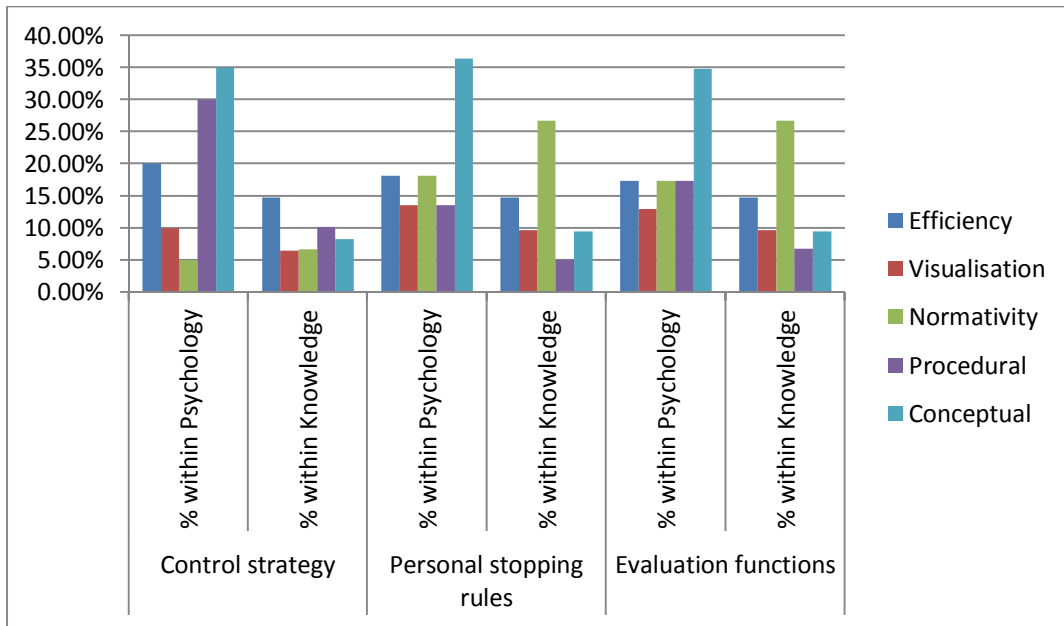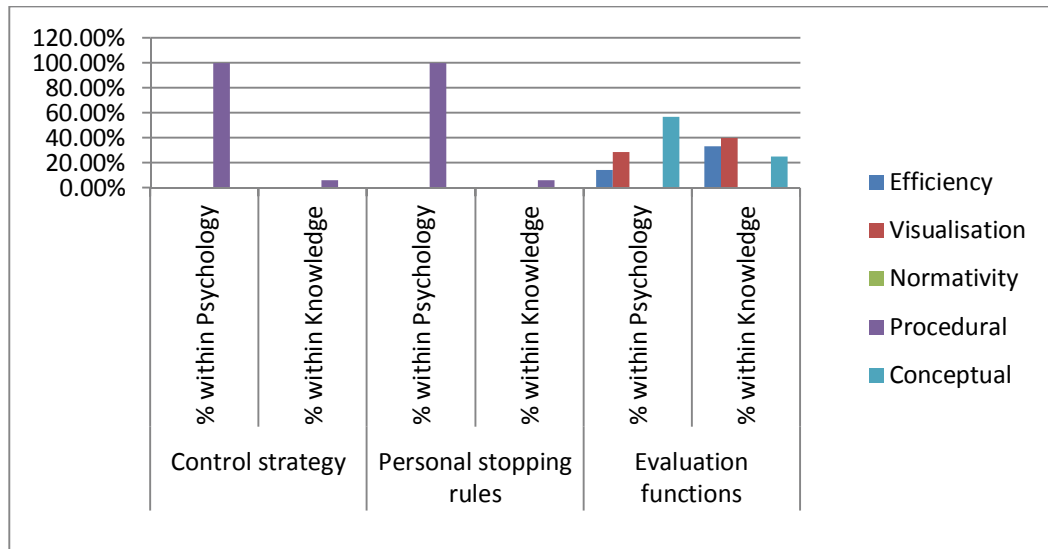
Figure 5.6: Interaction between Participants P-I's knowledge types, external and internal processes in their problem structuring phase

I observed intention-attention activities of Participants P-I in combination with their use of knowledge types as they engaged and applied control strategies, personal stopping rules and evaluation functions when they solved their design task, as presented in Table 5.13.

Table 5.13: Knowledge types applied by Participants P-I in their problem solving phase

PSYCHOLOGICAL CHARACTERISTICS	EMBODIMENT PRINCIPLE	KNOWLEDGE TYPES				
	INTENTION-ATTENTION	Efficiency Series 1	Visualisation Series 2	Normativity Series 3	Procedural Series 4	Conceptual Series 5
Control strategy	% within Psychology	28.60%	0.00%	28.60%	14.30%	28.60%
	% within Knowledge	8.00%	0.00%	6.20%	8.30%	4.00%
Personal stopping rules	% within Psychology	0.00%	0.00%	50.00%	0.00%	50.00%
	% within Knowledge	0.00%	0.00%	3.10%	0.00%	2.00%
Evaluation functions	% within Psychology	19.40%	8.30%	25.00%	8.30%	38.90%
	% within Knowledge	28.00%	25.00%	28.10%	25.00%	28.00%

When they were solving their design problem, Participants P-I's statistical data indicated that they applied efficiency knowledge to a limited extent in combination with control strategies, but primarily used this to support their evaluation functions, while it was absent when they applied their personal stopping rules. This implied that they, in general, entertained their own personal stopping rules relatively infrequently when using any of the various knowledge types. They engaged in the application of control strategies and in particular evaluation functions. The relatively high proportion of conceptual and procedural knowledge that Participants P-I used

when evaluating issues, lead me to conclude that they consciously and subconsciously used a cognitive strategy of applying objective evaluation functions instead of personal stopping rules when they developed a solution for their design task. Ascertaining whether the industrial designers applied objectivity consciously or subconsciously, did not fall within the scope of this study. The lack of visualisation together with low counts of use of normative, procedural and conceptual knowledge when Participants P-I engaged in control strategies indicates their limited use of control structures when developing their design problem in general. This pattern suggests their openness and flexibility, which was supported by the relatively large number of alternative ideas that they visualised and subsequently evaluated without fixating too early on one particular idea (Appendix D and H). Figure 5.7 presents the trends discussed here and tabled in Table 5.13 (see p.189).
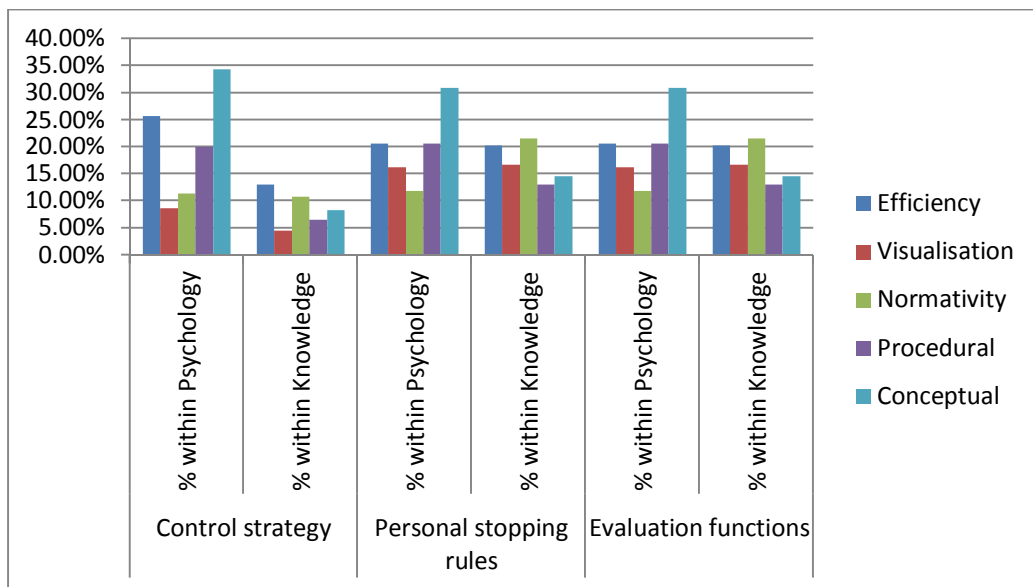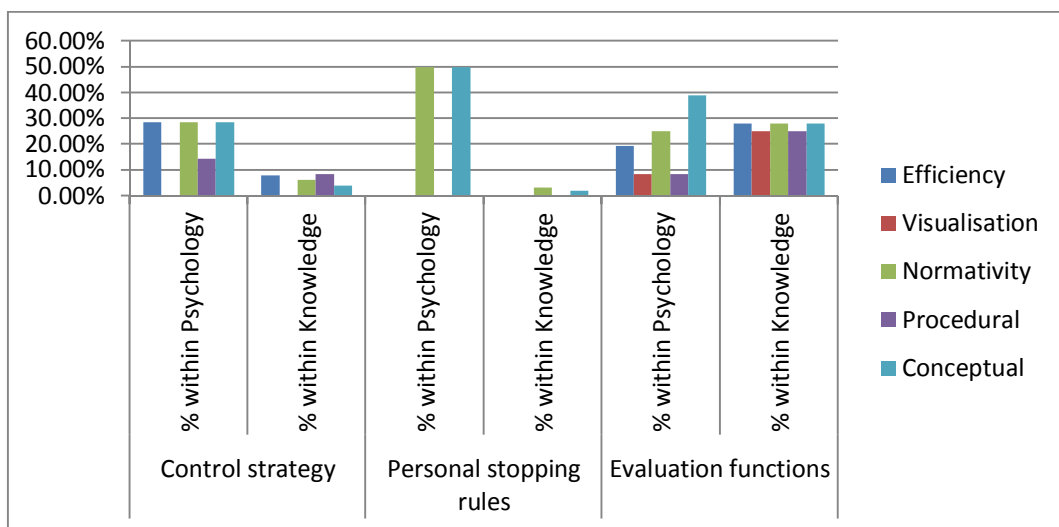

Figure 5.7: **Interaction between Participants P-I's knowledge types, external and internal processes in their problem solving phase**

From the statistics presented in the tables and graphs above, I deduce that, during the problem structuring phases, the participants' intention-attention behaviour could primarily be associated with their use of visualisation and normativity knowledge use. In the case of Participants P-A, it can be inferred that the participants in the majority of cases, when they intentionally paid attention to something, used procedural knowledge and sketches when they applied control strategies. This observation subsequently lead to the emergence of a research question that I consider in Chapter 6 with regard to the possible relationship between sketching ideas and knowledge of procedures of implementation plans in order to achieve aspectual and functional intentions.

Participants P-A also used their sketches when they applied their evaluation functions and at the same time to support them when they made normative statements. In the case of Participants P-E, I argue that the participants in the majority of cases, when they intentionally paid attentions

to something, used knowledge of efficiency when they applied their limited control strategies, while their personal preferences and evaluation functions were both driven by normativity. It is therefore possible to deduct that intentions imply normative thinking. It is the inference that the combination of intentions and normative thinking is an important mechanism to activate and direct interaction between internal and external processes. Participants P-I, in turn, used procedural knowledge (which correlated with that of Participants P-A's pattern) when they employed their own control strategies. When they applied their personal stopping rules through expression of their preferences about something, they dominantly used explicit procedural knowledge. When they applied their evaluation functions, their sketches served as expression of their judgment of what they considered as better ideas than others (which also correlates with Participants P-A's pattern).

When participants engaged in idea generation, the development of ideas and detailing them during the problem solving phases, a common pattern occurred in the dominant use of normative knowledge in evaluation functions amongst all participants. There was namely a common dominant pattern of normative knowledge between Participants P-A and Participants P-E when they applied their personal stopping rules. Participants P-E, however, made approximately the same percentage of efficiency statements when they stated their personal preferences. Interestingly enough, Participants P-I did not express any personal preferences when solving their problems and made normative and efficiency statements only. A possible explanation could be a domain specific culture that determined that they do not involve their personal preferences with their solution development, although, when they structure their design problems, it does play a role. It is therefore possible to conclude from these patterns that expressing their intentions generally occurred more often during the problem structuring phase than during the problem solving phase. In turn, from these percentages, supported by close and intensive studying of the video material, I could assume interaction between internal and external resources. The dynamics of these interactions are discussed in detail in Chapter 6.

5.8   CONCLUSIONS

In this chapter, I reported on some of the salient results obtained during the quantitative parts of my study. In addition I briefly reported on the content, nature and structure of the participants' problem solving space in order to provide a holistic view of the results. I discussed the results in terms of the underlying theory of my study, namely information processing, embodiment and socio-technological knowledge types involved in design methodology.

In the following chapter, I continue to present the results of my study. I discuss the results of the qualitative parts of my study and present them as findings. As a result of the emerging importance of intentions in decision making in design methodology, I explore the intentions as the driving force behind the psychological behaviour characteristic of the problem spaces of the participants within the context of their external design task environments. In doing so, I consider the types of thoughts and their dependence relations with intentions of the participants. I further examine the internal goal and implementation intentions and their possible relations with external elements, the process of making commitments and transforming their ideas.

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CHAPTER SIX

Findings of the study:
Overview of qualititative results

Findings

THEME 1
Hierarchical thinking of designers

Sub-theme 1.1: Aspectual Intentions
Sub-theme 1.2: Functional intentions
Sub-theme 1.3: Functional intentions
meet physical elements

underlying

THEME 2
Personalisation of intentions
Resulting in reversal of transformation direction

observed in

THEME 3
INCREMENTAL DEVELOPMENT OF ARTEFACTS
Are supported by the dual nature of representations
And result in

Sub-theme 3.1: Continued and short attention duration to content and sources of subsequent thoughts

Sub-theme 3.2: Synthesis of relations between thoughts

THEME 4
Control in multi-directional thinking

Sub-theme 4.1:
Control structures

Sub-theme 4.2:
Vertical couplings

Sub-theme 4.3:
Making and propagating commitments

THEME 5
Transformations, constructing and manipulating models

6.1   INTRODUCTION

In Chapter 5, I presented salient statistical results of my study, thereby providing an overview of the central role of the participants' internal and external cognitive processes during the early phases of their design processes. It seems evident that context played an important role in explaining the thinking strategies and cognitive actions of the participants. The contexts were based on assumptions about design task environments (5.2.2), problem spaces (5.2.3), the representational power of symbol systems validating the use of pictorial data (5.2.4), and the internal and external resources designers use when structuring and solving design problems (5.2.5).

In this chapter, I aim to extend Goel's (1995) characterisation of the problem solving space by explaining some examples of design behaviour in terms of a synergetic relationship between internal and external cognitive processing that involves the mental state of intention. I uphold the expanded view championed by Shani (2012) that the intentional state extends internal cranial processing and can be located outside the head. This includes sketches and physical objects in design task environments. My extension of conventional exclusivity theories of internal processing and of ecological embodiment approaches is based on the assumption that there is a 'division of labor' (Shani, 2012, p.3). I employed a dynamic systems approach in an attempt to link in-the-moment intentions of the participants to the things they thought about by tracing the primitive cognitive activities they executed (Dillon, 2010). In order to be able to make these connections, it was necessary to trace the origins or causes of the intentional state and the propositional content of the participants that moved from an unsatisfactory to a satisfactory state through a process of transformation.

6.2   THEME 1: HIERARCHICAL THINKING OF DESIGNERS

In this section, I contextualise the notion of 'hierarchical thinking' in the design process. This theme entails three sub-themes, namely aspectual intentions, functional intentions and functional intentions meet physical elements. In order to trace the hierarchies evident in the participants' thinking and how they influenced their intentional states, it was necessary to track the content of their propositions. It is a well-known practice of design cognition researchers to identify and study the propositional content of the intentional state by mapping and analysing the content of designers' thoughts (Suwa, Purcell & Gero, 1998). Similarly, various coding schemes have been devised to analyse the thoughts of designers (Dillon, 2010; Goel, 1995). Whereas these research strategies primarily focus on the thoughts represented in the design development phases of design processes, I considered the links between thoughts in the problem structuring and problem solving phases. For this purpose, I mapped the origin of thoughts and the internal connections between the aspects that the participants considered

their different intentions and physical aspects, by linking these to their hierarchical thought processes. From philosophical studies that draw on empirical evidence of design behaviour, it seems clear that researchers do not fully comprehend how physical structure and functional intention meet in the design and making process of technological artifacts. Kroes and Meijers (2002, p.3) state:

> *It is still a problem exactly how the intentional and the physical description of artifacts hang together. If functions are primarily seen as 'added to' the physical substrate, or as realized in physical objects, then the question remains how these functions are related to the mental states of human individuals, which, after all, form the core of the intentional conceptualization. If functions are primarily seen as patterns of mental states, on the other hand, and exist, so to speak, in the heads of the designers and users of artifacts only, then it becomes somewhat mysterious how a function relates to the physical substrate in a particular artifact. But relating them is exactly what happens in the design of artifacts.*

The aim of this section is to clarify some issues around the following limitations in current technology research literature as identified by Kroes and Meijers (2002), by building on Goel's (1995) theory of abstraction hierarchies:

- the relation between technical function and physical structure
- the intentional aspects of technical functions and their relation to the intentionality and actions of designers and users
- normative judgments that apply to the functioning of artifacts and the origin of this normativity
- ontological commitments that are involved in describing and using artifacts
- the design process of technical artifacts and the way the structural description of the artifact-as-physical-object and the functional description of the object-as-intentionally-formed-artifact are combined during this process.

In light of the focus of this study, namely to explore links between socio-technological knowledge and dynamics in the interactive processing of information, what I aim to add to the above list is:

- the relation between design aspect, social and technical function (called functional intentions)
- the relation between design aspect, socio-technological function, implementation intentions and physical structure.

The epistemological consequences of the design aspects, functional and implementation intentions and hierarchical thinking are dealt with in Chapter 7. What this study does not explore in depth is the relationship between personal stopping rules and the predominance of LTM in the hierarchy of thought, as I assumed it to form an integral part of each decision and action taken by the participants. I furthermore did not analyse the relationships in the leaky phases of the participants in particular. The complexity of their involvement in design work warrants a separate study.

Accounting for the way in which intentions and physicality meet necessitated a systematic examination of the way in which the participants' hierarchical thinking took place. I found that, Goel and Pirolli's (1992) strategy, which they devised to analyse hierarchical thoughts in the development phase of the design process, was equally useful to analyse in the problem structuring phase. I therefore applied these authors' idea that design thoughts can be analysed in terms of the level of abstraction as it allowed me to study the participants' thoughts in both these phases in order to establish the relations between aspects, intentions and physicality. I considered two suggested orthogonal hierarchies, which are illustrated in Figure 6.1. The first hierarchy involves the 'types of information' (Goel & Pirolli, 1992) and the second relates to 'the level of generality or detail' in reference to aspects of design.

In the context of this study, I did not consider the concept 'hierarchy' as one of superficial emerging chronological order, but rather as an order of internal negotiation of the perceived importance of concepts that determined the chronological order of the participants. Such negotiation of the order of importance implied thinking about artifacts, what they stand for and what they are able to achieve. I assumed that, during this internal negotiation process, the participants' personal and professional bias towards particular intentions and their domain specific knowledge played a central role in their thinking. The notion of 'level of generality or detail' connects well with Goel's notion of abstraction and pattern recognition as well as with the embodiment principle of 'specificity' (Anderson, 2003) (Chapter 3), and was therefore useful in this study in that it bridges the divide between the inner and outer dimensions of the design process. This implies that all aspects were abstract ideas of different modalities of socio-technological existence and thus entailed pattern recognition. However, it does not imply that all abstract thoughts in the protocols were aspects. I thus attempt to extend current design cognition theory by focusing on the relationship between mental states and cognitive processes, considering extended interaction.

I regarded three categories of information as evident of hierarchical thinking, namely: design aspects, intentions (functional and implementation) and physical elements. These types of information fitted well within this study's interactive framework, which advocates an integrated approach to explaining, not only the actions of the participants, but also the way they thought about the artifacts that they designed for a particular purpose. Each of these broad categories of information provided data regarding Goel and Pirolli's (1992) second orthogonal hierarchy, namely the level of generality or detail found in reference to aspects of the participants' designs which they considered. However, I do not discuss the role of implementation intentions and how they are formulated in this section as I decided to integrate this in section 6.6, where I explored the participants' processes of making and propagating commitments. The reason for this decision is that I assumed, on theoretical grounds (Brandstatter, Heimbeck, Malzacher & Frese,

2003; Gollwitzer & Schaal, 1998), that implementation intentions couple closely with the notion of commitment.

6.2.1   SUB-THEME 1.1: ASPECTUAL INTENTIONS

The first sub-theme of the hierarchical thinking involves participants' thinking about design aspects as intentions. Design aspects refer to qualitative abstractions of what the participants thought was most important to strive for in their solutions. As such, they qualify as content of intentional states. I used Dooyeweerd's modalities framework (De Vries, 2005) which consists of fifteen possible aspects to identify such abstractions. Dooyeweerd's model (Appendix M) enabled me to individuate social as well as technical aspects in the various domains. I used this framework to understand how the various aspects the participants considered gave meaning and direction to the way they selected and developed ideas, committed to some and rejected others. The underlying assumptions of Dooyeweerd's framework is that, in terms of aspectual theory, each aspect has its own set of laws and is irreducible, but may be transgressed (Basden, 2000). This implies that when the participants referred to a particular aspect, their knowledge of the laws were implied and not necessarily explicated. It further means that the participants could choose when to apply and pursue particular aspects, and when to contravene them without rejecting their validity. In the following sections I thus explain how the participants considered design aspects and created connections in their hierarchy of thoughts.

In my discussion, I examine the role of design aspects[26] articulated by the participants, and its relation to functional goal intentions and physical aspects of objects. I used the semantics of vocal utterances of the participants in the category 'abstraction hierarchies' (Appendix D-Psychology) to inform me about their content, whereas the syntactics (structural elements of external representations) informed me about the specificity and how much information they contained. I found supporting evidence in the participants' conceptual sketches (Appendix H) where I asked the following ontological questions: *What is a design aspect? Which aspects did the participants consider? How much information did it contain? Where did it originate? and What role in the hierarchy of the participants' thoughts did the aspects play*?

6.2.1.1   Participants P-A: Aspectual intentions

Participants P-A's consideration of distinct design aspects was characterised by generality and vagueness. An example of how they derived particular design aspects from vague expressions is demonstrated in Excerpt 6.1.

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[26]Dooyeweerd defined 'aspects' of objects as 'qualifying functions' or 'founding aspects', which meant 'what the object' is primarily meant for. Dooyeweerd listed fifteen aspects which he considers as part of daily life. Aspects play a deterministic or normative role, are irreducible, and all aspects contain echoes of each other (Basden, 2000).

Excerpt 6.1

ANDREW 00:32:24
I think what we should look at, if we have to do something … this transparent …. It should connect with this, and then at the concrete, in terms of its uses. And to … this …. If one looks at this little building, just this small façade that sits here, has somewhat of an Aldarossi feel to it.
JONATHAN 0:32:27
'A very rational feeling.

In the context of their protocol, I could deduct that 'Aldarossi' referred to the 'language' or 'message' of the choice material, size and shapes, which placed this expression in the 'lingual' aspect category. This means that Participants P-A recognised the visual 'language' of the building as typical of designs by the architect Aldarossi. In Excerpt 6.1 it is thus evident how the laws of the lingual aspect for the participants implied that there should be visual unity amongst the different physical elements of the existing buildings and the new elements that they were designing. The architects did not explain what they meant by 'Aldarossi', but it became clear later on during their protocol, from the context, that it implied the shape and material of the façade at issue. Their protocol indicated that they intentionally and incrementally worked on including shapes and materials that 'spoke' the same visual language as the case in order to create visual unity of the new theatre and the existing 'Aldarossi' building. In itself, such visual coherence implied aesthetics and lingual aspects in the same episode (Basden, 2000), which they applied normatively, and which assisted them to make decisions about including or excluding the existing sculpture on the site, as demonstrated in Excerpt 6.2.

Excerpt 6.2

JONATHAN 00:32:51
So, I think this thing is completely out. It does not connect with anything here, I mean, it is completely out of context, the shape of this thing, you know? And it doesn't seem to have any meaning.

The implication of Excerpt 6.2 is that more than one aspect intersected in one episode of utterance. This insight aligns with the philosophical view of Basden (2000) that an inter-aspect analogy can exist between various aspects. This also means that Participants P-A considered both spatial[27] and kinematic[28] aspects (Table 6.1, p.223) in one instance, even though they were implied and not specified. As such, the vagueness and non-specificity of their statement correlated with the problem structuring phase in which this thought about aesthetics was produced. Other than the reference to the shape of the sculpture that was out of place, they provided no detail descriptions of the physical nature of any of the objects at issue in this dialogue. Goel's (1995) study on the correlation of the syntactic and semantic quality of pictorial

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[27] Spatial aspect refers to continuous space (Basden, 2000).
[28] Kinematic aspect refers to movement (Basden, 2000).

representations with the structure of thought processes is therefore evident in the equivocal implications of Participants P-A's vague aspectual references. The fact that they did not specify the specific rules underlying their preferred aspects did not mean that they were confused by its unspecific nature, but rather emphasises their expert knowledge in the concepts it implied.

6.2.1.2   Participants P-E: Aspectual intentions

The aspect of economics is implied in Participants P-E's consideration of simplicity and functionality in Excerpt 6.3, which occurred during their problem structuring phase. The level of vagueness in this episode bordered on abstraction. As was the case with Participants P-A, Participants P-E did not elaborate or link this with any specifics of what they considered the function to be, or what they meant by simplicity. It is only through inference that I could interpret this episode (Excerpt 6.3) through the consideration of the aspect of economics[29].

Excerpt 6.3

EDWARD 00:20:50
... because to me it looks as if this thing is about simplicity, functionality.

Participants P-E assumed that they would provide additional artifacts in their design, and therefore included lighting and sound systems, although it was not required in their brief. As they were structuring their problem, they furthermore considered the aspect of physics[30] which implied a normative evaluation of technical efficiency dependent on sufficient electric power, as captured in Excerpt 6.4.

Excerpt 6.4

EDWARD 00:21:00
Sound maybe – but lights definitely not – you need a strong current ... One would probably put the light box somewhere here – and it will have to be a rather big cable.

The fact that they did not specify what they meant by 'rather big' implied that Participants P-E understood the necessity of having a strong current provided by a rather big cable and would decide on the details at a later stage in the process. This lack of specificity indicated to me that Participants P-E's consideration of the physical laws involved in selecting a suitable electric cable resided in their domain specific conceptual knowledge stored in their LTM.

In turn, aspects that materialised from the environment during a leaky phase are apparent in Participants P-E's protocol, as evident in Excerpt 6.5. Their perception of the site and the functional possibilities its physical character offered triggered the engineers' thoughts about an

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[29] Economic aspect refers to frugal management of resources (Basden, 2000).
[30] The aspect physics refers to the involvement of energy, mass and forces (Basden, 2000).

economic way to get props and other objects onto the theatre platform that they were designing. They connected their domain specific knowledge of the accessibility of standard battery driven fork lifts as a way of achieving economical design.

Excerpt 6.5

EUGENE 01:13:20
Okay – now, I thought if you had a trolley here – say, a battery driven trolley – such as a fork lift -.
EDWARD
Yes! … It is simple thing – you can buy those things standard. It isn't a fancy thing.

Their perception of the site triggered Participants P-E's ability to connect their concern for the economic conservatism aspect with a physical object and this implied that they were able to recognise abstract patterns of simplicity that were embodied in objects. Being able to make this connection in turn suggested that Participants P-E linked their knowledge of objects opportunistically with a new situation, emphasising the necessary role of interaction between internal and external cognitive processes and sources of thoughts. This awareness corresponds with the findings in Reffat and Gero's (1999) study on architects which demonstrates the connection between prior knowledge and its application in new situations, and therefore extends theories about architectural thinking to engineering thinking. Shani (2012, p.6) explains this close coupling of internal and external variables as cyclical causal patterns, with a feedback loop in which internal and external variables are 'synergically coordinated'. This notion of cyclical process configuration as a whole in turn connects with the Gestalt theory of coherence as explained by Kieran (2011). The implication of such connection is therefore that a sense of coherence can only be instantiated through relevant internal and external cognitive engagements. I found a similar trend in the thought processes of the industrial design participants which involved their consideration of design aspects.

6.2.1.3   Participants P-I: Aspectual intentions

The primary design aspect that Participants P-I considered was also that of 'economics', which they voiced during their problem structuring phase. In the context of their protocol (Appendix D and F), I interpreted their use of the term 'simplicity' as an economic consideration. In their articulation, economic considerations apparently governed their suggestion to identify an existing control device which is flexible, as evident from Excerpt 6.6, and occurred during a leaky phase.

Excerpt 6.6

ADRIAN 00:33:32

Ja. So, and to an extent I was so ... have written keeping it simple and cheap to do, so and almost ... So, what 'Brian' was saying, is questioning whether it needs to be a fancy device or whether there's and easy device to do it or a system that is flexible, you know where.

The lack of information given about what they thought 'simplicity' meant suggested to me that Participants P-I understood this to be a manifestation of the underlying laws of the aspect of economics. They confirmed their preference of simplicity repeatedly throughout their protocol, as demonstrated in Excerpt 6.7.

Excerpt 6.7

ADRIAN 01:55:08

If it is in bags, or in whatever. But then you know ... I still like the weighing idea because of its simplicity.

During their problem solving phase, Participants P-I connected the aspect of economics with the concept of weighing the Lego™ instead of counting them as an economic way of managing control. What was clear from the protocols of all three sets of participants was that their direct and indirect references to particular design aspects demonstrated the abstract and non-specific nature of the aspects. The nature of the aspectual statements was furthermore characterised by its general lack of connection with physical objects, but a connection with functional intention statements. This may be attributed to the context of the utterances in the sequence of the participants' protocols. The introduction of design aspects into their thinking processes primarily ensued when the participants framed their problems in the problem structuring phase in cases where little thought had been given to detail about the artifacts. This demonstrates a hierarchy of importance in their thinking, as Participants P-I seemingly justified their personal preference of the 'weighing' bags on the grounds of 'simplicity' (and therefore 'economics').

A general lack of explanation about what particular aspects entailed also seemed apparent. This lack of specificity and qualification of the aspects in the utterances of the participants indicated to me that the laws governing particular aspects were implicit and not explicit to them. These insights correlate with philosophical studies' characterisation of 'aspects' (Basden, 2000), which claims that specificity of content is implied and does not need explication.

6.2.2   SUB-THEME 1.2: FUNCTIONAL GOAL INTENTIONS

The second sub-theme of the participants' hierarchical thinking relates to how they identified functional intentions and thought about them. In this section, I demonstrate how and where design aspects met end functional goal intentions in the participants' protocols. Functional

intentions refer to behaviour of artifacts, the way they work or which function they serve. By implication, functionality, because of its close connection with concrete objects, facilitates the concretisation of the abstract nature of aspects. In order to understand the interactions contributing to the development of the participants' abstract thinking into concrete thinking, I traced the utterances of the participants where aspects and functional intention statements occurred in the same instance. I assumed that aspectual thinking and pattern recognition are closely associated, together with its facilitation of normative judgements discussed earlier. I thus present evidence of how the participants' thoughts connected aspects and functionality, when in the design process it occurred, what the internal-external origin or cause of the connection was, and how specific or general the information contained in the connections was.

In general I found that, in the internal processes functional thoughts materialised from participants' interaction with combinations of various internal and external sources, including their design briefs, expert domain specific knowledge, general design experience, personal stopping rules, professional bias and preferences (Appendix D-Psychology). I also found connections between functional intentions and aspects that the participants indicated as important. As such, the majority of functional goals originating internally could be found in the problem structuring phases of the participants. The second possible source of information regarding intentions relates to functional goals that did not originate from any of the internal sources mentioned earlier, but rather emerged from the situation, including the participants' briefs, their sketches and in particular from the physicality of the environment.

I learned that all participants formulated their functional goals throughout the entire protocol. However, their sequences did not display one particular pattern that encompassed all the protocols. This non-generalisation of when functional thoughts were generated was also found by Goel (1995), who ascribes this trend to the characteristic incremental solving of design problems which means that designers discover sub-problems as they go along, with the emergence of new functional intentions throughout the process.

I furthermore found data informing me about the specificity levels of participants' functional goal intentions in the sub-categories of embodiment episodes that were related to 'intention-attention' and 'specificity' (Appendix D-Ecology). The level of specificity for these functional intentions varied throughout the participants' protocols and was dependent on the context of its surrounding thoughts. In general, the distribution statistics (Appendix E) indicated that, in the case of all the participants, goal intentions were uttered when they structured their problems, and during leaky phases. In the following sections, I present evidence of instances in the participants' protocols where abstract design aspects met with functional intentions.

6.2.2.1   Participants P-A: Functional intentions

In Excerpt 6.8, one of the architects, after reading their brief, and asking some questions of the client (researcher), immersed himself in a scenario recalled from his LTM. The brief seemingly triggered a memory of a theatre he encountered previously. In his dialogue, he suggested a social aspect of theatres that had a history of putting performers on a stage, which was separated from the audience, which was disregarded in the case he recalled. The protocols indicated that, by using internal as well as external resources integratively the participants could refine their intentions and connect these to the design aspects. All the protocols demonstrated that recognition of patterns relied on internal as well as external resources and processes. The statistics in Chapter 5 indicated that memory retrieval was a predominant internal process in all the protocols. This observation correlates with Kirsh's (2009) study which emphasises the central role of memory recall in recognition behaviour. However, it did not fall in the scope of this study to do an in-depth exploration of the way in which the participants' recall of memory related to pattern recognition and to the particular design aspects designers perceive as the most relevant to their design tasks. This warrants a study on its own.

Participants P-A connected their abstract thought about the social character of theatres with the functional intention of interactivity.

Excerpt 6.8

JONATHAN 00:16:05

I was in a theatre in São Paulo, hey, that, it is actually a refurbishment of an old workshop.
What they did there … they tried to break away from the conventional way of how theatres work. The whole theatre can seat about 1 500 people, but there is no stage….
it is an interactive theatre … there is such a small stage on the side, but that is just for when people are coming to the front, and the whole play then 'announces' itself. And then this whole play takes place between the seating.

While busy with the dialogue in Excerpt 6.8, the participant (Jonathan) made rough sketches visualising and explaining what the theatre in São Paulo looked like and how it worked (Photograph 6.14, sketch 1, p. 266). He also provided information about the functionality of the theatre that he recalled. I recognised this case as an example of an unconventional theatre which confirmed the participant's pattern recognition ability, implying that he was knowledgeable about what is conventional and what is not. Jonathan's sequential actions indicated a constant move between his inner world (recalling the case) and abstracting its social aspects, and his outer world constituting the sketches he made which externalised his internal abstract thoughts. In another incident that emerged from an integration of information from their environment, which they perceived while walking on the site, and their domain specific knowledge and experience, Excerpt 6.9 captures how Participants P-A's connected the aesthetic aspect with

formative and technical functionality. For Jonathan, the aesthetic aspect of the theatre he had in mind was intertwined with the lingual aspect of what exposure of structural and service functions of the theatre conveyed about the concept 'honest design'. This implies an intricate network of connections that originated in the mind of this participant. By constantly recalling the abstractions in case (Excerpt 6.8) as standard for honest and unconventional design, he was apparently dwelling in his inner world.

Excerpt 6.9 suggests that Participants P-A, in spite of their apparent uncertainty, already internally visualised what the abstraction 'honesty' looked like, even though the information that they provided was vague and non-specific. They could link it with physical structure and with the provision of services to the theatre. Furthermore, they admitted that their interpretation of the abstraction is subjective, which implied a close coupling with context.

Excerpt 6.9

JONATHAN 00:55:05
Yes, it depends on how you look at it. Honesty of the structure and the honesty of the services is actually part of the aesthetic.

Participants P-A's strategy was to link multiple aspects and physical elements with each other. They obtained information of the patterns of movement of the people using the campus and their interaction with the spatial arrangement of objects (which could be linked to the kinematic aspect referring to people's extensive movement). They connected these patterns with a drive to understand 'how this campus works'. The theoretical implication of their behaviour is that perceivable information could become useful in the design context only when integrated with internal processes and resources by connecting existing internal domain specific knowledge and personal preferences. This means that Participants P-A's internal-external integration consisted of aspectual intentions, functional intentions and physical elements, which extends Kroes and Meijers' theory of the dual nature of artifacts (Kroes, 2002).

6.2.2.2   Participants P-E: Functional intentions

Participants P-E's first apparent articulation of a functional intention stemmed from their reading of their design brief (Appendix C). Originating from the instructions in their brief and their internal domain specific knowledge, Excerpt 6.10 demonstrates how they attempted to understand the functional intentions of the rotating platform they were required to design. Participants P-E connected the function of rotation to their domain specific knowledge of the abstract aspect of physics.

Excerpt 6.10

EUGENE 00:03:36

Okay. Now, my question to begin with was - is this platform, that is supposed to move – except that it is very large and should move around – does it have an x and y axis or should it be anywhere?

Participants P-E demonstrated the way they connected the functional intentions with the required rotating platform by determining the direction and scope of the movement and at the same time judging the required size of the required rotating platform as a result of reading their brief. In this instance, Participants P-E moved between their inner world of domain specific knowledge and the external world of their brief's functional requirements.

In another instance, Participants P-E connected a design aspect with functionality, which emerged from perception. They perceived the existing sculpture on site, and in spite of their design brief that required them to ignore it for the purpose of their platform design, they nevertheless indulged in speculating its usefulness for their design. Excerpt 6.11 demonstrates how they connected the sculpture's lingual aspect and its importance as cultural symbol, with a probable technical function.

Excerpt 6.11

EDWARD 01:06:37

If this is not a holy cow – if it really is a functional thing, then one can certainly use it.

EUGENE 01:07:03

Look, in the end this platform will be more or less in a fixed place. And if you then have to move this thing in case it should fit in precisely, without messing with the aesthetics – or whatever – then it is will also be okay...?

The metaphor 'holy cow' that Participants P-E used in Excerpt 6.11 indicates their concern about the cultural aspect of the sculpture. Lacking knowledge regarding which functional intention it could serve in the theatre design, they did not connect aesthetics with technical functionality. However, by considering aesthetics in the same instance, Participants P-E's knowledge of the aspect, and its possible contravention by keeping the sculpture on the terrain, indicated their tolerance for uncertainty and ability to adapt to a new situation. Their consideration of the sculpture's possible functionality led to a stream of ideas in Participants P-E's subsequent dialogue. There was a distinct increase in their specificity regarding objects, including the sculpture and its intentions and possibilities of using it in various ways. They suggested how to include the sculpture in their platform design and speculated about its direction of fit. Their uncertainty, however, was reflected in the leaky modules they engaged in. Participants P-E attempted to block the leaks by generating a series of ideas related to lighting, sound and storage. Goel (1995) also found that designers block their leaky thoughts, which they are not able to resolve, by attending to intervening thoughts, as captured in Excerpt 6.12.

Excerpt 6.12

EDWARD 01:10:31

And if you install poles to provide additional light, it is close enough to light up the stage with spot lights with even noticing the lighting.

Nevertheless, Participants P-E's sequence of utterances that follow Excerpt 6.11 suggests that they hypothetically considered the sculpture as not being a 'holy cow'. This indicated that clearing up the aspectual meaning took precedence before functionality in the sequence of the engineers' thoughts. It furthermore demonstrated how eliminating the cultural aspect (even hypothetically) enabled them to generate alternative ideas for using the sculpture. This empowering role of aspects in design reasoning, to trigger off many ideas, correlates with philosophical studies in aspectual theories as explained by Basden (2000).

6.2.2.3   Participants P-I: Functional intentions

Participants P-I's first connection of aspects and functional intention of the artifact/system occurred during their problem structuring phase. Their strategy to figure out the functional intentions of the device or system they were required to design was to get a clear understanding of the context in which it would be used as apparent from Excerpt 6.13. Participants P-I initially intentionally paid attention to the client (researcher) for access to information about the intended functionality of the required artifact. They emerged from their internal understanding of the context of their design task, after which they connected the abstract formative aspect with the functional intention of discovering Lego™ components, captured in Excerpt 6.13.

Excerpt 6.13

ADRIAN 00:19:49

I sort of initially got two different ideas. The one idea was sort of like a, almost like a box where it is like a puzzle… to…You know you got like kids … where you've got different slots where you push stuff in or…
But, I think, I think my concern with that idea is that there's a challenge in terms of discovery So, if you got any sort of box with a lot of stuff in you are only discovering what you could see. So, you know, if you got something that gets stacked together or built together as a carry box has, then you only going to see the stuff on the outside …

Excerpt 6.13 demonstrates the normative role of aspects in design thinking. Adrian expressed concern regarding the idea of a box with slots and, not being able to provide visual access, he then passed a normative judgement based on his conceptual knowledge of how visual discovery may lead to constructing knowledge in the educational context of the design task. Whereas normativity is often associated with functional intentions, as discussed by Kroes (2002), Excerpt 6.13 is indicative of the normative role of aspects as well. Excerpt 6.13 furthermore indicates an increase in the amount of information and specificity generated when aspects and functions are connected, as opposed to referring to aspects on its own.

As Participants P-I progressed in their problem structuring phase, they integratively used the information afforded to them by the physical nature of the Lego™ in their environment. In an attempt to figure out the functional intentions of their required artifact, they simultaneously perceptually explored real Lego™ blocks. They compounded their activities by asking questions about the context, which contained evidence of their consideration of formative[31] aspects of the use of Lego™ as highlighted in Excerpt 6.14.

Excerpt 6.14

> BRIAN 01:20:05
> Here I'm looking at a… specifically trying to find a high tech solution. Uhm… the first direction was sort of low tech. In other words, something without sophisticated devices or some basic electronics, materials (?). Or …specifically going to try and look, not that there isn't a solution...uhm so it kind of goes immediately ... computers ... So, possibly Lego™ has got part recognition, uhm … technology could be quite small and compact, uhm … and in this case it would need the mobile; and particularly small.

Excerpt 6.14 demonstrates that the consideration of design aspects is an internal process that Participants P-I used to elaborate on the functional as well as physical elements of objects. It furthermore indicates that consideration of the implicit laws of the aspect of economics opened up many possibilities for them to consider, and did not serve as a restricting factor in their reasoning process. Weighing up the idea of sophistication against that of a low-tech device triggered the thought that there might be an existing sophisticated part-recognition device available, but which would then have to be adapted into a more compact and mobile device in order to be functional in the context of their problem.

Clark (2006) states that any mental activity that drives the process along should be taken seriously and not be abandoned. For this reason, I considered the way in which aspectual intentions served as a trigger for normative measures, justifying the suitability of Participants P-I's ideas. They apparently developed their ideas about the device and based it on their knowledge of the implied principles of the formative aspect, without specifying the rules.

In all the participants' protocols there was a consistent pattern involving the cognitive function of aspectual intentions. The particular aspects that the participants selected constantly served as a normative guide, which supported their ideas and guided their transformation of ideas. The internal alignment of particular aspects with relevant functional intentions implied a self-regulating mechanism which drives the participants' coherent evaluation of their judgements in an attempt to achieving Gestalt coherence (Kieran, 2011). This ability of aspects to drive evaluation functions seems to confirm the priority of aspectual intentions above functional intentions in the hierarchy of design thinking.

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[31] The formative aspect refer to achievement, construction, history and technology (Basden, 2000).

In this section, it seemed evident that identifying and articulating aspects is a process that started early during all the participants' problem structuring phases. However, there were instances when they initiated and continued considering the same aspect through entire protocols.

6.2.3   SUB-THEME 1.3: FUNCTIONAL INTENTIONS MEET PHYSICAL ELEMENTS

The third sub-theme of the hierarchical thinking of designers relates to the way in which participants connected functional intentions with physical elements. In this section, I explain the way in which the participants' functional intentions of their envisaged artifacts met physical elements, and by implication met with aspects. I do not focus on how the participants dealt with physical elements in isolation, but regard physical elements, in the context of the design process, to be intertwined with processes of selection, combination and adaptation. This implies a process whereby the participants not only established a fit with functional intentions, but also aligned selected physical elements with design aspects (section 6.2.1) throughout the entire protocol. In this section I asked the questions, *when did the participants connect functional intentions with physical elements? where did the connection originate?,* and *how much information did a particular representation contain?*

In order to establish the generality-detail levels in the function-physical relations, I individuated instances of specificity in the syntactics of the participants' verbal data throughout their entire protocols. I searched for tangible evidence in the category 'conceptual knowledge, objects-physical nature' (Appendix D-Knowledge). I observed that the majority of instances of specificity that occurred during their problem solving phase corresponded with references to physical elements of objects. This in turn could be linked to the incremental development of the participants' artifacts once the participants explicated their preferred design aspects and articulated their functional goal intentions, of which some were in line with the design aspects, while others transgressed them.

I noted a general trend in all the protocols regarding the levels of specificity and amount of information, which increased visibly in the participants' verbal as well as visual representation. Their initial vague abstractions turned into detailed expressions of thought. Arnheim (1993, p.16) ascribes designers' ability to develop abstractions into concrete representations to a close coupling of abstraction and perception:

> But because all abstract thinking relies on some perceptual referent, even the most abstract theme is tied from the beginning to concrete images. These images supply the designer with the primary nucleus from which the actual structure develops.

In turn, Goel (1995) found a correlation between the increase in clarity in sketches of designers which he ascribes to the ability of sketches as symbol systems to reflect the cognitive phase in

which designers are at particular instances during their design processes. Based on the results of this study, the same could be said about all the participants' verbal utterances, which correlated with the corresponding sketches they made (Appendix H). This pattern can be ascribed to their increase in addition of detail that consists of physical elements the participants envisaged to use in their designs in order to accomplish their functional goal intentions. They demonstrated how they envisaged the achievement of their functional goals as they added detailed references in their verbalisation and visualisations. An increase in references to physical properties of objects was evident in the increase in counts of object-physical nature in the category 'conceptual knowledge' in all participants' data sets (Appendix E-Statistics). The increase was incremental towards the problem solving phases.

6.2.3.1 Participants P-A: Functional intentions meet physical elements

In this section, I explain the way in which end functional intentions met physical elements in the protocol of Participants P-A. During their problem solving phase, Participants P-A engaged in multiple instances when they referred to the material characteristics of objects in their own current design and in other cases (Appendix D and E). During this phase, I found a rapid increase of detail and specificity once they made the decision to remove the unfitting sculpture. As they articulated the unsuitability of the sculpture in the theatre site, their minds were seemingly free to generate multiple ideas related to physical objects and their properties in a relatively short space of time. The ideas that Participants P-A attended to are summarised in Table 6.1 (see p.223).

Their preliminary ideas that were suggested during a leaky phase, intertwined with instances of problem structuring, and indicated that Participants P-A initially referred to physical elements in broad terms, including shape and size (Appendix D). However, they incrementally started linking physical properties of objects with functional intentions. These preliminary ideas primarily emerged from internal sources, as demonstrated in Excerpt 6.16 (also summarised in Table 6.1).

Excerpt 6.16

JONATHAN 00:21:59
You will now – for approximately a thousand people – design a thing that works like a fashion show ramp...
So, it will be more of an elongated thing, which can shift the activity on the ramp from these people, to those ...

While uttering the words in Excerpt 6.16, Participants P-A produced a rough sketch (Appendix G) externally visualising their knowledge of the physical attributes that such a fashion ramp should have. The sketch contained information involving the shape and proportions it should

have in order to meet the functional intention (being able to shift the activities on the stage from one side of the audience to the other).

Together, both their verbal and visual representations indicated that Participants P-A had a clear understanding of the external pattern of the ramp and were able to connect it to their design task. Without the specificity of their sketch, it would not be possible for me to understand what the architects meant by 'shifting the activity'. Making sketches based on internal ideas in one's mind, where conceptual links are made between existing knowledge and applications in new situations implies internal processing. Shani (2012) philosophically attributes this ability of sketches to 'carry' the content of internal thoughts as the extension of intentions.

Empirical affirmation in the literature (Goldschmidt, 1991; Oxman, 2002; Suwa & Tversky, 2003) regarding the interaction between the participants' internal thoughts, the making of sketches and reacting on what the sketches represented, therefore contradicts the reductionist notion of embodied specification (Richardson et al., 2008) which claims that 'information' is reserved for perceiving and recalling patterns that uniquely specify properties of the world. Therefore, interaction between internalisation and externalisation when making sketches necessitates a theory of interaction and cannot merely rely on embodiment theories that explain problem solving behaviour only from a general theory of specificity perspective and ignore the necessity of a general theory of representation (Richardson et al., 2008). For this reason I reject the exclusive use of either the ecological theory or the internal process theories. I uphold an integrated approach to account for design behaviour in which instantiation is differentiated from transformation.[32]

Excerpt 6.17 is the result of Participants P-A's process of integrating perceptions of their task environment with their own internalised ideas, which originated from internal sources such as personal preference. Their positive attitude towards concrete as the choice of material and the strong protruding shapes is evident of these participants' personal taste and preference and was notable throughout their entire protocol. Although their functional intention is not clear in Excerpt 6.17, it demonstrates how Participants P-A's choice of physical elements was aligned with their positive mental attitude and preferred lingual and aesthetic aspects.

Excerpt 6.17

JONATHAN 00:29:39

I like this architecture, I like that era. I like the raw concrete, and for example, that gutter protruding like this, you know?

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[32]'Instantiation' refers to any causal structures or representations that carry content of, *inter alia,* mental states, while 'transformation' refers to any enduring material aspect of a cognitive process (Clark, 2006) which plays a particular role in facilitating the occurrence of a given instantiative representation.

Excerpt 6.20

JONATHAN 00:32:51

So, I think this thing is completely out. It does not connect with anything here. I mean it is completely out of context. The shape of this thing, you know, and it doesn't seem to have any meaning.

Participants P-A pursued moving the sculpture to a more suitable place, which implied their ability to identify a new functional intention for the sculpture. This seemingly enabled them to find a more suitable location. This in turn indicates that problems can be solved by consciously identifying physical objects' functional intentions, as demonstrated in Excerpt 6.21.

Excerpt 6.21

JONATHAN 01:19:40

So, this thing, it actually 'announces' this square when enter here, which says that this is now an important space. Now it also becomes a more 'urban space'.

Participants P-A identified the lingual aspect governing the interpretation of what the functional intention of the sculpture in its new location should be, namely 'announcing' the theatre space and thereby declaring it as important. In addition, this episode demonstrated that functional intentions do not necessarily occur during the problem structuring phase, but may occur during any time of the design process. This inference is supported by findings of other design cognition studies that emphasise the non-linearity of the early phases of the design process, including Cross and Dorst (1998), Mumford, Reiter-Palmon and Redmond (1994), and Liikanen (2009).

6.2.3.2 Participants P-E: Functional intentions meet physical elements

Most of the patterns that I observed and reported on in the case of Participants P-A, could also be found in the case of Participants P-E. The various cases in this study differed in terms of context and content, and not in terms of cognitive processes, which enabled the participants to make connections between functional intentions and physical elements. Therefore, in this section, as also in the case of my discussion of Participants P-I in the next section, I highlight instances where salient implications for design cognition theory may be drawn.

During Participants P-E's problem structuring phase, they primarily relied on personal experiences, rather than their professional knowledge, to support their understanding of the need of the client (researcher) for a particular type of theatre. Using this kind of knowledge when designing corresponds with what Goel and Pirolli (1989) call 'generic' design knowledge found in all design work, irrespective of domain. The participants used what Goel (1995) calls 'case immersion' to support their integration of internal processing of recalled experiences of how the physical nature of existing theatres afforded information of its functional intentions.

Their perception of the use of concrete in the existing buildings on the site assisted Participants P-A to recall domain specific architectural knowledge about styles and material. However, the embodiment theory of specificity of information, which claims that such information is only reserved for perceiving and recalling patterns, seems reductionist. Evidence of how Participants P-A specified information regarding the material and style, namely 'concrete' in the existing building, assisted them to visualise its use in their current design of terraces for the theatre, which contradicts a reductionist view. Perception therefore led to visualisation, which apparently contributed to them generating their own new patterns for the terraces that they planned during their problem solving phase, as captured in Excerpt 6.18.

Excerpt 6.18

JONATHAN 01:06:40

Then you can … say … a concrete edge, next to the grass…
ANDREW 01:07:12

And then there is this beautiful white edge, as you enter, then you see this (concrete edge). But it is rather flat, so you will actually see many white lines.

Although Participants P-A's functional intention with their choice of material and pattern of the terraces were not yet clear in Excerpt 6.17, it gradually became known during their embodiment explanation for intention-attention (Richardson et al., 2008). Seemingly, the participants focused attention on concrete as material used in the environment, connected with their intention to achieve the design aspect of visual unity (lingual aspect and aesthetic aspect). When they perceived the existing buildings, Participants P-A considered both the lingual aspect (Aldarossi feel) and aesthetic aspect (visual unity). In turn, these aspects met with the physical element of concrete that they selected to shape the terraces of the theatre with. This idea emerged from their perceptions and developed and transformed through their sketches during the problem solving phase, as demonstrated in Excerpt 6.19 below and Photograph 6.8 (p.263).

Excerpt 6.19

ANDREW 00:32:24

I think what we should consider, if we have to do something, the transparent … it should link with this, and then to the concrete, in terms of its uses. And to … when you look at this small building here … just this little façade here, has something of an Aldarossi feel to it.

Participants P-A consistently (and insistently) focused on creating visual unity (lingual aspect), as evident in Excerpt 6.20.

They made several sketches to illustrate their recall of historical performance arenas and theatres (Appendix G), which clearly demonstrated their pattern recognition ability.

Excerpt 6.23 illustrates their internal pattern recognition and ability to connect their implied abstract thinking to a concrete description. Participants P-E's reference to specific physical elements that embody information seemingly assisted them in mapping their new design task on an existing solution. Internal pattern recognition was evident in their vocal utterance. Participants P-E concretised their abstract idea through precise descriptions linked with physical elements, which were facilitated by recall. Excerpt 6.22 implies that Participants P-E's verbal representation is mental. This observation contradicts Gibson's (1977) claim that affordances are neither physical nor mental. Recalling this case through internal visualisation resulted in Participants P-E generating additional ideas that fall outside the scope of their brief. This facilitating role of their recall and visualisation demonstrates that, in this case, memory acted as what Shani (2012) considers the convergence of instantiation and processing. It seems evident from Excerpt 6.22 that the participants' process of implying links between functional intentions and affordance of physical objects is embedded in their internal process of recall.

Excerpt 6.22

EDWARD 00:40:07

All I sit and think about is this orchestra – as you find in Burgerspark – which has a roof - you know – with a little stage and balustrade – where the orchestra sits and then you sit outside, then they play to all. And anybody can sit around outside as they wish – on the grass – or on benches or on 'whatever'. And it is what this kind of thing is like.

An instance where the participants reacted externally on the information contained in their recall was triggered by recalling such physical elements and which functions they entail, as is evident in Excerpt 6.23. They reacted by suggesting additional physical objects that could serve functional purposes and did not fall in the scope of Participants P-E's design brief, being irrelevant to their task. Whereas embodiment theories indicate that designers merely react on information (Cross & Dorst, 1998) which they consider relevant to their design tasks, Excerpt 6.23 suggests that externalisation did not control Participants P-E's extended reaction in which they considered irrelevant functions and physical objects. However, Participants P-E's seemingly uncontrolled reaction could be ascribed to the embodiment principle of intention-attention dynamics regarding the manner in which external symbols, such as sketching and using labels, afford new perceptible targets that designers selectively pay attention to and thus find a new node indicating the control of action (Garner, 1994; Goldschmidt, 1994). Excerpt 6.23 demonstrates that such new targets may also be triggered by internal processes (internal visualisation which is then externalised in speech acts). This implies that the embodiment principle of intention-attention, which focuses on direct perception as trigger, can be extended to internal sources and processes.

Excerpt 6.23

EUGENE 00:40:38

Then we can put up a little roof for you – in a manner of speaking – which can serve as sound reflector – it will therefore not go up in the air.

Participants P-E pursued the idea of including sound systems and lighting, in spite of its irrelevance to their brief. Their pursuit of developing the idea of including sound and lighting therefore points to the equal power of internal processes of recall during design work to fixate on and develop particular ideas as demonstrated in Excerpt 6.24.

Excerpt 6.24

EUGENE 01:09:39

And I think it will be nice if one lifts the platform just above the ground – then you can build in things such as speakers …

6.2.3.3 Participants P-I: Functional intentions meet physical elements

In this section I report on the instances that have meaningful implications for the integrated theory of design cognition which is not explained in the case of Participants P-A and Participants P-E. In general, the strategy employed by Participants P-I to solve their design task, namely to design a device or system to count and organise large quantities of Lego™ blocks, differed from the other participants. From their sequence of thoughts it was evident that Participants P-I started sketching (Appendix G) various ideas simultaneously by structuring the problem before they articulated abstract design aspects. Their visualisation acts took up much of their effort at the beginning of the process, during which they made functional-physical connections before they declared their selected design aspect(s). In Excerpt 6.25, Adrian connected the physical aspects of a box with slots in it with its functional intention of pushing things through the slots. This utterance was complemented by a sketch depicting the 'puzzle-box' (Appendix G), which I interpreted as a vehicle of intent, a concept introduced by Rowlands, cited by Shani (2012).

Excerpt 6.25

ADRIAN 00:19:49

I sort of initially got two different ideas. The one idea was sort of like a, almost like a box where it is like a puzzle, to, you know you got like kids … where you've got different slots where you push stuff in or, or you could, it's maybe like a frame that you stack all the bits together like Tetris and then they, then you can see that they're all there …

By the time they made their first reference to the aspect of economic design, which they suggested be achieved through a manual system instead of a complex device (Appendix D), Participants P-I had produced six sketches that constituted a mixture of problem structuring and preliminary problem solving ideas. The perception process of their sketches seemingly

facilitated their analytical and subsequent evaluation functions which they represented in comparative tables (Appendix G). Together, the sketches and evaluations facilitated their abstraction, which in turn resulted in their commitment to the economic aspect. This implies that the sketches (Appendix G) not only served as vehicles of intent, but together with the tables, they also functioned as vehicles of cognition or process.

During their problem structuring phase, Participants P-I initially referred to physical elements in vague terms, and it primarily consisted of broad references to objects, as demonstrated in Excerpt 6.25. In the context of their protocol, they implied that one of the functional intentions of the device/system they were designing was that of sorting multiple sizes and shapes of Lego™. Their discussions and questions at this stage revolved primarily around the relative sizes and shapes of the Lego™ at issue. They implicitly connected physical properties with functional intention. Excerpt 6.26 demonstrates how their linkage of the physical properties and functionality resulted in the suggestion that contained the kernel of their eventual solution proposal. Clint proposed a system that allowed for sorting the Lego™ according to three sizes, into three category boxes. The non-specificity of his statement, demonstrated in Excerpt 6.26, implies abstraction based on pattern recognition. This abstraction could also be attributed to Participants P-I's shared expertise, which implied previous experience with canvas boxes that rendered it superfluous to elaborate on detailed descriptions.

Excerpt 6.26

CLINT 00:58:06
The small, medium and large, haven't known whether that represents possible solution? You know, with the canvas cover, canvas box.

Participants P-I individually and collectively considered the idea of a sorting and storage system that consisted of boxes (Appendix D and G), and laterally changed the instruction of counting into one of weighing as an alternative form of control, as captured in Excerpt 6.27. Participants P-I's connected weighing as a functional intention with physical elements ('*thousand small components together*'). Changing the direction of transformation from the client (researcher)'s instruction to their own functional intention demonstrated their experience with, and conceptual knowledge of control systems. During their problem solving phase they continued with lengthy discussions about the advantages, benefits and challenges of weighing Lego™ instead of counting them. These deliberations resulted in specificity, as captured in Excerpt 6.27. Participants P-I thus connected specific functional intentions in the form of expected behaviour (sensitive digital reader scale) of their suggested system of 'weighing' to the required physical properties of a scale to achieve their intention.

Excerpt 6.27

ADRIAN 01:55:28
The challenge also is maybe the fairly sensitive scale, because, ja … I mean if you got a bag full of those things it is OK. You … if there's a thousand small components together.

CLINT 01:55:47
… Well a digital reader scales, with those electronic scales; I mean they are very sensitive. I mean … you could record the weight of one of those, the weight of 500 of them.

The general increase in information and specificity in all the participants' connections between aspect, functional intentions and physical properties during their problem solving phases is apparent in the excerpts presented in this section. Although the notion of incremental development of designs of designers is not a new insight, accounting for it by connecting design aspects, functional intentions and physical elements is an extension of existing technological design theory, as explained by Cross and Dorst (1998), as well as Oxman and Oxman (1992). I argue that in order to secure aspects and intentions, participants had to generate and develop thoughts that were consistent with one another and with their intentions in order to achieve intellectual Gestalt (Kieran, 2011). Bratman ascribes the search for coherence in intellectual reasoning as 'principles of means-end' coherence.

Furthermore, in viewing the increase in references to physical elements as the participants' design processes progressed from problem structuring to problem solving, I gained an understanding of the centrality of recognition of patterns. The participants' expertise in recognising which physical elements, either emerging from the external environment or from their internally stored knowledge, resulted in their judgment of what would appropriately fit the selected design aspects and intentional functions of the artifacts they were designing. Such interactive acts of recognition correspond with Goel's (1995) notion of pattern recognition and Reffat and Gero's (1999) description of the designer as 'recogniser'.

6.3 THEME 2: PERSONALISING INTENTIONS

The second theme that emerged from the data was the way in which participants personalised intentions originating from the client or from objects. In his problem solving theory, Goel (1995) emphasises 'reversing the direction of transformation' as a psychological characteristic of the problem space. As such, the notion of 'reversal of direction' refers to instances where designers question the appropriateness of a suggested solution or requirement by a client, and subsequently devise their own intention. Designers are known to interpret a problem situation through their own personal knowledge and bias (Cross, 2007a; Lawson & Dorst, 2009). This in turn suggests that designers choose when they see fit to pursue their client's intentions and when to ignore or transgress these. Intentional studies (Dennett, 1995) furthermore corroborate

the need of problem solvers to interpret problems in terms of their own bias and personal stopping rules.

On a meta-theoretical level this notion of 'reversal of direction' is significant, as it involves adjusting the conditions under which satisfaction of intentional states could be achieved (Chapter 2, section 2.3.4, and Chapter 7, Figure 7.5). It furthermore implies that the direction of fit involves the participants' mind-to-the-world, and not the client's mind-to-the-world (Simon, 1996). Therefore, I assume that when the participants considered reversing the direction of transformation, they may have been influenced by their expert professional experience or by personal or professional bias, which acted as a personal stopping mechanism. However, I also acknowledge the influence of external variables in the participants' reversal processes.

In this section, I explore the relations between the intentional state of the participants and the way they interpreted their design problem situations when using particular types of knowledge. The purpose is therefore to understand and explain the driving force behind participants' reversal of the direction of transformation. The implication is that I had to consider the sources of their interpretation. I asked the following questions: *where did the interpretation originate? what were the contributing internal and external factors influencing the reversal?, and which role did the internal and external variables play?*

The role of knowledge application in design work has been widely researched, from a domain specific point of view (Kilgour, 2006; Vincenti, 1990; Wiley, 1998) and from generic perspectives (Ericsson, 2003; Lawson & Dorst, 2009; Popovic, 2004). Goel and Pirolli (1989) also contributed to the field of generic design knowledge, which is the approach I adopted for this study in general and for this section specifically. According to Goel and Pirolli's (1989) theory of generic design knowledge, two schemas of knowledge can be found in design thinking, namely general and domain specific schemas. Each schema can contain any combination of various types of knowledge as identified by De Vries (2005), including conceptual knowledge, procedural knowledge, normativity, visualisation, and efficiency and adequacy. Keeping Goel and Pirolli's (1989), as well as de Vries' (2005) theories about design and technological knowledge types in mind for each of the protocols, I observed that all the participants had definitive instances where they explicitly transgressed the client's (researcher) intention. This set off their implementation intentions which were based on their personal beliefs about what the problem was. They subsequently formulated intentions that were embedded in their normative judgments (Kroes, 2002), and connected to their domain specific knowledge.

6.3.1 PARTICIPANTS P-A: PERSONALISATION OF INTENTIONS

In the case of the architects, the client's requirement was to incorporate an existing sculpture in a new theatre design without removing it completely. Participants P-A, however, expressed their opinion that the sculpture did not belong to the theatre site as a whole, due to its formal and conceptual incongruence with the surrounding buildings. They expressed a strong sense of spatial relations, and actively interacted with the environment (through direct perception and studying the aerial photograph, (refer to Chapter 5, Photograph 5.2, p.154). This interaction seemingly resulted in Participants P-A's reversal of the clients' requirement for the existing sculpture. They partly adhered to the requirement of the client by moving the sculpture out of the theatre site to a position they felt was less conflicting and served a functional purpose. This means that they solved their own goal intention of aesthetic spatial coherence by conceptualising an implementation intention as evident in Excerpt 6.28.

Excerpt 6.28

JONATHAN 00:30:17
So, I think this thing is completely out. It does not connect with what … I mean it is completely out of context, the shape of this thing. You know, and it does not look as if it has any meaning… O yes, I think this thing can be right in the right place.

Proposing an intention that is different from that of the client, as demonstrated in Excerpt 6.2, links with the psychological characteristic 'reversing direction of transformation' that Goel and Pirolli (1992) identify as typical of the early phases of the design process. Reversing the direction of transformation function refers to the action by designers where they, rather than transforming initial problem states to a goal state, negotiate changes to the initial state and goal state. Reversing the direction of transformation implies that designers explicitly attempt to change the problem parameters by manipulating both the problem constraints and client's expectations. The reasons for wanting/needing to reverse the direction of intentions in this manner relate to designers interpreting their design task through the lens of their own personal experience and bias. This means that, due to their expert architectural knowledge and experience, they did not view the requirement of the client, and determined that the sculpture at issue should remain on the site of the theatre as a viable solution.

6.3.2 PARTICIPANTS P-E: PERSONALISATION OF INTENTIONS

In the case of the engineers, the client's requirement was that they should ignore the existing sculpture and only design a rotating platform that could be used in any design the architects might propose a new open-air theatre. From Excerpt 6.29 it appeared as if Participants P-E interpreted their brief to ignore the existing sculpture in terms of the client's intention.

Excerpt 6.29

Excerpt 6.29 was recorded during Participants P-E's problem structuring phase. They attempted to understand the function of the sculpture on the theatre site while in the studio. However, in spite of the design brief and the client (researcher) requesting them to ignore the sculpture, as the intention was that the architects should use it architecturally and that Participants P-E were meant to only design the rotating platform, they constantly and for long periods of time paid attention to the sculpture. Excerpt 6.30 demonstrates how they, when they saw the sculpture, acted on the visual stimulus and talked about and sketched (Photograph 6.25, p.274) an integration of the sculpture with the platform design, reversing the intention of the client.

Excerpt 6.30

EDWARD 00:50:19
This is quite a natural place …. You can put the piano there – an orchestra cannot fit in there….
EUGENE 01:01:57
But if you put your platform here – say you put it right here …
EUGENE 01:02:20
Yes – Let us measure it a bit – If you put it approximately here – then you can – they can see through this thing – There is a put – those legs cut it somewhat – but the guys on the stage also walk around – this is ten meters, man. It can be here – and there – and everywhere – so, at times you will see and at time you won't.

Therefore, in spite of the client's requirement, Participants P-E reversed the intention temporarily and pursued the thought of incorporating the existing sculpture for a relatively long time, as illustrated by Excerpt 4.30. From their dialogue, I inferred that Participants P-E did not reverse the direction of the intention as a result of their expertise, but rather as a reaction to the visual stimulus and the theoretical challenge of integrating the sculpture with their platform design. Consequently, they broadened the scope of their problem, a tendency Goel (1995) regards as typical of expert designers. They further broadened the scope of their problem by considering additional elements not required by the client, including lighting and sound systems, and a removable canopy for the stage.

6.3.3   PARTICIPANTS P-I: PERSONALISATION OF INTENTIONS

During their problem structuring phase, Participants P-I's first instance of reversal of the client's intention is captured in Excerpt 6.31. While the intention of the client was to obtain a tangible device or system to help organise and count things, Participants P-I said that the procedure should change, ignoring the requirement of such a concrete object.

Excerpt 6.31

ADRIAN 00:13:26
Your process needs to change, basically

CLINT
I think what the client wants ... is an easy to carry, easy to manage, no hassles system that they can take out and put into the car, take out the car and put back into the car with very little. I don't know if I'm being too ... here?

BRIAN
I don't know whether for example the client's going to be insistent on all the parts being disassembled, which personally I would think ...no you don't need to disassemble them. They've got to find them. That's what Craig were suggesting, there's a sort of ... they arrive there and they've got to pick out what they, if it need disassembling then that's what the students have to do.

Excerpt 6.31 furthermore demonstrates Participants P-I's own personal belief that the actual problem was intrinsically meaningful to them and constituted an immediate integral part of the way they made sense of the problem. They aligned their interpretations and subsequent suggestions with their understanding that the actual problem implied an incorrect process. Shani (2012) maintains that it is through such beliefs that agents understand and interpret external situations. The question that arises here is *what is the relationship between such beliefs, their strive for coherent alignment between the elements constituting design reasoning (connecting aspect, intentions and physical objects), and the psychological phenomenon of fixation?*[33] Excerpt 6.32 captures Participants P-I's explication of their belief about the actual problem, which is different from what they were asked to design, and their focus on changing the process, rather than designing a device.

Excerpt 6.32

ADRIAN 01:47:47
But we weren't asked to address, we would just ... by reading the scenario we asked questions about what, well you know, identify and counting is that really going to solve the problem or would it be visible? We're saying if we read the scenario, that the problem might be slightly different to what the solution is asking for, the problem is really the effort that it takes to split these things apart to check that everything is there, I think is the problem.

From the protocols, I inferred that the common trend among all the participants' reversal of transformation direction suggested an internal process whereby the direction of fit was directed towards what the participants believed about the needs of the world and not necessarily what the design brief required or what the client believed. When they conceded to the intentions of the brief, it was because the participants either prioritised the conceding act (without necessarily believing in the merit of the client's belief about what the actual problem was), or actually agreed with the problem. Comparisons between the cognitive processes of novices and expert designers, such as those conducted by Atman, Chimka, and Cross (1999), Eastman

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[33]This issue will partly be dealt with in section 6.5, control structures.

(2001), and Kavakli and Gero (2002), agree on experts' interpretation of design problems as a common phenomenon amongst experts, and base it primarily on their superior knowledge of design. However, these studies do not elaborate on an explanation for their decision making in a way that explains how designers are influenced by the interaction between internal states and external environments.

6.4   THEME 3: INCREMENTAL DEVELOPMENT OF ARTIFACTS

In this section, I explore what the participants thought about as they progressed through the phases of developing their artifacts, with the aim of further expanding Goel and Pirolli's psychological characterisation of the problem solving space of designers. I analysed the semantics of their representations and, through quantitative and qualitative processes, distinguished between continued attention to particular content and short duration of their attention to other content. The theme consists of two sub-themes, namely continued and short attention duration to content and the sources of subsequent thoughts, and the relationship between the aspects participants considered.

In analysing the data from an interactive position, I observed that some the participants paid attention to particular intentions for longer periods of time than to others. This observation gave rise to the following questions: *what were the driving forces of longer duration of attention to particular intentions', and what did the duration of attention to a particular intention say about the dependency-direction between intentions and perceivable physical elements?* By 'chunking' (Suwa et al., 1998; Suwa & Tversky, 1997) I could identify instances where the participants' consideration of external elements co-occurred with instances when they explicitly articulated intentions. Some chunks consisted of relatively many modules, while others contained only a few. In extreme cases, chunks consisted of only one isolated module. This meant that the participants, after shifting their attention to a new topic, did not pursue exploring it further before shifting their attention to another topic.

I individuated between the different intention-attention instances that the participants engaged in across their entire protocols. I asked *what were the things the participants paid attention to?, and how much time did they spend on thinking about these things?* Existing studies conducted by Suwa, Purcell and Gero (1998) served as guideline for my analysis and interpretation that is presented here. These authors developed a generalised set of codes that allowed for a structured model systematically capturing the types of things designers think about and the relationships between these things. However, the categories of 'things' these authors used in their model, was limited to functional and physical aspects and, in the context of this study, I needed an expanded model that allowed me to draw relationships between aspectual intentions, functional intentions, implementation intentions and physical aspects.

By expanding Suwa et al.'s (1998) model, I was thus able to trace the possible origins of the participants' thoughts to design aspects. The reason for tracing the origins of particular thoughts is that it provided me with a concrete handle on further tracing the direction of the participants' thought processes. Knowing where to search for the sources of long and short durations implied my understanding of the difference between sources located in internal content (intentional states), which is considered as an instantiative source and those located in the externalised cognitive processes, which are known as transformative sources (Shani, 2012), explained earlier.

6.4.1 SUB-THEME 3.1: CONTINUED AND SHORT ATTENTION DURATION TO CONTENT AND THE SOURCES OF SUBSEQUENT THOUGHTS

The purpose of this section is to describe what influenced prolonged attention, as opposed to short attention spans. To contextualise the particular things that participants thought about, it is necessary to link their thoughts to their sources.

6.4.1.1 Participants P-A: Continued and short attention duration to content

In Table 6.1, I present a summary of how Participants P-A's shifted their attention between their various intentions, which was also connected with particular external objects and elements inferred from their vocal utterances and sketches. Participants P-A pursued two design aspects, namely aesthetic coherence and spatial relationships, which prevailed in long chunks. In turn, they had two short chunks[34], both related to implied lingual aspects, namely 'honesty' and 'creativity, growth and playfulness'.

Table 6.1:   Participants P-A's intentions and their connection with physical elements

LONG CHUNKS			
Design aspects	**Physical objects/ elements considered**	**Functional aspects considered (Goal intentions)**	**Implementation intentions**
Aesthetics Attain cohesive aesthetic when integrating new elements with existing ones	• Visual language (symbols) • Landscape, trees • Cafeteria • Existing buildings • Sculpture	• Express energy • Provide visual clues to understanding conceptual and functional aspects • Provide walkways	• Move existing cafeteria • Plant trees • Create corridors and walkways • Consistent use of material • Consistent physical form
Spatial Spatial relations of elements to maximise effective	• Stage, shape • Theatre, shape, • Shape, long thing	• Interactivity • Allow maximum visibility and interaction	• Audience sitting around rectangular stage implementing 'golden circle' principle • Position where an activity catalyst

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[34]'Long chunks refer to modules (themes) in the protocols that continued over a relative long period of time and were repeatedly addressed in the dialogues. 'Short chunks' refer to modules of short duration, with only one or two instances of attention.

use and experience of space	• Like fashion ramp • Surrounding • buildings • Landscape, trees • Existing, distant cafeteria • Visual language • Walkways • People movement • Parking • Sculpture	• Improve flow and maximise use • Introduce possibility for catalyst activities • Create avenues • Create intimacy • Maximise use • Provide visual clues to enhance interactivity	already exist • Position where chance movement of people exist • Spatial relations • Add dressing rooms • Open and join parts of existing surrounding buildings • Put rooms on top of each other • Change landscape – add trees • Move cafeteria from current position to theatre • Position in sun • Reposition, reorganize elements
SHORT CHUNKS			
Lingual (visual) Honesty	• Theatre • Functional elements providing services	• Unspecified	• Do not hide functional elements • Underspecified
Creativity, growth, playfulness	• Theatre	• Unspecified	• Understate aesthetic • Underspecified

Their long chunks were seemingly driven by the participants' aspectual and functional intentions and were supported by implementation intentions in which they provided some detail about how to achieve their functional and aesthetic goals by manipulating existing space and elements and integrating new elements in a formal manner. I base this inference on the context of these long durations and the evidence of connection between the selected aspects, functional intentions and physical elements, in which Participants P-A deliberated the justification of their selection of aspects due to its theoretical basis in their domain.

Shani (2012) cites earlier situational explanations of selection of intentional content as a consequence of the ability to facilitate or perform certain cognitive functions. I uphold the philosophical views of Shani (2012) and Bickhard (1999), who argue that the selection of intentional content, is based on the knowledge of its potential success in solving problems. This theory links well with the empirical findings of design studies that report on how expert design reasoning revolves around arguments of fitness for purpose and suitability of choices to solve design problems (Cross, 2007a; Vincenti, 1990). It therefore makes sense to account long durations of attention to the ability of participants to make the internal connections between the suitability of their combined choices and the problem it is supposed to solve.

This argument, however, does not imply that short attention durations lacked this ability in this study. Another explanation should therefore be found for the occurrence of short chunks in the protocols of the participants. The implication is that it is not only the virtue of the selection or its assumed suitability that determine how much attention a particular internal content will

receive. With the theoretical apparatus that I selected, I could not find a satisfactory explanation for such short chunks, and therefore propose a separate study focusing on the variables influencing long and short attentions spans in design reasoning.

Participants P-A had two short chunks only; these chunks were characterised by the absence of detail and specificity as far as functionality and implementation were concerned. The origin of the intentions in both the long and short chunks did not seem to have an influence on the duration of Participants P-A's chunks.

6.4.1.2 Participants P-A: Sources of long and short chunks of attention

The aspectual, functional and implementation intentions of Participants P-A were furthermore characterised by close association with objects and their physical and functional properties. I firstly individuated themes within the modules and thereafter traced the sources of the participants' thoughts. Secondly, I connected the themes and sources with internal and external environments within the participants' cognitive phases. This procedure enabled me to trace the duration of chunks and map their distribution across the entire protocol. The origin of long chunks consisted of a mixture of client intentions, their own supplementary intentions and a reversal (refer to Section 6.3) of the client's intention (Appendix I). Table 6.2 summarises Participants P-A's distribution of their long and short chunks when structuring and solving their design task, as well as the overlaps of modules according to the source.

Table 6.2: Distribution of sources of Participants P-A's long (L) and short (S) chunks

COGNITIVE PHASE	PROBLEM STRUCTURING		PROBLEM SOLVING	
DURATION OF CHUNKS	L	S	L	S
SOURCE OF INTENTIONS				
External object**: Brief**	1	0	7	1
Internal content: **Design aspect - spatial relations**	1	0	4	1
Internal process: **Reverse direction of transformation**	1	0	8	0
Internal content: **Design aspect - aesthetics**	1	0	5	2

From Table 6.2 it is evident that the majority of long chunks were found in the problem solving phase. This pattern suggested to me that the implementation intentions contained the concepts that the participants needed to incrementally and systematically develop their solutions, which typically took place during the problem solving phase (Ho, 2001; Lloyd & Scott, 1994; Vincenti,

1990), and not when they structured their design problem. However, Participants P-A had a distinctive way of thinking. Table 6.2 summarises the way in which Participants P-A's sketch information supported their verbal information regarding long and short chunks and their commitment to ideas driven by their intentions.

Although Participants P-A referred to their own intention 'to create aesthetic cohesion', which represented a long chunk, aesthetic outcomes were not represented due to the early phase of their design process. It is typical to represent aesthetics only in development and refinement sketches. Although they had vague implementation suggestions regarding visual unity through the choice of material (including concrete, grass, trees and glass) and they judged the (in their opinion) inappropriate combination of shapes on the site, the way in which they planned to achieve such unity was not addressed in their sketches. In contrast, their additional personal intentions to approach the whole surrounding area as an integrated and efficient urban facility was addressed in most of their sketches and also contained several long chunks. This correlates with findings by Suwa (1997) and Lawson (2006), which confirm that architects typically attend to spatial relations during the early phases of the design process.

Participants P-A's sketches furthermore also addressed issues raised in their short chunks, these included the achievement of an 'intimate' atmosphere (Appendix G, Sketch A-3A) and 'honest' structure (Appendix G, Sketch A-3B). I inferred that they sketched this due to the fact that it could mainly be achieved by creating appropriate spatial relations and did not depend on detail decisions that would normally be made only much later in the design process.

In their dialogue, Participants P-A implicitly attended to their various goal intentions by elaborately describing cases related to a particular intention which accounted for much of their long chunks. The multiple 'case' sketches that they made to illustrate these intentions also contributed to the duration of the chunks. This means that, although the counts of their long and short chunks during the problem structuring phase is relatively low, they implicitly conceptualised implementation intentions based on domain specific conceptual relations and associations that they made between the client's requirements and their own goal intentions. They became more explicit during the problem solving phase, although they also immersed themselves in case scenarios (Goel, 1995; Lawson & Dorst, 2009) to justify their implementation goals.

6.4.1.3 Participants P-E: Continued and short attention duration to content

The way in which Participants P-E incrementally developed their artifacts is characterised by their continued and short attention to particular things. In Table 6.3, I summarise Participants P-E's shifts of attention between their various intentions, connected with particular external

objects and elements inferred from their vocal utterances and sketches. Participants P-E pursued two design aspects, namely physical, and economic in their long chunks, while they attended to the aspects of sensitivity and aesthetic in their short chunks.

Table 6.3:   Participants P-E's intentions and their connection with physical elements

LONG CHUNKS			
DESIGN ASPECT	**Physical elements of objects**	**Functional aspects of objects (Goal intentions)**	**Implementation intentions**
Physical Design should be flexible Platform and other elements to work efficiently	• Platform • Rail - detail • Sound system: speakers, electricity • Lights • Non-permanent • Position • Platform • Rotation mechanism • Platform • Landscape • Transport point • Wheels • Slope of ground on site	• Rotation • Provide sound • Enable visibility • Provide choice and how to and when to use elements • Enable rotation • Get props on platform • Provide stability	• Use when necessary • Modularity: removable parts • Provide electricity on theatre • Stay in one position • Determine angle of slope • Add wheels for stability • Access to electricity
Economic Design should be economic and simple	• Platform • Sound system • Height • Position • Direction • Platform • Landscape • Sound • Spatial relations	• Prevent having to erect additional structures • Provide rotation • Provide physical balance	• Lift platform from ground • Change shape of landscape • Hide sound system underneath platform without making ineffective • Do not use alternative energy sources
SHORT CHUNKS			
Sensitive Interactivity Additional services	• Theatre-audience • Visibility • Sound, lighting	None suggested	None suggested
Aesthetics	• Sculpture • Detail of finish		

I observed an overlap between the physical elements spread throughout the intentions of Participants P-E. This indicated to me the dependence of these internal intentions on the external physical properties as they emerged from the context of Participants P-E's design task. The functional aspects of these elements seem to externally emerge from the required behaviour of the platform that was stipulated in the brief. Making implementation intention statements

indicated to me that the engineers had considerable procedural knowledge which guided them in making plans to achieve their goal intentions. Excerpts 6.33, 6.34, 6.35 and 6.36 below are examples of a long chunk including both goal intentions and implementation intentions that depend on external elements observed in Participants P-E's protocol.

<center>**Excerpt 6.33**</center>

> EDWARD 01:31:17
> Our engineering therefore only functions in that thing that should rotate.

The goal intention in Excerpt 6.33 is clearly stated, namely to focus on a 'thing' that could rotate. In the dialogue following this explicit goal, specificity (height) demonstrates how participants depended on the external elements in the environment (ground level), to develop an idea (Appendix D) by adding specific detail.

In spite of the scope of their task as articulated in Excerpt 6.33, Participants P-E continued to add implementation intentions, which demonstrated a personal stopping rule that controlled their evaluation functions and subsequent decisions. Shani (2012, p.9) argues that the external variables, play a constitutive role in cognitive processes in the instantiation of designers' intellectual engagements. Such instantiation accordingly takes the form of a coordinative effort whose coherence and operational closure depend, in part, on the regulatory contribution of such variables. This explains the participants' consideration of the topographical levels of the site when deciding how high above the ground the platform should be.

Another example of Participants P-E's evaluation functions were aligned to their intentions, as captured in Excerpt 6.34. Directly after suggesting that the platform should be moved up and down, and not only rotated horizontally, Participants P-E evaluated the idea in terms of the economic aspect that they prioritised, namely keeping the design simple. They thus consequently discarded the idea, as seen in Excerpt 6.34.

<center>**Excerpt 6.34**</center>

> EDWARD 01:31:41
> I mean in terms of the entire hole – to lift the entire floor – then it comes in a shaft. I wonder if it has any meaning for this purpose. It is too fancy. I don't know – say… It is too fancy – keep it simple.

Once Participants P-E discarded this idea, they returned their attention to the rotating platform conceptualising the physical properties of elements and how it would allow them to achieve their aspectual intentions and functional objectives of the platform. Consideration of these details implied that they accessed their domain specific conceptual as well as procedural knowledge. Stating which objects, elements and material they would use to stabilise the

platform indicated their conceptual knowledge, while explaining how to use the elements indicated their procedural knowledge, as represented in Excerpt 6.35.

Excerpt 6.35

EDWARD 01:31:43
You can make a frame structure with enforced triangles and then you join the platform with the centre – you let the centre point turn on a bearing, running on a rail. With a small gear motor which you install here … and brrr….it turns.

6.4.1.4   Participants P-E: Sources of long and short chunks

Table 6.4 provides a summary of the things Participants P-E thought about while developing their artifacts. I classified the information according to the duration of their attention to a particular intention and the internal and external sources where their intentions originated. Participants P-E considered the client's intentions throughout their entire protocol, during short and long chunks. Suggestions to provide for additional services not included in their design brief were also relatively constant throughout the protocol.

Table 6.4:   **Distribution of sources of Participants P-E's long (L) and short (S) chunks**

COGNITIVE PHASE	PROBLEM STRUCTURING		PROBLEM SOLVING	
DURATION OF CHUNKS	**L**	**S**	**L**	**S**
SOURCE OF INTENTIONS				
External object: Client	2	2	2	2
Internal content: Additional functional intention – provision of services Interactivity	4	1	5	1
Internal process: Reverse direction of intention	5	0	4	0
Internal content: Functional intention – efficiency of platform	1	0	6	0
Internal content: Economic design	0	0	4	0
Internal content: Functional intention - flexibility of design	6	0	4	0

I attributed Participants P-E's long chunks of attention to the aspect of flexibility early in their problem structuring phase (Module 16, Appendix D) to the fact that they did not know which architectural specification would be required of them to do, and therefore suggested ideas that were adaptable and non-permanent. The participants' long chunks of attention to efficiency intentions related to their concern with the delivery and storage of props from an external truck that could serve as mobile storage space. Transporting props from the truck to the stage on a

forklift type trolley showed coherence with their 'flexibility' and 'non-permanent' idea. From the analyses of the protocol of the engineers, the dependence of goal intentions and implementation intentions on physical external objects or elements corresponded with the pattern which I observed in the protocol of the architects.

6.4.1.5   Participants P-I: Continued and short attention duration to content

The intention-attention data of Participants P-I indicated two long chunks and three short chunks. Their long chunks were governed by the aspects of 'economics' and 'physical', while they had one short chunk in which they also considered 'economics'. The fact that the same aspects were considered in long and short chunks confirmed my suspicion that 'aspect' should not be deemed as the sole variable influencing the amount of time spent on a particular chunk of thoughts.

It was possible to trace the dominant functional intention in Participants P-I's long chunks being that of efficiency, combined with the majority of the physical elements that they linked with their aspectual intentions (Appendix D-Ecology). These thoughts overarched the majority of statements explicitly in the intention-attention category (see Appendix D-Ecology). Participants P-I explicitly articulated their intentions and had few observable implicit intention-attention instances. They produced a total of thirteen explicit efficiency statements in structuring their problem, seventy-seven while solving their problem and twenty-five during leaky phases, which resulted in a total of one hundred and thirteen instances when implicit and explicit references were made to efficiency. The dominant continuing chunk in the industrial designers' protocol represented their thoughts about the aspect of economic design, which they translated as 'simplicity' and served as a strong personal stopping rule which controlled their evaluation functions and directed their thought processes (discussed in more detail in section 6.5) towards deciding on a manual system, rather than an electronic system. This tendency is captured in Excerpt 6.36.

Excerpt 6.36

BRIAN 00:31:03
My thought also go a bit well, what is the simplest possible solution with the least, uhm … parts and material and in fact should one just stick with this purely manual system what they have, but they employed people to do it. Systems …

Although they attempted to generate (for themselves) an alternative solution that complied with the expectation of a self-sorting device that could satisfy the client's requirements and dwelt on the thought for a relatively long time (Appendix D and F), Participants P-I questioned the appropriateness of a complex device functioning in the way their design brief suggested

(Appendix C). Table 6.5 summarises the things that the industrial designers thought about for longer and shorter durations of time.

Table 6.5: Participants P-I's explicit goal intentions and implementation intentions

LONG CHUNKS			
DESIGN ASPECTS	**Physical elements of objects**	**Functional aspects of objects (Goal intentions)**	**Implementation intentions**
Economic Physical	• Existing system – boxes • Other people • Sacks/Bags • Activities • Instruction cards • Material • Sizes • Rack • Lego™ • Bags • Weight • Material, • Handles • Fasteners • Sizes • Existing boxes • To be manufactured • Scale • Plastic bags • Trolley • Transport	• Sorting • Counting • Saving space • Allow discovery • Easy access to Lego™ pieces • Allow for various sizes • Easy transportation • Easy management • Weighing • Controlling access and recovery • Easy to carry • Durable • Open and close bags • Easy disassembly • Easy recovery • Easy sorting	• Use the least parts and material • Stick with manual system • Employ people to do the work • Change approach: Use existing manual system, Reorganise sequence of activities • Students to form part of management activities/ Put on scale Maximum weight per bag • Weigh – not count • Organise according to size of Lego™ pieces: large, medium, small • Allow for visibility • Clear front • Existing A4 paper boxes • Plastic bags in boxes • Weighing part of situation • Involve students • Employ other people
SHORT CHUNKS			
Economic	• Cost • Storage space • Labour • Sack • Digital management device • Flexible material • Different sizes • Draw strings • Convert sacks into working sheets on tables	• Transport • Storage • Recovery	• Use existing objects to lower cost • Employ people at low cost • Reorganise sequence of activities • Vertical hanging system working like shoe organising Need a clothes line • Different sized pockets • Sacks of three different sizes • Fit in car • Fit on tables • Involve users • Use convertible and multi-purpose objects

Table 6.5 indicates that Participants P-I's long chunks overlapped in the objects, the physical properties considered, the functional considerations of the objects as well as the implementation intentions envisaged. The participants aligned all of these with their goal to achieve economic and physical aspects approached from a holistic point of view. The implementation goal that bridged both of these intentions was the participants' conscious and deliberate reversal of the client's (researcher) intention to acquire a self-operating device that could count and sort the Lego™ pieces. They considered changing the approach to the whole act of managing the Lego™ by involving students and outside people instead of designing a self-operating device to save time and labour early in the process (Module 25, Appendix D). Their subsequent ideas, decisions and implementation intentions were apparently driven by these overlapping internal goal intentions. From the list of physical elements and functional aspects, it was apparent that Participants P-I's aspectual and functional intentions depended on the same selection of physical elements.

6.4.1.6 Participants P-I: Sources of long and short chunks

Table 6.6 presents a summary of the things Participants P-I thought about, classified according to the duration of their attention to a particular intention, and the internal and external sources where their intentions originated.

Table 6.6: Distribution of Participants P-I's long (L) and short (S) chunks per phase

SUMMARY				
Duration of chunks per phase according to the source of intentions				
COGNITIVE PHASE	**PROBLEM STRUCTURING**		**PROBLEM SOLVING**	
DURATION OF CHUNKS	L	S	L	S
SOURCE OF INTENTIONS				
External object: Brief Save client time and labour	0	3	0	5
Internal content: Domain specific - Efficiency (people-object interaction)	19	11	39	14
Internal content: Economic design	5	0	14	0
Internal process: Domain specific - Reversal of intention (holistic system, not device)	0	0	3	1

Participants P-I's short attendance to the client's particular requirements to save time and labour during their problem structuring phase was again attended to during the problem solving phase. They did not agree with the client's idea on the type of artifact to be designed. The majority of their concerns were to meet the client's requirement by pursuing their own intention of efficient interaction between their envisaged Lego™ management system and the people

involved in using it. Instances where I observed this behaviour of Participants P-I increased exponentially during the problem solving phase, once they articulated their reversal of the client's idea that the solution was a management device.

6.4.2 SUB-THEME 3.2: RELATIONSHIP BETWEEN THE ASPECTS PARTICIPANTS CONSIDERED

The second sub-theme in the incremental development of artifacts, involve the way in which designers were able to synthesise their intentions. In Section 6.2, I discussed the hierarchical thinking involved in the participants' consideration of design aspects and the intricate dependence between aspectual and functional goal intentions and physical design elements. In Section 6.3, I explained and justified the important role that the participants' reversal of direction of transformation played in their personalisation of intentions and decision making. Building onto these insights, the aim of this section is to model the synthesis of the various aspects involved in the synergetic relationship between access to internal and external sources that seemed to drive incremental development of artifacts. In order to map the processes involved in the development of ideas, I inferred the knowledge that the participants used from the participants' explicit and implicit expressions of their intentions, interpretations and judgements of the client's (researcher) intentions, their explanations, justifications and evaluations of ideas that they generated. Figure 6.1 further on (p.236) presents the way in which participants interactively used external and internal information when committing themselves to intentional actions and decisions.

In order to establish the nature of the relationship between the various elements in the model, it was necessary to establish what types of sources gave rise to a particular thought. As this study primarily focused on the interaction between internal and external sources and processes, I distinguished between internal and external sources that could possibly trigger particular types of thoughts and its content. I individuated modules in which the sources could be observed from the video material, which were noted on the various EXCEL coding sheets (Appendix D). I considered internal sources as 'reversal of transformation direction' (coded in the 'Psychology' coding sheet) when there were indications in the verbal data that the participants had intentions that differed from the client's (researcher) intentions. I furthermore regarded 'supplementary knowledge' as an internal source that related to domain specific design aspects and functional knowledge. As such, the content of the knowledge of design aspects and functionality could be found in both instances of reversal or supplementary knowledge. I extracted information regarding the external sources from observation notes woven into the various coding sheets regarding the sources that the participants used during their protocols (refer to Chapter 5, Photograph 5.14 to 5.17 for an example [p.170, p.1713]).
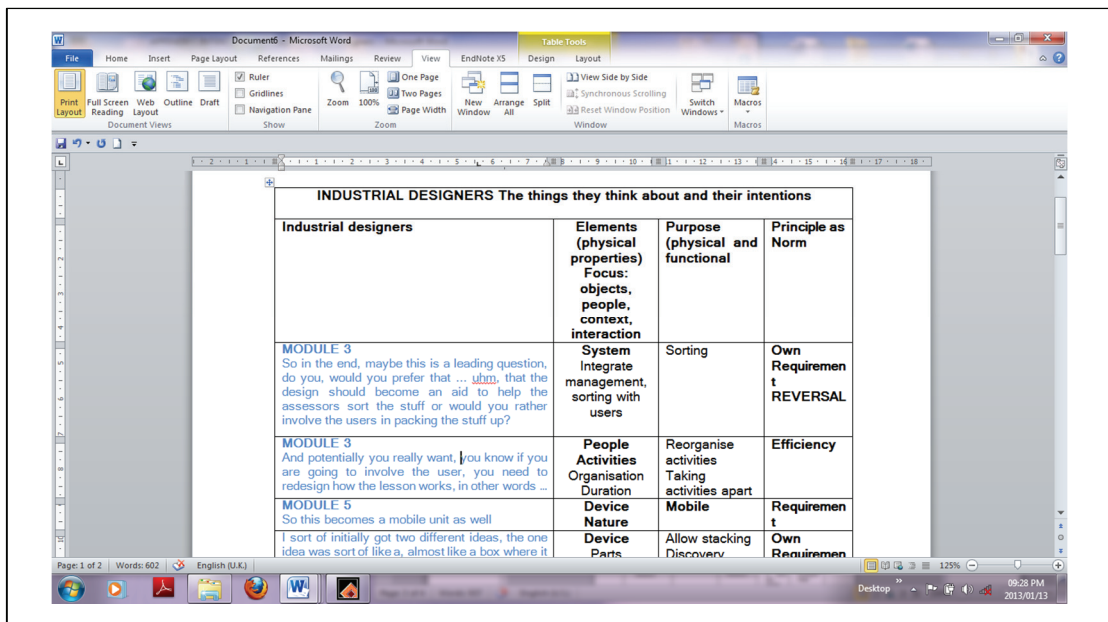
For this reason, context was central to individuate instances when the content of particular thoughts originated. This implied that external sources could trigger the participants' use of internal sources. The opposite was also theoretically possible, which implied that the participants could be sensitive to perceivable stimuli including the client's requirements in the brief, information afforded by their sketches and by the objects in their environments that enticed them to pay particular attention to particular points in time during their protocols (Shani, 2012). Central to the whole process of arriving at a meaningful model of the interrelationships was therefore the empirical semantic individuation of the 'things' that the participants thought about and how they could be coupled with the various types of intentions, as well as with possible internal and external sources. In order to identify patterns and relationships, I individuated themes in the various modules (themes in the transcripts) and classified them through a coupling process in the manner summarised in Table 6.7

Table 6.7: **Coding system through coupling various subcategories to determine the synthesis between internal and external processes and sources of information**

	PRIMARY INTERNAL SOURCE AND PROCESS		LINKS WITH OTHER INTERNAL AND EXTERNAL SOURCES
Item	**Sub-category**	**Category** (Coding sheet)	**Interaction between various sub-categories based on co-occurrence**
Goal intentions			
Aspectual goals	Abstraction hierarchies Patterns	Psychology	Coupled with: • intentions (Ecology) • normativity (Knowledge) • efficiency (Knowledge) • visualisation (Knowledge) to correlate with information in sketches
Functional goals	Abstraction hierarchies Patterns	Psychology	Coupled with: • intention-attention (Implies emergence and affordance) • visualisation (Knowledge) to correlate with information in sketches
	Normativity	Knowledge	Coupled with verbs indicating how objects work, function, behave
	Efficiency	Knowledge	Coupled with words indicating how well objects, arrangements, combinations work (implies evaluation and judgement)
Elements	Objects	Knowledge	Coupled with: • perceivable objects or parts of objects (Implies emergence and affordance) • visualisation (Knowledge) to correlate with information in sketches

My focus was to establish what the envisaged outcomes of goal-directed actions were or what the participants envisaged the outcome of artifacts (perceivable objects) could be. From their speech, acts and sketches I attempted to determine a characteristic of an artifact and its particular components and elements which did not yet exist, but visualising it, or talking about it, seems to make it more 'real' and allows goal directed addition of elements, components or characteristics. As such, I derived my coding in the context of artifacts being suitable to solve a problem in a particular context, functional, fulfilling a particular purpose and adhering to principles, norms and standards, thereby beliefs/knowledge.

This coding procedure also served as basis for the discussions in Sections 6.5 and 6.6. Photograph 6.1 captures an example of such coding from the 'implementation intentions' category.

Photograph 6.1: **Example of coding and classifying the 'things' Participants P-I thought about, and their intentions**

In Figure 6.1 (see p.236), I model the synthesis of the synergetic dependence relationship between internal and external sources of information that guided my investigation of the control structures and transformation processes, which I discuss in the following sections.
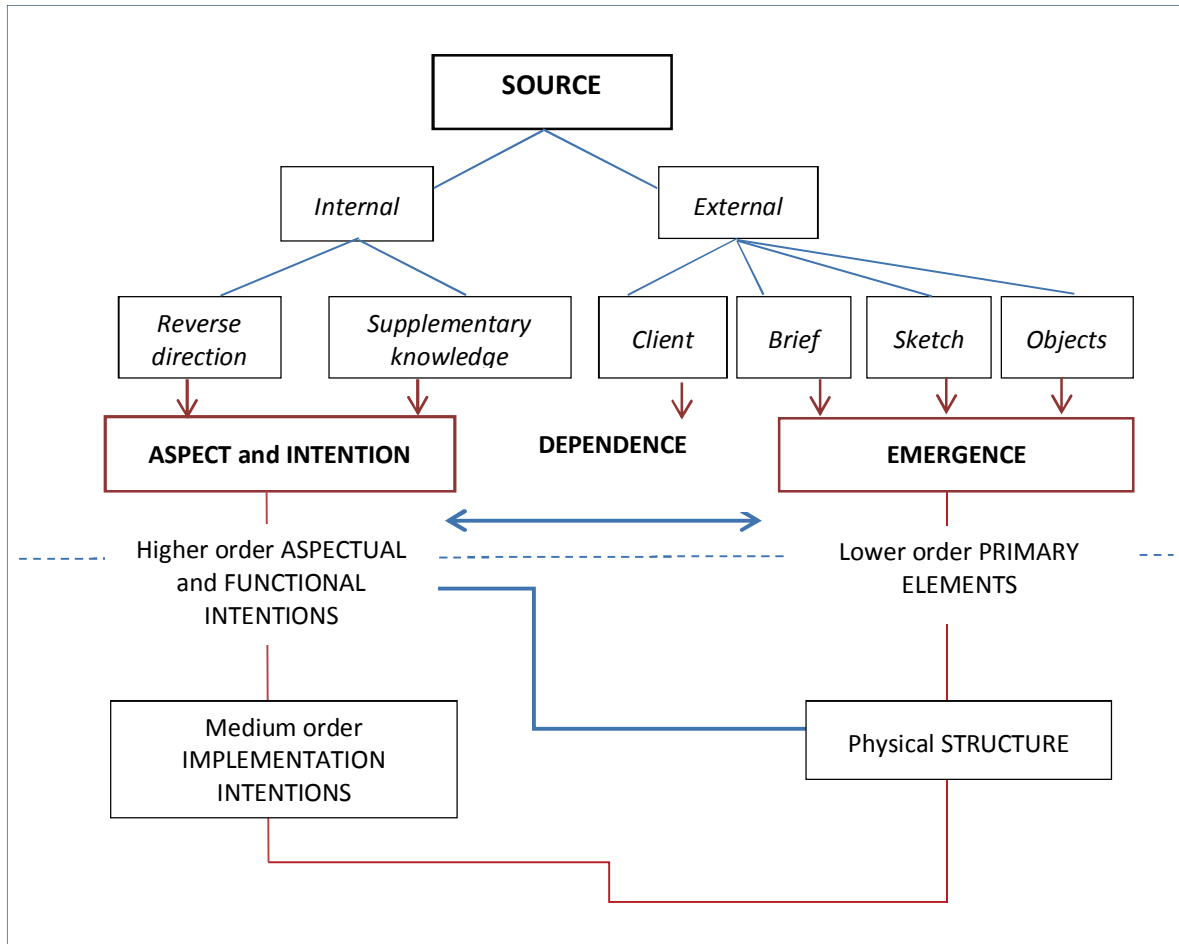
Figure 6.1: Model of synthesis between internal and external processes and sources of information

6.5   THEME 4: CONTROL IN MULTI-DIRECTIONAL THINKING

The fourth theme revolves around the way participants controlled their multi-directional thinking in the design process. Central to this theme are three sub-themes, namely control structure of designers, their vertical couplings of thoughts, and their making and propagating of commitments.

6.5.1   SUB-THEME 4.1: CONTROL STRUCTURE

Control conducting behaviour has traditionally been associated with internal processing (Goel & Pirolli, 1992), which adopts a stance for efficient causality as metaphor to explain how mental incidents affect problem solving behaviour. Such an approach towards empirical design research has, however, not yet offered plausible accounts of how the typified loose control structures (Liikkanen, 2010) of designers interact with embodiment theories that can explain behaviour in terms of perception-action cyclic causality.

The typical psychological understanding of designers' loose control structures supports the notion that expert designers have an extraordinary openness to consider multiple contexts (Goel & Pirolli, 1992; Liikkanen, 2009). Existing literature furthermore widely acknowledges designers' ability to increase considering design elements as part of particular solutions (Cross, 1997; Kim, Kim, Lee & Park, 2007). Controlling one's behaviour in this study therefore does not imply control through restriction, but rather denotes the ability to select and manage multiple options and delay final decision taking. However, instead of duplicating what Goel (1995) found, I extend his theory of loose control structure by connecting it with the role that internal and external sources of information may play in the early phases of the design process. In order to achieve this, I used Goel's (1995) theory to explore what drove this study's participants' commitment and the relationship between internal resources and situational information.

However, taking an interactive approach of perception-action cycles implies that perception plays a role in causality (Kim et al., 2007). Gero and Fujii (2000) have developed a model through the use of situated cognition, which describes the cycles of designers' interpretation of their environment as interconnected sensation, perception and conception processes. In order to explain these cycles in terms of parallel processes, these authors imply data and expectations as possible causes for the actions of designers. No situational studies I consulted thus far, however, connect cyclical reasoning with the loose nature of designers' control structures, which is the focus of this section.

I focussed on how the strategic role of aspectual and functional intentions (Kilgour, 2006) in the interactive Gestalt processes (Arnheim, 1954; Wiegner, 2005) influenced the way in which the participants managed their attention to particular ideas, while discarding others. For this purpose, I searched for vertical coupling among intention-driven events on multiple time scales that allow for the establishment of links between previous and subsequent changes to become apparent (Van Olden & Holden, 2011). The focus of this section, thus, is not to explore self-regulating feedback loops in the perception-action as in situated studies, but rather to explain the way in which various sources of action interacted and established coherence despite the loose control structures of designers.[35]

Based on the quantitative results of this study (Chapter 5), I assumed that the characteristics of personal stopping rules and evaluation functions form part of the mechanism of control structure in terms of Goel and Pirolli's (1992) problem space theory. Therefore I did not explore the particulars of personal stopping rule and evaluation functions and their intersection with control structures. This aspect can be addressed in a separate, follow-up study. The results of

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[35]The converse of 'loose' control structure is 'tight structure', which is typically found under scientific experimental conditions where instructions and other aspects of laboratory control define 'boundaries' that limit the behavioural options of participants (Van Olden & Holden, 2011). Design experiments do not comply with these conditions and as the boundaries provided in design briefs are insufficient and ill-structured, the control structures of designers are loose, giving them much freedom.

this section, originated from the data where the temporal overlaps between these characteristics occurred.

In order to find such information, I searched for the origins of thoughts and mapped the vertical (top-down/bottom-up) direction in which it developed through iteration and transformation. For this purpose I used the coding system discussed illustrated in Photograph 6.1 (see p.236 and Addendum I). I wanted to understand what such a thought and its development depended on, or what the driving force behind a participant pursuing an idea was. If an idea originated in a goal intention (aspectual and functional), I considered its direction as top-down, which meant that the intention drove the continuing acts of iteration and transformation of a participant. If an idea originated opportunistically through the perception of an in-the-moment emerging physical property or element of an object, I considered its direction as bottom up. This would then mean that the subsequent continuing cognitive activities, including forming new intentions (goal and implementation), would be dependent upon lower order emerging elements.

In this section, I therefore consider intentional content contained in references to design aspects, or functional intention, or implementation as a unifying 'whole' when top-down processes were used. In contrast, the idea of bottom-up mental relationships are embedded in embodiment theory that focusses on individuating the specific and detailed information embedded in lower, primary elements such as space, shape and texture (Dillon, 2010), that contributes to forming such a whole. The implication of the bottom-up notion of relationships is that the 'whole' is dependent upon the individual parts (Suwa & Tversky, 1997). In my study, I considered the detail involved in the participants' reaction to individual situational aspects (elements) and the techniques that they incorporated in their designs to achieve their unifying intentional application of selected principle(s). This consideration necessitated my interpretation of the data in order to determine the place and function of each element and technique with regard to one another (Arnheim, 1986).

All the participants engaged in repetitive consideration of particular external elements, which indicated the different combinations of intentions and elements that show commitment. However, participants considered various combinations, shapes and sizes of the physical elements before committing themselves. The different combinations demonstrated loose control structures, which allowed for openness, flexibility and adaptability. All the participants, during their protocols, stated that the ideas they generated and committed to on paper at the end of their sessions were not necessarily the best solutions or only possible concepts that would solve their design problems. They all agreed that, in real life, their ideas would need much more thought and refinement before they could be considered complete. This indicated their regard for the relative size and complexity of the design tasks.

6.5.2   SUB-THEME 4.2: VERTICAL COUPLING OF INTERNAL CONTENT (INTENTIONS) AND COGNITIVE PROCESS

In order to determine the driving forces of participants' conduct controlling behaviour, I examined their vertical transformations. Building on the previous section in which I explained the sources of participants' thoughts (Table 6.2 [p.225], 6.4 [p.229], 6.6 [p.232]), I was able to map the vertical direction of their thoughts. In the cognitive processes of all the participants of my study, I observed (Appendix D and Figure 6.8, 6.9 and 6.10) that their thoughts typically developed in two vertical directions, namely top-down and bottom-up, which corresponds with several design cognition studies, including L. T.M. Blessing and Chakrabarti (2009), Goel (1995) and Visser (2004). Bottom-up processes refer to lower-order elements that facilitate subsequent synthesis into the various higher-order intentions, which I interpreted to be driven by external forces. In contrast, top-down processes refer to people who first form higher-order intentions, which in turn facilitate analysis into lower-order components. As such, I interpreted these processes as driven by internal forces. I had no preconceived ideas about a particular process dominating another, but was rather interested in the dynamics of the participants' moving 'in' and 'out' internal goals and external elements (Kirsh, 2009).

The data I present in this section suggest some degree of interconnection among internal intentions (design aspects, functional intentions) and external elements (physical elements). In all the participants' protocols it was clear that they, in addition to an attempt to accommodate the client's requirements, also participated in interpreting what the actual problem was, that in some cases was different from what the client understood as the problem. This tendency is well documented by various design cognition researchers reporting on the fact that expert designers often interpret design problems differently from the client (Cross, 2007a; Dorst, n.d.; Lawson & Dorst, 2009).

In an attempt to address the limitation of Suwa et al.'s (1998) failure to account for top-down processes, I extended their analysis apparatus to equally focus on the participants' intentions, knowledge and activities. This allowed me to consider the following questions: *which primitive design actions play an integral role in design thinking?, how do these actions play this role,* and *'what is the origin of generated ideas?* I present my observations of the participants' dynamic interaction with their internal intentional states and the external world of their sketches which indicates the top-down and bottom-up directions in which their thought processes developed when intentionally attending to particular aspects of their designs.

Instances of repetitive attention to particular intentions and/or external elements indicated to me the participants' commitment to articulated implementation intentions. Participants' recursive attention to their intentions served as control strategy which drove their generation of

solutions. Consideration of their intentions and/or external elements did not show consistent, steady and linear movements (Cross, 1997; Gero & McNeill, 1998; Goel, 1995) throughout their protocols, but rather indicated repetitive, cyclical and flexible control structures which characterises the sequence in which they committed to ideas.

Repetitive reference to particular lower order external elements (Table 6.1 [p.223] 6.3 [p.227], 6.5 [p.231]) and objects signified the participants' constant interaction between internal knowledge of principles and preliminary commitment to a goal intention and their external task environment. Not generating implementation intentions yet implied that participants needed more external information. The cognitive mechanisms involved during the problem structuring phase were primarily their evaluation functions and control structures, driven by participants' personal taste (Appendix D-Psychology) and domain specific knowledge (Appendix D-Knowledge and Appendix E-statistics). I interpreted the participants' use of particular design principles as the driving force of their actions as part of their personal stopping rules (Goel, 1995).

I modelled the participants' complex and interactive behaviour in the diagrammes by devising five levels that organise particular types of mental activities. These diagrammes are based on my analysis of the sketches of the participants (Appendix H). They were designed to illustrate the different levels of thinking as well as the direction of dependency between higher order internal goals and lower order physical elements based on the semantics of the sketches. I used straight lined connectors to indicate dependency. I furthermore related intentions to their origins in order to emphasise the interaction between internal and external resources and processes. I indicated the connections between the semantics in the sketches with connectors, which at the same time indicate long or short duration of heeding particular thoughts represented by the sketches (Appendix G). I used acronyms, colour and graphic marks, including arrows, connectors, nodes and loops as coding identified in Figure 6.2, which served as key to interpreting Figures 6.3 [p.244], 6.4 [p.247] and 6.5 [p.250].

KEY		

LEVEL	CODE	INTERPRETATION
Level 1		
INPUT* (Code)		
RE-E	Resource External Environment (Site)	
RE-PH	Resource External Photograph	
RI-B**	Resource Internal Brief	
RE-S	Resource External Sketch	
RE-RB	Resource External Reference Book	
RE-PSK	Resource External Previous Sketch	
RE-L	Resource External Lego (in existing bags and boxes)	
RI-LTM	Resource Internal Long Term Memory	
Level 2		
ORIGIN OF GOAL INTENTIONS		
I-1	Client Intentions	
Colour*** aquamarine		
I-2	Reversal of client Intentions by participants	
Colour*** orange		
I-3	Additional own Intentions	
Colour ***blue		
Colours	Link intentions with Levels 3 and 4 to indicate vertical connections between levels	
Level 3		
VISUAL OUTPUT (sketches and writing coinciding with talking)		
NS	New Sketch	
R	Reinterpretation (of previous sketch)	
LT	Lateral Transformation	
VT	Vertical Transformation	
IS	Identical Sketch	
W	Writing	
Nodes and loops	Link sketches horisontally to indicate conceptual links between sketches	
Level 4		
PHYSICAL ELEMENTS meeting with FUNCTIONAL INTENTIONS		
Ph-F	Physical elements'	
Level 5		
PHYSICAL ELEMENTS' PROPERTIES		
Ph-Ob	Physical Object	
Ph-Ob-Pe	Physical Object-People interaction	
Ph-El-Pr	Physical Element Properties	

Background
Levels are graphically separated with various gray tones, which bear no conceptual interpretation apart from visually separating the various levels.
Vertical Gray Arrows
Within the context of the Levels 1-5, arrows indicate approximate time of origin, horisontal duration of vertical direction of thoughts

*I did not consider partners as sources of input as I considered combined pairs or team behaviour as a coherent unity
**For the purpose of this section, I considered the 'Brief' as internal to the design task environment although in previous sections it was classified as an external source when it related to the participants' internal cognitive processing
*** The colours of the connectors originating in Intentions (Level 2) link with Levels 3 and 4 in order to indicate vertical connections

Figure 6.2: **Key for Figures 6.3, 6.4 and 6.5 interpreting direction of the participants' thought processes inferred from its sequence, origin, connection with intentions and interconnections with one another**

This key enabled me to infer the vertical direction of thought processes and revealed patterns of dependency within each protocol. As such, I reserved Level 1 for the sources of participants' thoughts while Level 2 implies the source of higher order functional intentions (including required behaviour of artifacts) modelled on Level 4. Level 5 implies the lower order physical

elements, including primary shapes, sizes and properties of concrete objects. Level 3 represents the sketches of the participants as mode of output from which I deducted transformation of thoughts. Thoughts that originated at Level 2 therefore represent a top-down process while thoughts originating at Level 5 represent a bottom-up process, indicated by the dark grey arrows in the background of the diagrams further on (Figure 6.3 to 6.5 [p.244, p.247, p.250]).

However, each code that I allocated to a particular instance, which indicated the origin of thought, or a directional change, was carefully considered in the context of the participants' protocols. I made use of multiple data sources to validate my coding process as well as the constructs that I dealt with, which is implied in Levels 1 and 2 of Figures 6.3 to 6.5 further on. I combined the classification schedules in Appendix I, which I also used with the coding schedules of the participants' sketches (Appendix H) in order to code Level 3, which refers to the participants' sketches and writing. This combination enabled me to draw connections between Level 1, 'Input' (resources that the participants used), Level 2, 'Intentions', and the visual modes of output, namely sketches and writing. I used a colour coding system which connected particular intentions to particular sketches, functional and physical thoughts. I used graphic connectors to indicate these connections.

In order to find information to code Levels 4 and 5, I once again used Appendix I, which already contained broad indicators of thoughts about functional intentions and physical elements. These indicators assisted me to position nodes on relevant sketches in Level 3 and draw connecting loops between the sketches which shared the same content. The nodes and loops therefore represent iteration and development of particular ideas. I coded the participants' development of ideas as N (new sketch), LT (lateral transformation), VT (vertical transformation) and R (reinterpretation) (Appendix I).

I subsequently refined the codes for Level 5 by using the 'Knowledge' coding sheet from Appendix D. I used the 'conceptual knowledge' sub-category and developed it into sub-sub-categories that indicate conceptual thoughts about objects and object-people-interactions in order to verify the participants' thoughts about functional and behaviour properties of the intended artifacts. When thoughts originated on Level 3, the mid-grey horizontal area on the diagram, I considered the sketch/writing as a physical object, which was then reflected in Level 5. I did not consider Level 4 as representative of origination of thoughts, but rather as a synthesis of thoughts, namely physical objects meeting functional thoughts and could therefore connect with ideas represented in Level 4 (sketches) with physical elements (Level 5), or be connected to Level 3 and Level 2 (intentions) through stimuli from Level 5.

In order to find reliable positions for the large grey arrows in the background of Figures 6.3 to 6.5, I used the verbal output coded in the EXCEL coding sheets (Appendix D). I matched the

spoken words with the relevant sketches where I detected an explicit indication of the origin of thought, namely from the top, which could thus be resourced by the input (Level 1) or intentions (Level 2). I detected thoughts that originated from physical objects (Level 5) by closely watching the video material in combination with the verbal coding sheets (Appendix D). For the purpose of mapping the vertical direction of the participants' thoughts, I thus used sketches that connected sequentially, semantically and syntactically with a directional change as nodes for positioning the grey arrows. When these grey arrows originate from the top, it means that the physical elements at the bottom merely interacted at those points in time. In contrast, when the grey arrows originated from the bottom, the physical elements in its vicinity served as the source of the sketches connected to them.

The process of coding the diagrams revealed some salient patterns across participants regarding input, origins of intentions, number of sketches, connections between thoughts enabled by their sketches, functional goal intentions and its connections with physical elements. In the following sections, I describe tendencies of the participants' vertical couplings of their thought processes.

6.5.2.1 Participants P-A: Mapping vertical coupling of thoughts

Figure 6.3 (see p.244) indicates that Participants P-A did not use any writing (Level 3) apart from two occasions when they calculated scale and proportion (Chapter 5, Photograph 5.1, p.152). For this they used a mathematical formula as symbol system, which correlates with Goel's (1995) theory that designers typically use multiple symbol systems when representing their ideas. They made a total of twenty five sketches that encompassed their entire design process. Of these, twelve were new (Level 3, NS) and one was a reinterpretation sketch (R). One sketch represented lateral transformation, while three sketches pointed to vertical transformation. The semantic connections between the different sketches (Appendix G) signify complex iterative movements between sketches (Level 3 nodes and loops), as Participants P-A considered the various aspects of their concepts. This complexity can be attributed to the architects' habit of making sketches in which they illustrated abstract design principles which they then later used as aspectual intentions, and adapted these in construction and transformations of their sketches. This suggested a constant switch between top-down processes (higher order abstract design principles originating in both their reversed and additional intentions) with mini bottom-up processes indicated by the grey arrows on Figure 6.3 (see p.244). Intertwined with these processes was the seemingly scaffolding role of Participants P-A's case-based sketches (Appendix G) as discussed in Section 6.2.2 and also illustrated in Chapter 5 (Photograph 5.9, p.164), in which they illustrated the design aspects they prioritised, as visualised in Figure 6.3. These patterns of intermittent changes of direction of thought of Participants P-A accords with Dennett's (1995) findings related to computer programs on

designers behaviour. Dennett (1995) furthermore concluded that when perceiving something, designers' process is bottom-up, while it is top-down when expectation-driven.
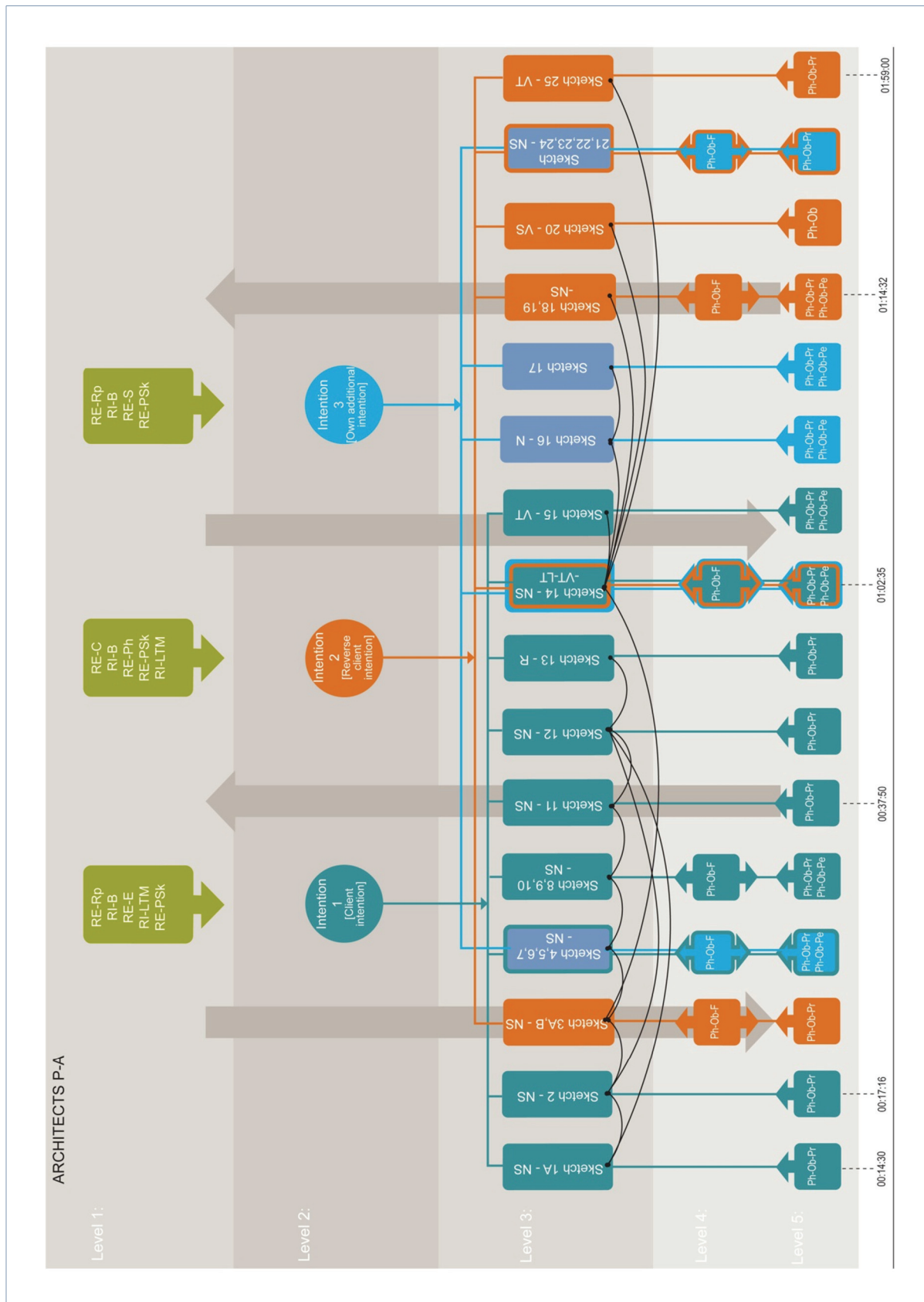

Figure 6.3: **Mapping the vertical coupling of Participants P-A's thought process** (Refer to Appendix J for enlarged image)

When they constructed their sketches (Level 3), Participants P-A generated a total of six functional intentions (Appendix H). Three of these functional ideas occurred during their problem structuring phase (Appendix D-Modules Phases), which indicated that they used their sketches as external scaffolds to understand the intentions of the design task and not to generate solutions. Each of their sketches (Level 3) represents the physical things they thought about and was therefore connected with Appendix I. During their problem structuring phase (sketches 1 to 13, Appendix G), the majority of their thoughts revolved around the physical properties of objects or elements, with a gradual inclusion of thoughts about object-people interactions during the problem solving phase that commenced with sketch 14 (Appendix H).

The overall pattern of the thought processes of the architects showed an equally distributed top-down and bottom-up dependency throughout their entire protocol. Participants P-A considered the client's (researcher) requirements in sketches 1 to 14 (Level 3 and Appendix G), when they terminated to think about it. Sketch 3, consisting of two parts, A and B (Level 3) coincided with their explicit articulation of what they perceived as the functional intention of the theatre that they were required to design by relating this to the shapes and use of a concrete open-air theatre recalled from their LTM (Level 1). During this stage of the process, a clear top-down direction of their thoughts was revealed. This means that they used the intention of the client, as well as their reversed intention in their intentional attention to particular concrete physical elements.

Two functional intentions resulted from their heeding of the client's intentions. On Level 3, Sketch 14 (Photograph 6.2 and 6.3 [p.246]) seemed to play a pivotal role in the participants' thought process. It originated as a new sketch (NS) in the architects' studio. Its multi-layered (physical and conceptual) nature suggested the dynamics involved in its construction and use. This sketch represented thoughts about diverse objects and concepts and originated from all three types of intentions (Level 2), namely the client, their reversal of the transformation direction as well as additional intentions. By closely linking the emergence and conceptual (semantic) development of Sketch 14 with the sequence of their protocol (Appendix D) and the things they thought about (Appendix F, H and I), I determined the various directional changes taking place in the various layers of this sketch.
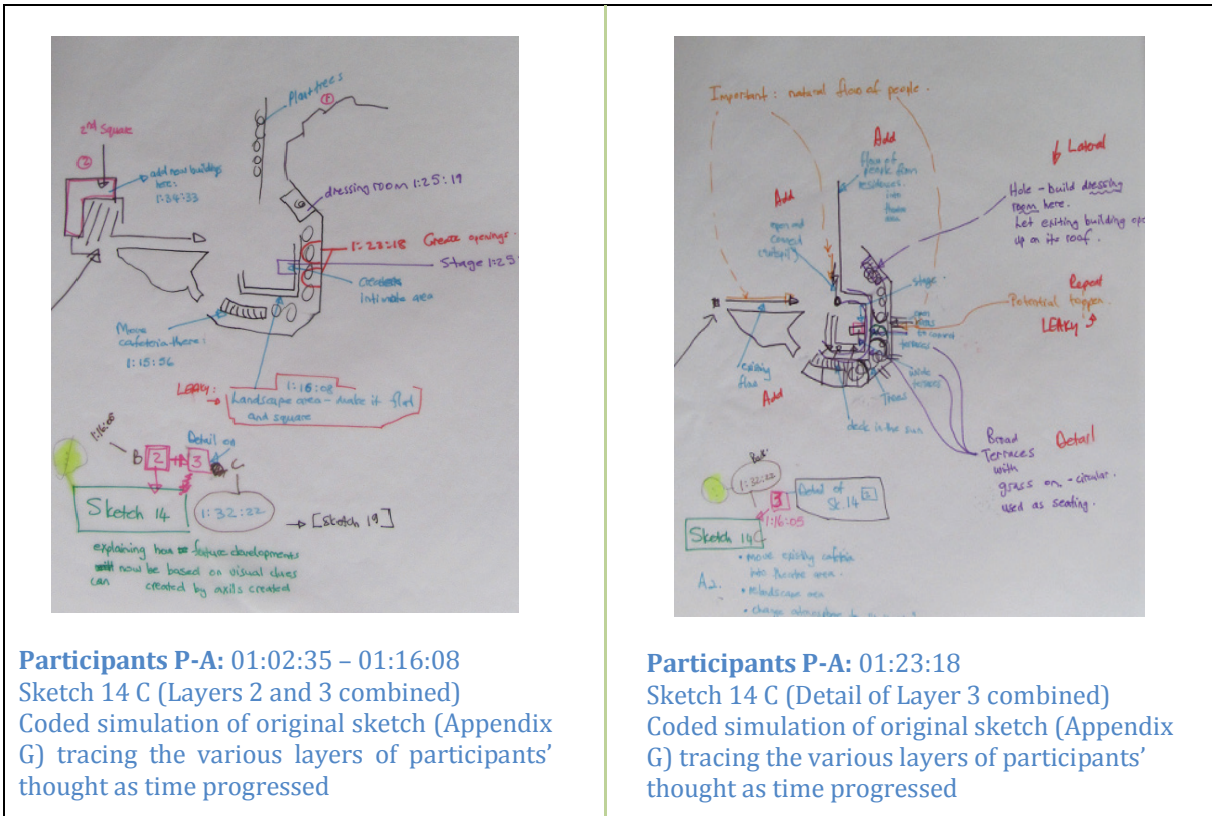
Participants P-A: 01:02:35 – 01:16:08
Sketch 14 C (Layers 2 and 3 combined)
Coded simulation of original sketch (Appendix G) tracing the various layers of participants' thought as time progressed

Participants P-A: 01:23:18
Sketch 14 C (Detail of Layer 3 combined)
Coded simulation of original sketch (Appendix G) tracing the various layers of participants' thought as time progressed

Photograph 6.2 & 6.3:
Coding of Sketch 14 C by Participants' P-A illustrating the complexity of their thought processes

Participants P-A pursued their reversed intentions (Level 2) by referring to it again in sketch 14, and from sketch 18 up to the completion of their task in Sketch 25 (Level 3 and Appendix G). Participants P-A articulated that four of the six functional intentions (Level 4), (Appendix I) for the theatre could be connected with their reversal of transformation (Level 2). Ten sketches (Level 3) resulted from Participants P-A's observance of emerging visual clues that originated in physical elements (Level 5), either from the site, the aerial photograph they used, or previous sketches they made (Appendix I). Interacting with these physical elements visually resulted in their articulation of various intentions additional to what the client required, or what their reversed intentions implied. This means that the conceptualisation and representation of their higher order additional intentions in Level 2 when making these ten sketches was dependent upon them perceiving and paying attention to lower order physical elements, which implies a bottom-up process. I could connect only two functional intentions that they conceptualised to their additional intentions.

6.5.2.2 Participants P-E: Mapping vertical coupling of thoughts

In Figure 6.4, I model the engineers' direction of thoughts and its dependence patterns. This figure captures the salient patterns that I inferred regarding the engineers' interactive behaviour.
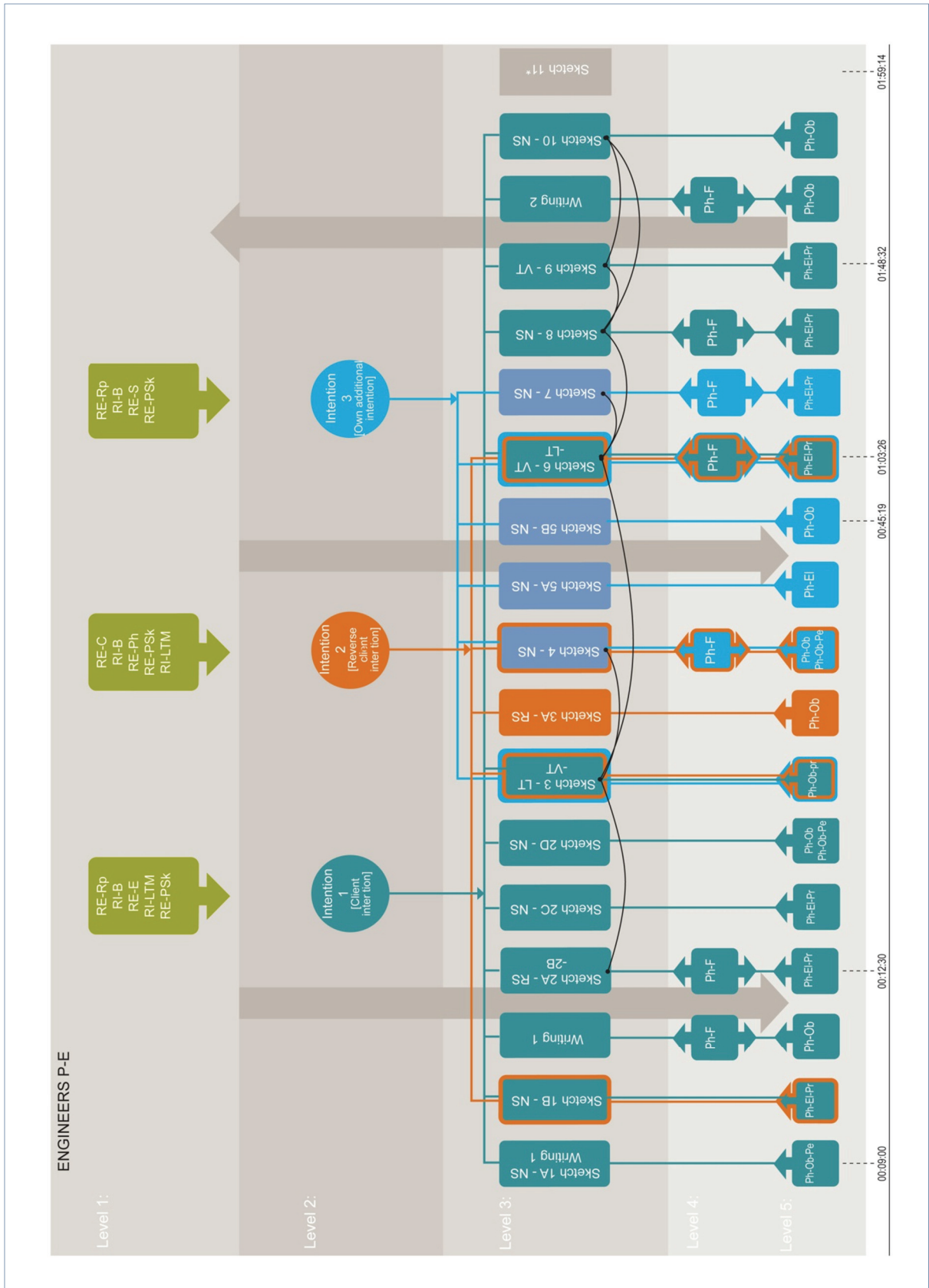
Figure 6.4: **Mapping the vertical coupling of Participants P-E's thought process** (Refer to Appendix J for enlarged image)

Kirsh (2009) found that problem solvers often use alternative ways in the form of external objects or representations to scaffold their thinking. This was confirmed by Participants P-E who

wrote their specifications while they were sketching (Level 3 and Appendix G). They seemed to use these modes of output to scaffold their understanding of the requirements of their design brief. It is widely acknowledged in cognitive literature that designers use their sketches to help them think (Ferguson, 1992; Goldschmidt, 1994; Oxman, 2002). In this regard, Goel (1995) states that designers typically use writing and sketching to alleviate their cognitive load. Vincenti (1990) states that invariably the best visual thinkers are the best designers.

Participants P-E made a total of sixteen sketches (Appendix G and H) that encompassed their entire design process. They made ten new sketches while they reinterpreted two sketches (Level 3). In turn, they made two lateral and three vertical sketches. The semantic connections between these different sketches implied a linear progression in their consideration of the requirements of their brief. In spite of the fact that the majority of Participants P-E's sketches (Level 3) represented physical things (Level 5), they thought about (Table 6.3, p.227) their primary drive was the requirements of their brief (Level 1 and Level 2), which offset a predominantly top-down process. In spite of their dialogue (Appendix D), which suggested that they reacted on what they perceived from the environment, as well as video material that implied much interaction on what emerged from their sketches (Level 3 and 5), Participants P-E's repeated references to the brief's requirements seemed to dominate their own emerging ideas.

Nonetheless, Participants P-E reversed the directions of transformation (Level 2) by questioning the specification of the size of the theatre stage in their brief (Appendix C). They constructed sketch 1B (Appendix H) to judge the size of the theatre. Evaluating it as excessively large, they adapted its size to dimensions of their own subjective choice. This means that their sketches served as an external mechanism that activated their evaluation functions and contributed to their commitment and decision to change the size of the stage to a size they believed appropriate. I found no clear indication that this decision of Participants P-E was generated by domain specific knowledge (Level 2), and I inferred that it originated in their personal experience. Participants P-E pursued this decision throughout their entire protocol, which resulted in a long chunk. Suwa and Tversky's (1996) study has shown how designers' sketches pare thoughts with long duration because of sketches' ability to carry information feeding their decision making processes.

The engineers had four other particular instances in which they reversed the transformation direction (Level 2 and Appendix D-Psychology). These instances were distributed closely to one another and occurred during their leaky phase, while on site. Although the perception of physical elements on site seemed to strongly influence their generation of additional ideas about the inclusion of the existing sculpture in their design of the mechanical objects, they later disregarded this idea on the basis that it fell outside their domain as well as their brief. This is confirmation of their dominant top-down approach (Level 1) to solving their problem.

I found it difficult to identify visual evidence of Participants P-E's consideration of design aspects. I could not distinguish explicit visualisations of their apparent preference for economic design and efficiency, which they explicitly stated and implied in their multiple references to 'simple' design. However, coupled with their multiple sketches which include physical elements, I found evidence of seven functional intentions (Appendix F) by coupling their sketches (Appendix H) with their dialogue (Appendix D-Ecology). Two of these instances occurred during their problem structuring phase when they made case-based sketches (Photographs 6.19 and 6.20). This implied that they used their sketches as external scaffolds to understand the intentions of their design task which was set out insufficiently in their brief. Although I found that the model (Figures 6.4-6.6) is able to implicitly provide rich information about the dynamics of the participants' thoughts in a condensed form, it is limited in the information it provides regarding the distinction between aspectual and functional intentions on Level 2. The refinement of the model at this level could be considered in a follow-up study.

I found Sketches 3 and 6 (Level 3) and Photograph 6.25 of Participants P-E (Appendix H) interesting as they represented complex thought processes. In Figure 6.4, I traced the input sources (Level 1) of these two sketches, as well as the physical elements (Level 5) that the engineers included in all three sources of intentions (connection between Level 1 and 2). This simultaneous drive from their internal and external resources suggested the alignment of their coherent Gestalt. This furthermore implied that Participants P-E considered physical properties of elements from various points of view. It seemed that this assisted them to generate both lateral and vertical development of ideas (Level 3).

6.5.2.3 Participants P-I: Mapping vertical coupling of thoughts

After coding the participants' sketches and writing (Appendix H), I grouped their sketches semantically and selected ones in which a common idea was being pursued. As a result, I used a total of thirteen sketches (Appendix G) to construct a model visualised in Figure 6.5. Of these sketches, I classified three as new, two belonging to the reinterpretation type, four as vertical transformations and three as identical sketches. The semantic connections between the different sketches illustrated how Participants P-I systematically progressed and considered their combined ideas as modelled in Figure 6.5.
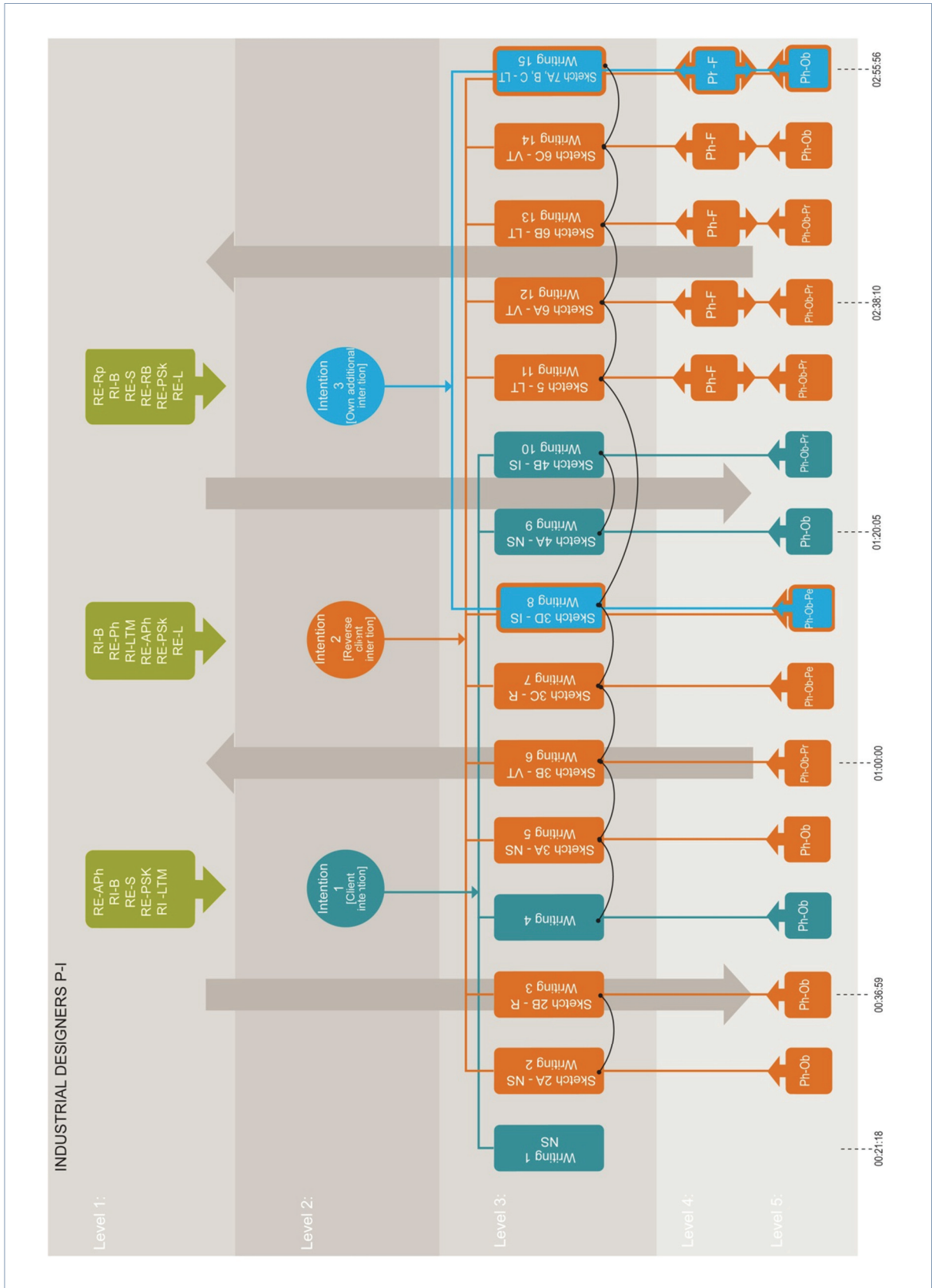
Figure 6.5: **Mapping the vertical coupling of Participants P-I's thought process** (Refer to Appendix J for enlarged image)

From Participants P-I's sketch behaviour, I inferred a combined progression of thought processes that encompassed all team members throughout the entire combined protocol.

Participants P-I had a distinct style of working that was markedly different from the engineers and architects. They started with writing (Level 3) the requirements of the client's brief, articulating its intentions (Level 1 and 2) in all the sketches relevant to their vertical map (Figure 6.5), Participants P-I combined writing with sketching. Writing thus seemingly played an important role in Participants P-I's process. One participant (Brian) drew tables in which they weighed up advantages and disadvantages of their ideas (Appendix H, Participant P-I [Brian] Writing three) as represented in accompanying sketches. These tables seemed to play a significant role in organising their thoughts and combining different elements in the accompanying sketches when the participants made their choices. Another participant (Adrian) made notes suggesting the intended functions of artifacts and how they could be used. In this way, sketches and writing complemented each other and structured the participants' thoughts. Their repetitive use of writing further seemed to clarify their thoughts. Writing allowed for interactive problem solving, continuously changing the direction of Participants P-I's thought processes, which supports Goel's (1995) argument that designers require multiple symbol systems when designing.

The dynamics involved in Participants P-I's interactive use of vocal, visual and written modes of output was furthermore evident in both their problem structuring and problem solving phases. Their top-down procedure (Level 2) resulted from the early reversal of the direction of transformation (Level 2, Appendix D-Psychology), which is represented in the map by its continuous influence on almost all Participants P-I's sketches. The orange colour in almost all the sketches and connectors between Level 2, 3, 4 and 5 depicts this influence. The intentions that the participants articulated during this reversal (Sketch 2A, Level 3 and Appendix H) were pursued to the end of their protocol. Although this behaviour suggested a top-down dominant process for Participants P-I, the details regarding the origins of their thoughts (Level 1 and 5) indicated a constant change of direction. I found four distinct instances where major change of vertical direction took place. This is represented by the grey arrows in the background of the map. Changes from bottom-up to top-down decisions were visible in the thoughts represented in sketches 3D to 7A (Level 3, Appendix H), which originated in their commitment to particular physical objects (existing boxes and plastic bags), (Level 5). In turn, these commitments were stimulated by their perception of the real objects and the constant presence of the Lego™ in the studio (Chapter 5, Photograph 5.11, p.168), which confirmed the direction giving ability of external objects, as also indicated by Dennett (1995).

Intertwined with these commitments were Participants P-I's articulation of functional intentions (Level 2 and Level 4) of selected physical objects (Level 5) in terms of their interpretation of the need of the client (Level 1). Earlier in their protocol they only thought about the physical properties of the objects that they depicted without relating them explicitly to any functional

intentions. This can be seen in their map when viewing the left bottom part of the map which lacks items on Level 4. The tendency of attending to physical properties first (and not to functionality), is well documented in studies by Suwa and Tversky (2003), Goel (1995) and Gero (1998). To me, this showed that Participants P-I did probably not commit to any of these physical elements until they constructed Sketch 5 (Level 3), where inclusion of functional items occurs for the first time on Level 4. The construction of this sketch seemed to mark a distinctive instance of commitment and development of a particular solution (Appendix H). This behaviour also signified Participants P-I's loose control structures, and their need to keep their options open until relatively late in their decision making process.

Participants P-I started their process in a top-down manner by writing the requirements of the client's brief, articulating its intentions. While considering an aspect specified in their design brief, they started making a series of sketches that represent their understanding of the brief's intentions, while immediately including written evaluation of the ideas implied by their sketches. This procedure resulted in Participants P-I's early reversal of the direction of their transformation. The intentions that they articulated during this reversal (Sketch 2A) were pursued right to the end of their protocol. Although this behaviour of Participants P-I suggested a top-down dominant process, the details in the sequence of their activities indicated a constant change of direction.

6.5.3 SUB-THEME 4.3: MAKING AND PROPAGATING COMMITMENTS

According to Goel and Pirolli's (1992) theory of problem solving, making and propagating commitments can be seen in the variety and quality of modes of output of designers during the early phases of the design process. In Chapter 5 (Section 5.6), I provided evidence of the modes of output together with a discussion of the quality of the sketches and the nature of their marks that accompanied the participants' verbal statements. In consideration of the context of each such instance, I attempted to determine the dependency relationship within intentional modules and statements. The entire design process of all the participants consisted of many dependency chunks. This sub-theme entails two categories, namely verbal commitments and visual commitment.

6.5.3.1 Category A: Verbal commitments

In this section, I extend on Goel's theory and propose an additional way in which to study the way experts make commitments and propagate them, by considering the semantics in the verbal

statements that contain evidence of implementation intentions.[36] Although I found literature dealing with implementation intentions in organisational psychology (Brandstatter et al., 2003) and language studies, I could not find design cognition studies that focus explicitly on the connections between implementation intentions and other functional intentions. I therefore aim to introduce implementation intentions to the research arena of design studies in the discussions that follow.

Implementation intentions refer to those intentions in which people declare activities that they think may assist them in achieving other goals (Gollwitzer & Schaal, 1998). Through the interpretation of the information contained in the incremental development of their ideas, I based my interpretations of implementation intentions of the participants on intentional theories in cognitive science that differentiate between goal intentions and implementations (Dewitte et al., 2003; Gollwitzer & Schaal, 1998). Whereas goal intentions operate on the strategic level ('I intend to achieve A'), implementation intentions operate on the planning of execution level ('I intent to achieve A by doing B'). The condition for qualifying as an implementation intention in this context was that the 'objects' referred to had to be the object or system the participants designed, and not an existing object, unless the latter was incorporated in the current design. The distinguishing feature of implementation thoughts is the reference to an activity, for example, 'you can "put" the truck here, and you "transport" things here, you "put" your stuff in the container and "take" the container back' (refer to Tables 6.1, 6.3 and 6.5 for lists identified from the protocols). It did not fall within the scope of this study to investigate the long-term effect of implementation intentions on the quality of the end results of the participants' designs.

In consideration of the hierarchical thinking of the participants as discussed in section 6.2, I asked the following questions: *what is the relation between implementation statements and higher order design aspects and functional goal intentions?,* and *what self-regulatory role did implementation intentions play in the participants making commitments?, which constraints did the participants identify?* and *how did aspects assist them to circumvent constraints?*

Answering these questions implied that I looked for evidence of associations between making commitments and propagating them, personal stopping rules and evaluation functions in the verbal utterances, and accompanying sketches and writings of the participants. I individuated implementation intentions by establishing where making commitments, within the psychological characteristics data set (Appendix D-Psychology), intersected with functional intentions (in conceptual knowledge), personal stopping rules, control strategies, and evaluation

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[36]While implementation intention is not a new psychological characteristic of general problem solving behaviour to be studied, it has recently reappeared in the literature of cognition, asking questions about how problem solvers' external situations influence their articulation of intentions and their subsequent effect on the success of goal attainment (Brandstatter et al., 2003).

functions (Tables 5.8 to 5.13). I did not plan on focussing on implementation intentions as a separate category when initiating my data analysis, while I interpreted the previously discussed themes in this section. However, I became aware of the potential of exploring 'implementation intentions' as cognitive element in design reasoning for expanding current philosophical studies in the dual nature of technological artifacts, such as studies by Kroes (2002).

a)　　　　Participants P-A: Implementation intentions meeting verbal commitment

Making and propagating commitments seemingly emerged from the participants' environment. Participants P-A generated an idea during the problem solving phase, which was triggered by their perception of the parking area on the campus, close to the theatre site. Participants P-A connected their prioritised spatial design aspect to the possibility of reusing the existing parking space. Their implementation intention that the parking space should be moved in turn lead to their insight into where to place the 'unwanted' sculpture. This implies that the connection between the aspectual and implementation intention involved in one particular sub-solution opened possible solutions for the use of other non-related physical elements. Basden (2000) explains this opening up of opportunities through the consideration of aspects as a characteristic of aspectual thinking. I take this explanation one step further and connect it to Arnheim's (1969) position on abstract thoughts. On the basis of his proposition that designers have kernels of pictures of abstract ideas in their minds, I argue that the participants in this study connected these pictures in their minds with external opportunities emerging from the environment, which enabled them to generate meaningful in-the-moment ideas.

Excerpt 6.37 demonstrates how engagement with physical objects, which the participants could manipulate on their sketches, contributed to finding a solution to the sub-problem of what to do with the sculpture, which did not transgress the client's (researcher) requirement that the sculpture should be incorporated in their theatre design in some way.

Excerpt 6.37

> ANDREW 00:38:55
> I think one can create this, because the entrance from below, where the sports field is.

When they solved the sub-problem of creating an open space by moving the parking area, Participants P-A's cognitive load seemed to be alleviated and freed them to shift their attention to one of the requirements they set themselves, namely to create an intimate theatre. They connected this social aspect to the functional intention of bringing people closer to each other. In addition, they committed to a way of implementing these intentions by connecting operational concepts with physical elements, as demonstrated in Excerpt 6.38.

Excerpt 6.38

> ANDREW 01:17:11
> Yes, and another thing about this, is to do this. Jonathan, you know what we will do? We move these things forward, exactly what you did there … bring them closer to each other. This is how we now create an intimate space that I talked about here. Because, if you want to have so big that everybody must be accommodated, and this guy sits there at the back, then he will in any case hear the music.

Another example of how Participants P-A's solution to one sub-problem lead to the solution of another, thus creating cycles of problem solving, is demonstrated in Excerpt 6.39. A series of fast flowing implementation ideas by Jonathan followed directly after Excerpt 6.38, while Participants P-A were paying attention to their sketches on the transparency that covered the aerial photograph. Based on the repetitive cyclic patterns of generating solutions to sub-problems through articulation of implementation intentions, I believe that implementation intentions can be considered as facilitators of internal processes, as much as external structures can mediate transformation. This implies that transformation processes are not only mediated by external structures, but may also be facilitated by internal connections between mental states (implementation intentions) and physical elements already committed to.

Excerpt 6.39

> JONATHAN 01:17:32
> You see, what one should also do now, one should actually, what you actually want, is for people to pass and also see what is going on at the back, not only at the front. So, actually this thing should work to the other side. Maybe one should emphasise this avenue from here on, and then you put in trees here so that a more intimate … Then you walk down here, and you look in that direction. It actually works the other way around from what I have sketched here. Then you also do not look into the sun, as we have said. Then the stage is here, and then we can still hide those buildings behind, in the hole, or whatever. There the stage is now. And then that sculpture should actually be in this corner - then this corner becomes something like a public speaking …

The specificity of the information contained in Excerpt 6.39 constitutes multiple connections between various functional intentions, physical elements and implementation intentions, which culminated in participants 'seeing' what to do with the sculpture that constrained them. This episode lead me to conclude that internal perception is as much a part of designers' neural substrates of visual experiences as external perception, and therefore plays an equal role as bearer of mental content and externalised perception in the form of sketches.

b)   Participants P-E: Implementation intentions meeting verbal commitment

I observed similar trends of implementation intentions that played a facilitating role in Participants P-E's making and propagating commitments, as those found in the protocol of the architects. An example of an implementation intention by Participants P-E is demonstrated by Excerpt 6.40. The participants added detail in terms of physical objects and connected it to an

implementation intention. They internally visualised how to organise and use the objects to achieve their functional intention, in this case the provision of a system or artifact that would give access to stage props and offer storage possibilities.

Excerpt 6.40

EDWARD 01:12:22
If you stand here … and you can put the truck here, you transport the things from outside. Then this is sort of a permanent fixture – and you transport things here, and when you're finished, you put your stuff in the container and take the container back.

Participants explained how they envisaged incorporating a sound system in their platform design without having to erect a separate structure. As such, they would implicitly achieve the economics aspect, as represented in Excerpt 6.41.

Excerpt 6.41

EUGENE 01:19:14
Especially not that side. This side – you will almost have to cut it level – so that it is only horisontal. Then it may show a little on that side. Just lift it a little so that your speakers show somewhat.

Excerpt 6.41 demonstrates how Participants P-E developed detail of the mechanical part of the platform design that they articulated, showing how they would ensure the functional intention of rotation, which confirmed their commitment to the requirement of the client. Additionally, their reaction to the visual information provided by their accompanying sketch (Appendix G) seemingly helped them to see an opportunity to add the electric box on the floor of the platform. They connected this possibility with functional and implementation intentions by providing an additional physical element, namely a pillar. Making such connections was also found in studies by Brandstatter et al. (2003), which they conducted in an organisational education context.

I interpreted the repetitive use of the word 'simply' as indicative of the participants' (Appendix G, dialogue 01:46:50) consideration of the implementation as easy, and not as a complex process, which also aligned with their aspectual idea of economic design. Participants P-E used the visual and conceptual cues that their sketches provided, and connected these with their procedural knowledge, as illustrated in a diagram that they drew of their design process to formulate their conclusive implementation intentions (Appendix G). Participants P-E furthermore considered the successful integration of the architecture involved in the theatre design and the implementation of their engineering task, to which they committed, as captured in Excerpt 6.42.

Excerpt 6.42

EUGENE 01:45:15
So... what we say is basically – where is that picture of the phases? ... Here ... the interface with the architect – there are two things: we say there are two things: we need a path. He must give us access ... And it can be very simple. Two rails, or so ... that's good enough .... And then Edward said .... One can .... That is an option we have ... Then he can repeat the pentagonal structure on the platform and build a frame. And then, we build the rotating platform inside the frame - in such a way that the edge of the frame is on the narrow side – together with – you know – against the edge of the platform. Then he can build such an angular structure – there – if he wishes – with the platform that rotates inside.

c)   Participants P-I: Implementation intentions meeting verbal commitment

Participants P-I's commitments materialised in the way that they verbally articulated their internal visualisation of implementation and aligned them with their aspectual intentions. I noted that their interactions between verbal and visual articulation of implementation intentions stimulated them to such an extent that they considered expanded functions and incremental addition of detailed physical elements. In Excerpt 6.43, Participants P-I imply the interaction between sketches and implementation intentions. They connected the spatial aspect implicitly with their functional intention of physical objects, namely standard found boxes, which they intended as storage system.

Excerpt 6.43

BRIAN 01:20:05
... And because it has also goes into the car and uhm ... Here is then a trolley with standard boxes that fit into each other on top of the trolleys. So we can fit a lot of boxes on the single trolley. It could be very skinny or flat, so it has a folding handle it could slip into a small space like a car.

Excerpt 6.44, from Participants P-I's protocol, contains operational words, ('take it... put it into the car, take the car, pull bag out...') explicating how the participants intended to implement one of their suggested ideas for storing and managing Lego™ used in educational situations.

Excerpt 6.44

CLINT 01:50:55
Ja, I've got a bag, take it ... bag, put it into the car, take the car to the venue, pull the bag out, open it up and it's there, and, and ... physically identify all the little bits that is the components. The students can access them, they can assemble - they can have their assembly assessed and they can put it back to where they got it.

This finding extends Goel's (1995) theory of 'incremental development of solutions' in the problem solving space of designers. Goel (1995) found that statements supporting the thinking about adding ideas and detail, take place through repetitive revisiting of ideas. However, he did not distinguish between implementation ideas and functional intentions. The value of individuating implementation intentions for this study was that it assisted a fine calibration of

the analysis of intention-attention instances. In addition, it provided information about the incremental development of the participants' solutions, and their expert ability to visualise how they intended their envisaged artifacts to function effectively in various contexts.

Acquiring an understanding of the overall structure of the participants' design process as discussed in Chapter 5, it became evident that the participants' design processes proceeded in cycles. From attention to aspectual intentions, their mindfulness to functional intentions followed. Intertwined with these internal engagements, they explored conceptually related ideas. When they reached a stage of either temporary or final exhaustion of a particular functional intention, they turned to another intention.

6.5.3.2   Category B: Visual commitments

Sketches as structural objects can be considered as extensions of designers' knowledge and intentions, not because of their functional equivalence, but rather because of their distinct symbolic characteristics which are explained in Chapter 2. At the same time, sketches function as a mediator of transformation of mental states when involving designers' making and propagating of commitments[37]. The purpose of this section is to explore the relationships between internal content and sketches as bearers of such content and their external transformational functions as introduction into the area of design studies.

In this section I thus integratively discuss the use of multiple symbol systems and how the construction and manipulation of visual models were used by the participants not only to arrive at, but also to assist them in the articulation of their implementation intentions as signs of their commitment to ideas. Sketching as an external act while talking is considered as a sign of relative commitment to an idea during design work, as is writing. Commitment is also believed to be demonstrated through the number and nature of marks accompanying verbal statements, which suggests the seriousness of the commitment (Goel, 1995). In the light of this theory of Goel (1995), I considered sketches that contain more marks than others as indicative of commitment. I derived the results of this section from the syntactics of sketches made by the participants.

From the sketches of the participants that supported their vocal utterances, I inferred their cognitive function in facilitating participants' development of their ideas. This finding is confirmed by design researchers including Goldschmidt (1994) and Oxman(2002). The marks made by the participants, irrespective of the degree of vagueness or specificity (Goel, 1995), served as memory aids (Larkin & Simon, 1987; Shani, 2012) that supported their thought

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[37]Rowlands (2006) explains the concept 'dual-component interpretation' of vehicle externalism, which seems closely connected with Mitcham's (2002) and Kroes' (2002) notion of the dual-nature of artifacts.

processes at different stages in the design processes. From the excerpts and figures included here, I could deduct the close and intricate coupling of internal visualisation knowledge, conceptual knowledge, procedural knowledge, intentions and external sources of information.
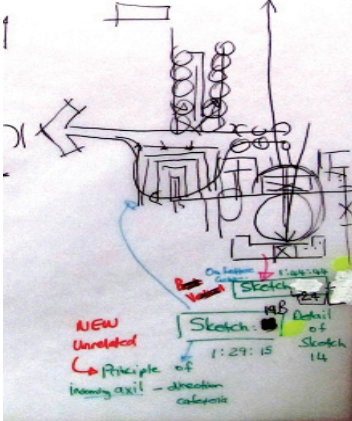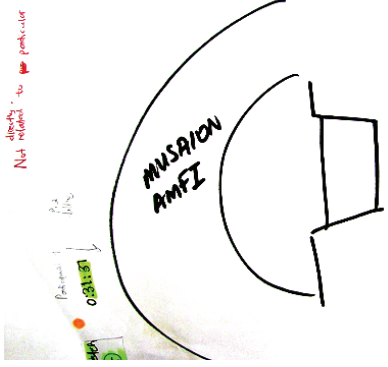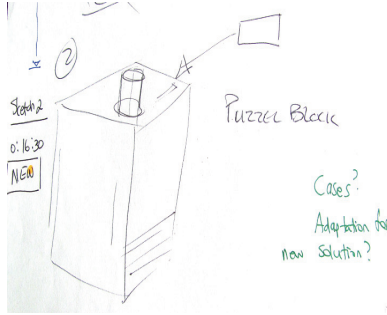
I found that the participants used primary physical drawing elements, including line, shape, form, tonal value and texture to depict objects, or visualise an object's ability to hold or contain something. Their rough sketches seemed to depict how something was weighed, stored and transported. Some sketches expressed 'atmosphere' or provided visual cues to users interacting with space thereby serving as one of the salient bridges between lower order primary elements and higher order intentions. This finding is in line with Goodman's (1976) theory of pictorial notational systems, which he views as being equally informative about thoughts and intentions, rather than verbal symbol systems. I furthermore found that the participants' sketches served as cognitive building blocks that scaffolded the transformation and development of their ideas, as also supported by interactivity theorists such as Kirsh (2009). This function of sketches can be attributed to the external nature thereof (Suwa, Gero, et al., 1998), which affords emerging information about the physical and functional nature of envisaged artifacts in the context of the in-the-moment problem it should solve.

Based on the theory (Shani, 2012) that sketches are simultaneously instantiating and transforming, I used Goel's (1995) suggestions to analyse the syntactics and semantics of both verbal and pictorial data generated by the protocols of the participants. I was able to detect the different cognitive phases in which the participants were at different stages. I was also able to determine what the participants committed themselves to and what not. My analysis of them making and propagating commitments indicated that the participants directed their commitment to different things and in various degrees of specificity when structuring and solving problems.

In the case of the sketches, I examined syntactic quality in terms of vagueness and ambiguity in order to provide information regarding participants' commitment levels. The less ambiguous and vague sketches were, the higher I considered their levels of commitment (Goel, 1995) and the closer they were to declaring their intentions. I classified the sketches of each participating team into categories of case sketches, figuring sketches, principle sketches, idea generation sketches, development and detailing sketches[38] (Appendix H). Making case sketches, the participants relied on their long term memories of similar previous designs. These sketches contained embodiments of physical properties of artifacts by using primitive physical elements, including shapes, spatial relations, combination of elements, textures, as well as the functions of

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[38]See Appendix H.

objects or elements. All the participants made use of case sketches for the duration of the protocols, as captured in Photograph 6.4, 6.5 and 6.6.

Photograph 6.4	Photograph 6.5	Photograph 6.6
Participants P-A Sketch 19: 1:29:15 Case sketch of parts of another campus. The purpose of the sketch was to illustrate the principles of hierarchy of buildings and visual axis. This sketch was made while working on Sketch 14.	**Participants P-E** Sketch 4: 0:31:37 Case sketch of an existing open air theatre. The purpose of the sketch was to understand the concept 'open air theatre' for which they had to design a rotating platform.	**Participants P-I (Adrian)** Sketch 2: 0:16:30 Possibly a case sketch of a 'puzzle box' storage/ educational object. I was unsure if they referred to a specific case. The seeming purpose of the sketch was to experiment visually with the concept of 'storage device' required by the client

Photograph 6.4, 6.5 & 6.6:
Case sketches drawn by the various participants while interacting with external elements in their design task environments

I considered the development and detailing of sketches as visualisation of increasing commitment. Together with ideas that were written down in the form of requirements or specifications, and the number of repeated instances, I counted the number of sketches in the broad category of commitment graphics. Moving from problem structuring to problem solving through multiple leaky phases, the sketches showed progression in the number of semantic details, which participants added to their sketches. This result correlates with Goel's (1995) finding that the external syntactic qualities of the marks participants generally use correlate with the structure of their thoughts. This furthermore demonstrates that participants' reluctance to make final decisions was seemingly represented by lack of precisions in their sketches. It follows that such reluctance to represent their commitment to decisions was in synergy with their openness and flexibility. Such behaviour is explained by Goel (1995) as a result of expert designers' loose control systems, which Liikkanen (2010) considers as typical in design problem solving.

a)   Participants P-A: Visual commitment to implementation intentions

Participants P-A visualised their commitments in interesting ways, characterised by their strong sense of Gestalt. Excerpt 6.45, which occurred during a leaky phase, demonstrates Participants P-A's metacognition regarding their own understanding of the importance of consciously focusing on design aspects (a philosophy) before generating ideas, as they explicitly articulated their consideration of the social meaning theatres could have. On its own, this articulation can be seen as an implementation intention – declaring their reasoning strategy. They further made a clear connection between design aspect (social), functional intention and physical elements, as demonstrated in Excerpt 6.45.

Excerpt 6.45

JONATHAN 00:55:40
See, I think, hey, before one make a mark on paper, one should …
ANDREW 00:55:49
Find a philosophy behind the thing.
JONATHAN 00:55:57
Actually to debate, where does this come, how is a theatre used, where does it come from and where is going to. You know, exactly what talked about this morning. Does a theatre today still work as in the olden days? The one guy that we all look up to or is it now completely interactive, or is it, how does it work? Nowadays you get mobile theatres also. Trucks that drive in, then the truck's side flips open and that is then the stage.

To me, this association confirmed the bottom-up dependence of intentions, irrespective of the duration of the chunks in which they occurred. Internal pattern recognition seemed to play an important role in Participants P-A's thought processes. It was primarily based on internalised knowledge of the architectural history of theatres, as implied in Excerpt 6.45 and which can be connected with Participants P-A's Gestalt (Kieran, 2011) use of the social design aspect. In order to compare the new situation of modern theatre concepts to historical uses of theatres, and the physical properties that fulfilled different concepts' needs, knowledge of patterns that can embody such fit for purpose is required. As such, internalised pattern recognition seemed to play an important role in Participants P-A's connection to the social aspect of theatres, their functional intentions and physical elements. The external tokens in their sketches (Photograph 6.14 [p.266]) apparently facilitated their internal recognition of the applicability of previous solutions (fashion ramp idea combined with the concept of interactive theatres) in their design problem.

By visually articulating their implementation intentions, Participants P-A portrayed the kind of physical shape and proportions expressing potential 'intimacy' as well as sufficient seating for the required thousand people. However, the shapes that Jonathan drew were arguably ambiguous, using rough and thick marks, with little detail. I could only interpret the marks by studying the sequencing on the video material together with an examination of the verbal

utterances made at the same time. The necessity of studying supporting research data to assist researchers in deconstructing designers' sketches in the early phases of the design process was also reported by Gero and Kannegieser (2006).

The sketch in Photograph 6.7 (see p.263) represents the primitive basics of the physical characteristics of Participants P-A's intended theatre. They used ambiguous lines and shapes that indicated the broad concept and proportions of the whole theatre. No detail regarding the shape and exact layout of the terraces is apparent in this sketch, which could embody their functional or implementation intentions, and it is debatable whether any of their aspectual intentions could be derived from this sketch. However, the participants used arrows that indicated the intended direction of the audience in terms of the stage, vaguely suggesting an implementation intention. Suwa et al. (1998) also found that architects use graphic marks, such as arrows, to enhance the communication of their ideas in their sketches, without which it is impossible to interpret. The ambiguous marks suggest the vagueness of their idea of terraces that provide seating for the audience as required by their brief.

In contrast, Photograph 6.8 (see p. 263) suggests how Participants P-A visualised a clearly conceptualised implementation intention. They propagated a commitment to the way individual terraces' shape and proportions should achieve their functional intentions. In Photographs 6.8 and 6.9 the participants' increased attention to detail of the intended terrace and the unambiguity of its shape suggests their commitment. They apparently used the concept of an inclined plain and transformed it into a functional object that could provide seating. Although still somewhat ambiguous in shape, Participants P-A's commitment to the terrace idea is suggested by the addition of vague shapes of human figures sitting on the terrace, while keeping in mind the ergonomic proportions. The implication of this is that visual symbol systems are able to express implementation as well as functional intentions, which extends Goel's (1995) theory of symbol systems. In addition, I argue that the participants were able to visualise their ideas unambiguously once they committed to implementation intentions.

Photograph 6.7	Photograph 6.8
Arrows suggesting audience's viewpoint	
Participants P-A Sketch 14 (detail): 01:02:35 Propagating commitment to spatial relations of the basic elements of the theatre. Conceptual sketch indicating where terraces in relation to rest of theatre will be	**Participants P-A** Sketch 15 (Detail): 01:07:07 Propagating commitment to shape of terrace. Developing the idea of terraces by enlarging it, adding specific shape to it. Clear, unambiguous shapes and lines correlate with clarity of their idea in mind.
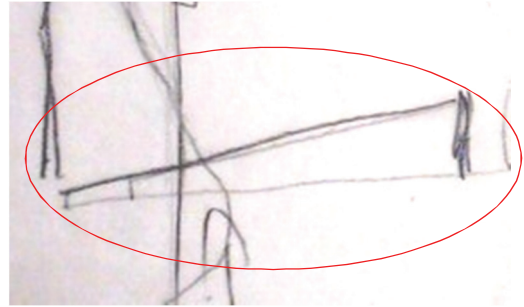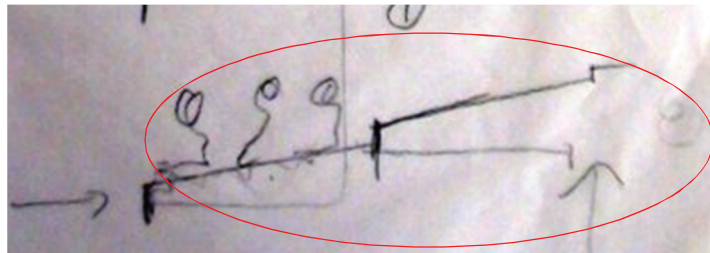
Photograph 6.9
Participants P-A Sketch 15 Detail: 01:07:07 Commitment to shape and proportion: Clear detailing of idea of people seated on concrete and grass terraces, proportion and shapes taking on specific form

Photograph 6.7, 6.8 & 6.9:
Participants P-A's commitment through visualisation developing from ambiguity to specificity

b)   Participants P-E: Visual commitment to implementation intentions

Photographs 6.10 to 6.13 demonstrate how the engineers committed themselves visually to their implementation intentions. It is apparent from these sketches how they transformed vague and ambiguous shapes, such as triangles and rectangles interchangeably (6.10 and 6.11), which is in line with what Goel (1995) found. However, as they focused on the platform and considered the mechanical system that could make it rotate (implementation intention), their ideas became clearer and subsequently their sketches became less ambiguous, as demonstrated in Photographs 6,11, 6.12 and 6.13.

Photograph 6.10	Photograph 6.11
Participants P-E: Sketch 3A 01:03:16 **Plan view of generating** idea of platform using ambiguous and unspecified shapes to represent the parts enabling rotation.	**Participants P-E** Sketch 7 01:36:07 **Vertical** development showing detailing of working parts inside the rotating platform
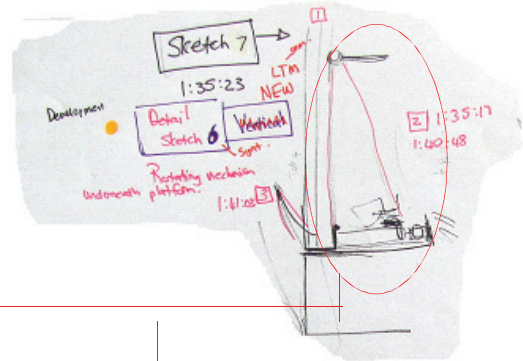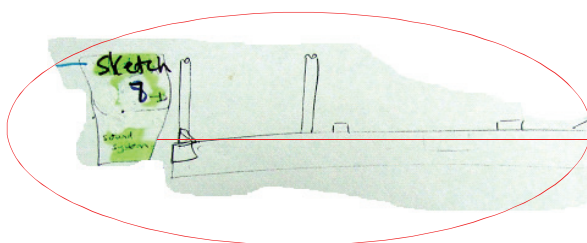
Photograph 6.12	Photograph 6.13
Participants P-E: Sketch 8 01:27:42 **Side view of sketch in 6.10 showing specifics of** the idea of the platform accommodating specific elements such as speakers for sound and a centre point from which rotation should take place	**Participants P-E** Sketch 9 01:36:07 **3-D front view of detail showing vertical** development of idea of 'sliding ring' providing the horisontal rotational movement of the platform
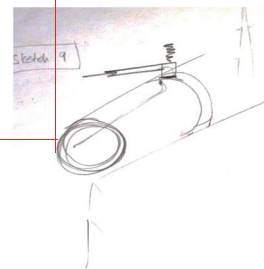
Photograph 6.10, 6.11, 6.12 & 6.13:
Participants P-E's commitment through visualisation and transformation

c)   Participants P-I: Visual commitment to implementation intentions

In Photograph 6.14 to 6.16 (see p.266), the sketches and notes written by Brian demonstrate the industrial designers' commitment to their idea of adapting the existing storage and management

system consisting of boxes, by changing the sequence of events and involving students to help lecturers manage their use of Lego™. Their sketches suggest the participants' understanding of educational procedures where students participate in the control and management of the Lego™ that they will use as learning aid.

Brian's additional use of writing suggests his aspectual considerations of economic design, which is not visible in the sketches captured in Photograph 6.14 to 6.16 (see p.266). The vague shapes in these sketches were developed laterally[39], as demonstrated in the sketch captured in Photograph 6.15. The basic rectangular shapes represent tables and rough sketches visualise people moving and participating in unpacking, standing at tables, rolling and unrolling cloths serving as containers. Brian included a primitive sketch of a motor vehicle with an open boot, which suggests transportation as functional intention. In Photograph 6.16, the detail in the sketches suggests lateral and vertical transformations. The vertical transformations are embodied in the sketches which included boxes stacked onto each other and loaded on a trolley, which indicated their implementation intention. Brian's repetitive visual reference to 'motor car' alluded to his commitment to the concept of a storage system that could fit in a motor car. He also repeatedly sketched how the relevant people might use the artifacts (boxes, tables, trolleys) involved. Therefore, showing the interaction between objects and people became a way of expressing Participants P-I's implementation goal of involving users in the management of the Lego™. In the case of Brian, it did not seem to be the inclusion of detail that expressed commitment, but rather the repetitive use of the same physical elements.

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[39]Participants P-I generated multiple lateral ideas suggesting slightly alternative shapes and types of containers (Appendix G)

Photograph 6.14	**Photograph 6.15**
Participants P-I (Brian) Sketch 1 00:29:30 **Generating** idea	**Participants P-I (Brian)** Sketch 4 01:03:54 **Lateral** development of idea
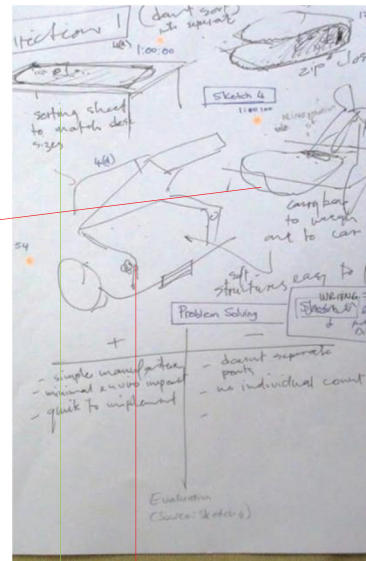
Photograph 6.16

Participants P-I (Brian)
Sketch 8 02:55:56
Conclusive sketch – **lateral
and vertical** development of idea
with written specification
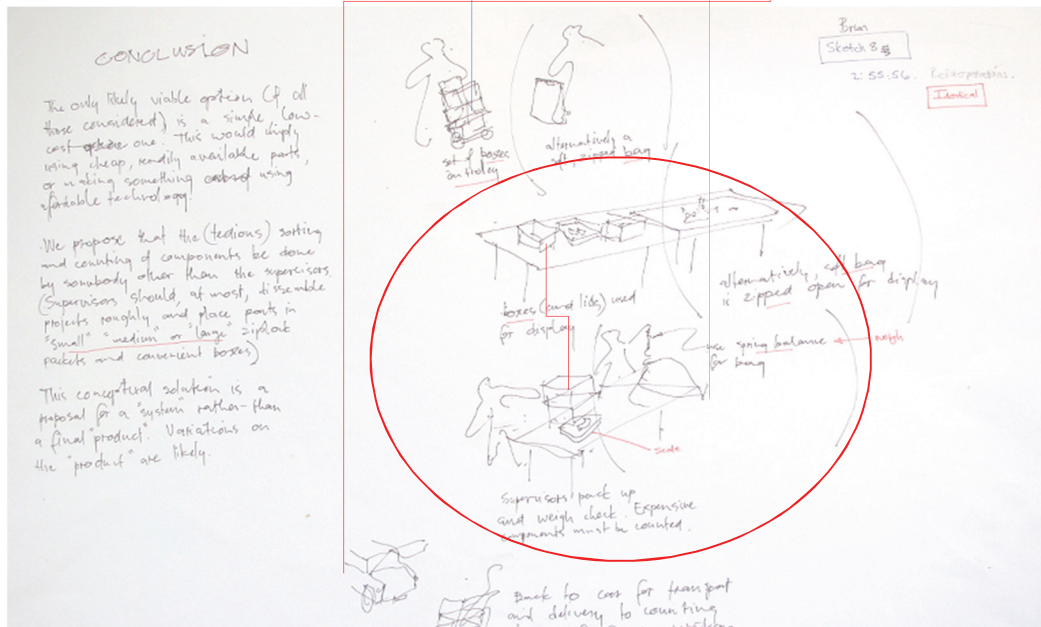
Photograph 6.14, 6.15 & 6.16:
Participants P-I's commitment through verbalisation, visualisation and transformation

Writing, which accompanied their sketches, played a considerable role in Participants P-I's externalisation of their thought processes (Appendix G). In spite of Goel's (1995) view that

multiple modes of output signify commitment, Participants P-I's writing rather implied its scaffolding of their evaluation functions and not of making final decisions. This alternative symbol system of Participants P-I seems to be a professional or personal procedural habit of interaction between their inner and outer worlds.

I found that the participants transformed their sketches as a means of adapting their behaviour to changing contexts. Clearly articulated implementation intentions, together with sketches, demonstrated how their visualisation, perception and procedural knowledge contributed to the articulation of their intentions as well as the transformation of their ideas to instances of propagating and making commitments. As such, transformations through constant construction and manipulation of their visual models seemed to be an integral part of their extended cognition. The interactive behaviour of all the participants, through the use of their sketches to propagate and make commitments, is supported by Kirsh (2009, p.269) who explains that problem solvers "constantly translate moves in their abstract problem space and then act in the world". I therefore argue that the participants' ability to internally recognise patterns of function of existing and new objects can be linked to the way in which the participants approached their external acts of making sketches and using writing. Their purposeful integration of the internal problem space with an internal registration of their knowledge and beliefs in order to achieve coherent and logic reasoning adds further insight into the way designers' interactive processes work. In this way, I extend on current embodiment theories that seemed to insufficiently explain external cycles of perception and action (Gero & Kannengieser, 2006).

6.6   THEME 5: TRANSFORMATIONS, CONSTRUCTING AND MANIPULATING MODELS

Closely linked to the use of visual modes of output to represent commitment, is the notion of transforming ideas through construction and manipulation of models. In this section I consider how revisiting previously drawn sketches or constructing new sketches may suggest that designers will spend prolonged time on the ideas that they are committed to. There seems to be a strong relation between making and propagating commitments, visualisation knowledge, and lateral and vertical direction transformation observed in the visual models that designers construct and manipulate. Oxman (1997, p.329) states that "The design sketch can be considered as the basis of a visual and mental transaction between the designer and the representation, which evokes a discrete graphical response".

According to Arnheim (1969), the cognitive operations in perception and visualisation are closely linked. These operations include the ability to distinguish structural relationships in the images represented in design sketches, which fits well with previous discussions (section 6.2) of the participants' intentional attention to the structure of the artifacts that they observe and

envisage when committing themselves to choices regarding the physical elements that would satisfy their intentions.

My analysis of the construction and manipulation of the physical and spatial configurations of the participants' sketches and their sequential progress assisted me to trace their cognitive lateral and vertical transformations. I traced the development of ideas in the early phases of the design process by studying the progressive stages and transitions of states in the syntactic and semantic properties of sketches. Following Goel's (1995) methodology of analysing the direction of transformation of designers, I traced the semantics by mapping them on the things the participants thought about as represented in their vocal utterances, discussed in section 6.3 and Tables 6.1 to 6.4.

I interpreted the syntactics of the sketches in terms of their grades of ambiguity and density. Richness of marks with clarity of shapes indicated cognitive activities including development, experimentation and decision taking of ideas in the minds of the participants. Density and ambiguity of marks was typical during this phase and characterised lateral transformation. Researchers who are involved in the cognitive role that design sketches play agree that it is the ambiguity and semantically disjointedness of sketches made during the preliminary phase that allows designers to generate multiple ideas (Goel, 1995; Goldschmidt, 1991; Tversky, 1999).

I furthermore adopted Goel's (1995) approach to determine the two primary directional changes that such activities could represent. The first direction refers to lateral transformation, which primarily occurred during the participants' preliminary phase of problem solving. Lateral transformation of a sketch indicates movement from one idea to a slightly different idea through the modification of an original drawing into another related, but distinctly different drawing.

The distribution of the participants' directional changes of thought suggested transformational patterns in the early phases of their design processes. The distribution of the participants' transformations of their thoughts was confirmed by their vocal utterances (Appendix D-Modules and Phases, Direction) which are summarised in Table 6.8 below.

Table 6.8: **Total number of changes in direction of thoughts of all the participants across all phases**

Direction	Cognitive phases									Total		
	Problem structuring			Leaky module			Problem solving			Directional changes across phases		
	P-A	P-E	P-I	P-A	P-E	P-I	P-A	P-E	P-I	P-A	P-E	P-I
Lateral	9	11	0	6	11	6	10	18	22	25	40	28
Vertical	7	14	2	12	16	17	18	45	46	25	75	65

Back	7	13	5	4	7	13	5	23	50	4	43	68
Repeat	2	6	1	9	8	11	20	17	26	9	31	38
TOTAL transformational moves per phase	**25**	**44**	**8**	**31**	**42**	**47**	**53**	**103**	**144**	**101**	**189**	**199**

The counts indicate the number of instances that the participants engaged in individual moments of directional changes, which I interpreted as transformation, even though they do not indicate how much time was spent during each instance. My analysis indicated that the architects' individual episodes of verbal utterances were on average longer than the other two teams, while the industrial design team, because they spent sixty minutes longer in total on completing their task, had more temporal opportunities for making verbal utterances. As mentioned previously, it is therefore more productive to interpret the statistical data of individual participating teams than to compare the groups with one another.

I could not find logical patterns of connections between intentions, resources, commitments, things the participants thought about and the direction of transformation in their thoughts. These seemingly individualistic thinking strategies might be attributed to internal tacit procedural knowledge, which apparently played a role in consciously and sub-consciously guiding the participants' thinking strategies (Vincenti, 1990). Each participating group, as experts, knew when and how to introduce the things they thought about, proposing and adding them incrementally. They also knew how to structure their arguments around the various requirements in their briefs. I found that not all new ideas of the participants were developed through transformations and that not all lateral moves were developed into vertical refinements. Goel (1995) also observed that not all the participants in his study developed all lateral and vertical ideas.

Apart from the perceptual stimulation of the external situations that contributed to the way and sequence in which the participants transformed their ideas and sketching on top of the aerial photograph, the perception of their growing body of sketches in cycles of perception-action also contributed to their transformations. Transforming ideas through sketches in such cycles of perception and action is well described and accounted for in situated design studies (Gero & Yan, 1994; Suwa et al., 2001) from information processing perspectives, such as Goel (1995), as well as from an interactive point of view, such as Shani (2012) and Clark (2006).

Through my analysis of the lateral and vertical transformations of ideas through model construction and manipulation, I took the stance that the participants' sketches represented mental states that include intentions. This does not mean that the sketches became a substitute for the internal processing apparatus, as suggested by some interactive design researchers

(Shani, 2012). Instead, I consider sketches as carriers of internal states as well as facilitators of the transformation processes that designers need to develop their ideas.

6.6.1 PARTICIPANTS P-A: TRANSFORMATIONS, CONSTRUCTING AND MANIPULATING MODELS

Photograph 6.17 to 6.18 present examples of the salient transformations observed in some of Participants P-A's sketches. Photograph 6.17 captures a sketch Andrew made as an illustration of a case of a theatre that he considered as 'intimate' while considering the requirements of their brief (Appendix C).

Photograph 6.17	Photograph 6.18
Participants P-A Sketch 3A and 3B 00:17:16 The case of theatre in St Paulo containing the idea of 'honest' theatres and 'interactivity'	**Participants P-A** Sketch 5 01:16:30 Suggests idea for interactive theatre on site, based on 'golden circle' principle that formed the basis for their idea for the stage in Sketch 14
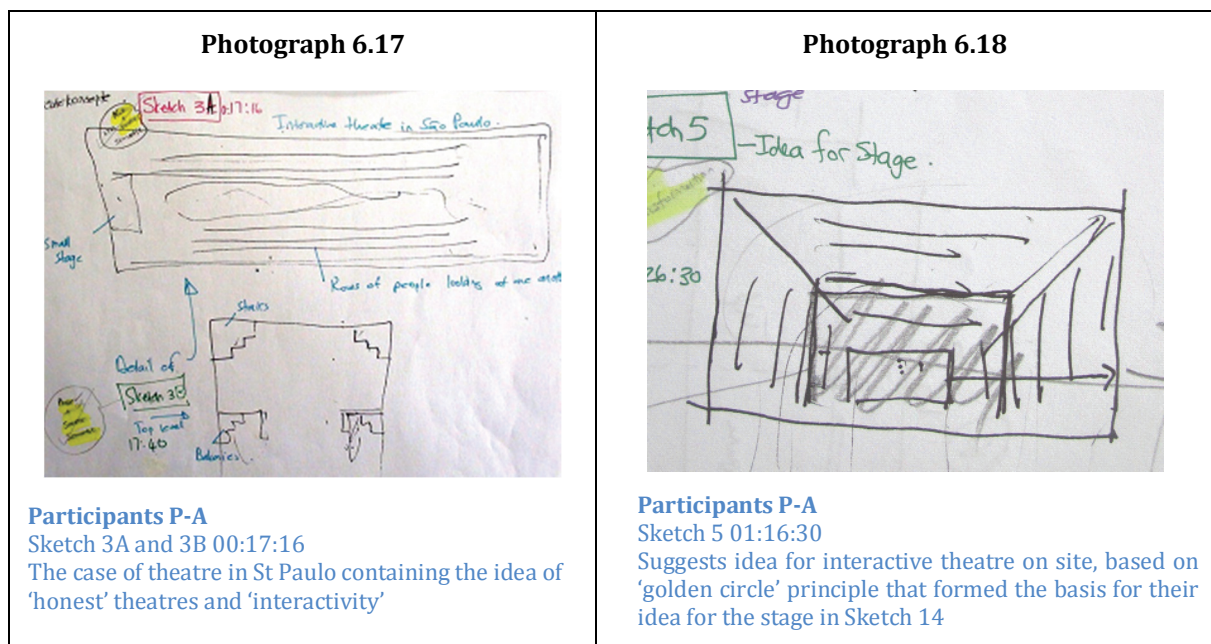
Photograph 6.17 & 6.18:   Participants P-A's adaptation of existing ideas

In Photograph 6.18, a sketch by Jonathan is captured, which is apparently based on his interpretation of an architectural principle of 'the golden circle' (Appendix D). This reportedly relates to the ideal distance between actors on a stage and the audience in order to ensure effectiveness. This idea developed from previous statements in Participants P-A's dialogue during their problem structuring phase when they discussed cases in which intimacy was achieved (Appendix D), as well as from the case based sketch (Photograph 6.17), which they made during this dialogue. This pointed to Jonathan's ability to transform their intentional state into a state of satisfaction. It is furthermore evident of Participants P-A's ability to externally transform their previous sketch (Photograph 6.17) to the current sketch (Photograph 6.18).

Photograph 6.19 provides another example of vertical transformation. Participants P-A continued developing the theatre area by resuming Sketch 14 (captured in Photograph 6.2 and 6.3, p.246). The transformation was seemingly triggered by emerging opportunities for

development of the whole surrounding area and the spatial connections between the theatre area and existing buildings in the vicinity. The participants furthermore suggested walkways which they intended to create by planting trees.

Original sketches   Coding

Participants P-A
Sketch 16 and 17 01:09:00
Vertical transformation (Sketch 16) by adding detail development of the rear of terrace area, including walkways by planting trees and showing how to connect new theatre area with existing buildings (Sketch 17)
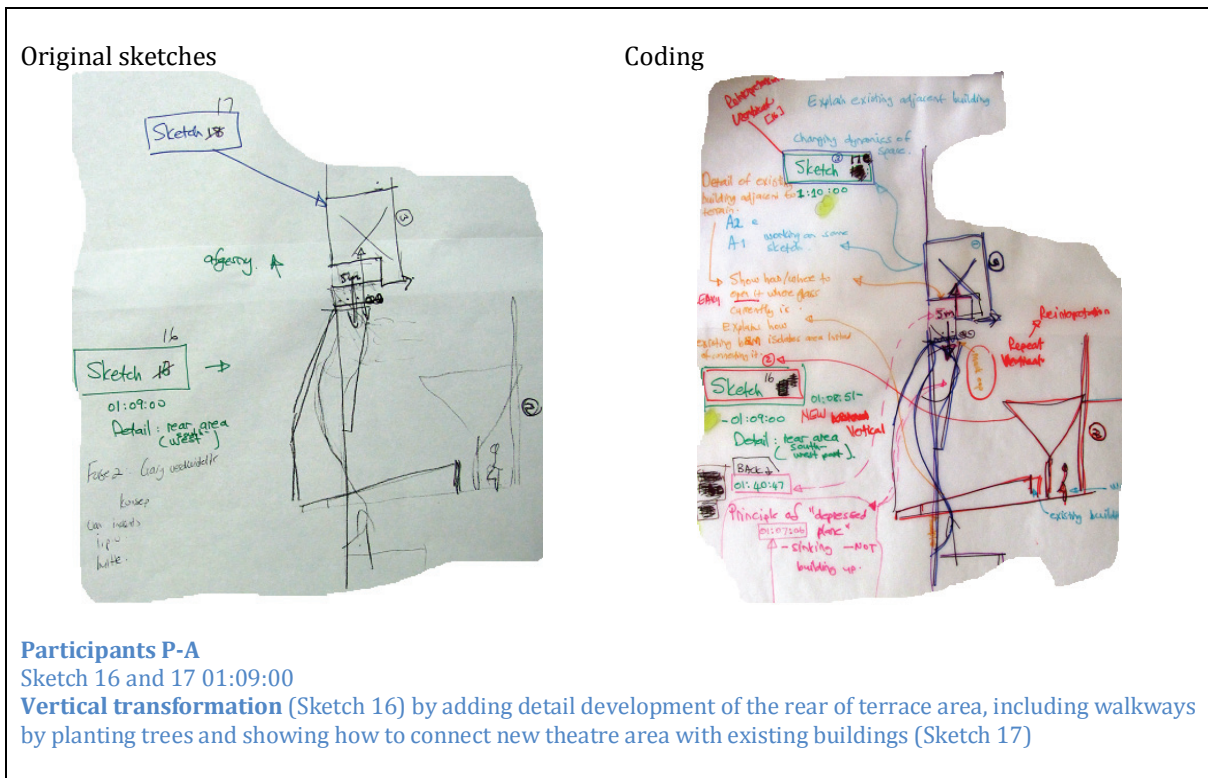
Photograph 6.19:   **Participants P-A's vertical transformation of ideas**

In another transformation captured in Photograph 6.20, the sketch represents detail of Sketch 14 by showing depth of the terraces. The sketch represents a vertical transformation that was captured verbally, as also indicated by Excerpt 4.46. As such, sketch 23 (Photograph 6.20) was the conclusive sketch that these participants made.
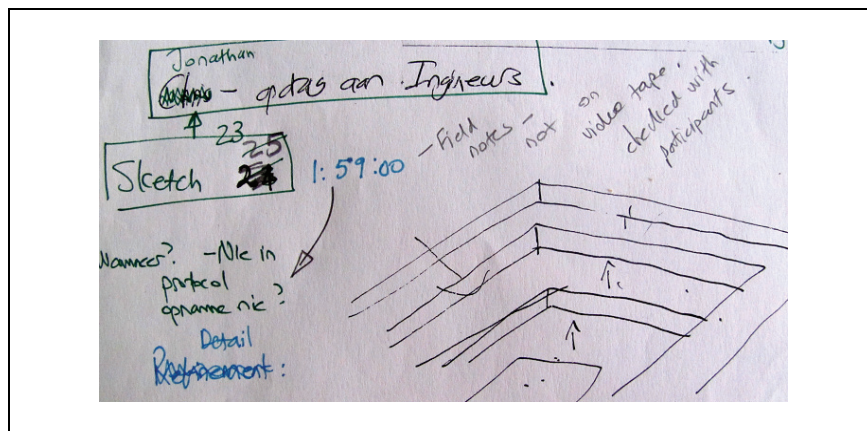
Photograph 6.20:   **Participants P-A's development of ideas adding detail through a change in viewpoint**
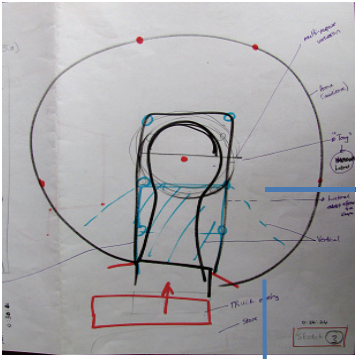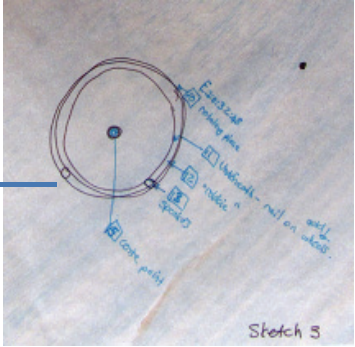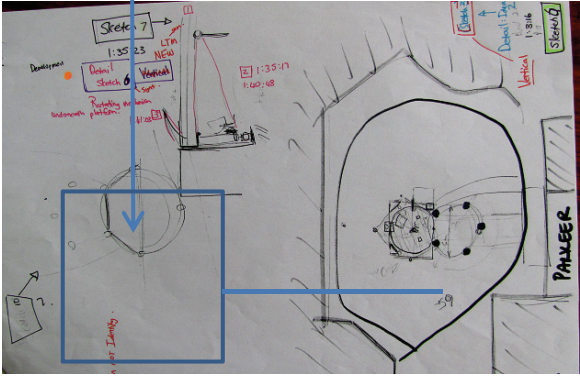
Excerpt 6.46

JONATHAN 01:59:00
Maybe we should give the engineers something to design? A roof that can open
and close? Or something like that?

6.6.2 PARTICIPANTS P-E: TRANSFORMATIONS, CONSTRUCTING AND MANIPULATING MODELS

Photographs 6.21 to 6.23 provide a visual summary of Participants P-E's lateral and vertical transformation in the construction and manipulation of their visual models. The participants generated their first idea as captured in Photograph 6.21 and 6.22, based on the design brief (Appendix C). They seemingly registered their own knowledge of the physical properties of the concept 'theatre' and domain specific knowledge 'rotation', and used this sketch to confirm their interpretation of the brief. The ideas in Sketch 6A include provision for functional elements of the participants' understanding of which physical parts are required to provide expected performance from the platform.

Photograph 6.21

Participants P-E
Sketch 3 00:25:38
Idea 1 generated for platform

Photograph 6.22

Participants P-E
Sketch 3 Detail

Photograph 6.23

Participants P-E
Idea 2: Unidentified sketch replicated on Sketch 6A 01:30:16
The basic concept suggested in Photograph 6.22 is adapted for their second idea namely to fit the platform into the existing sculpture and accommodate additional elements such as lighting and sound
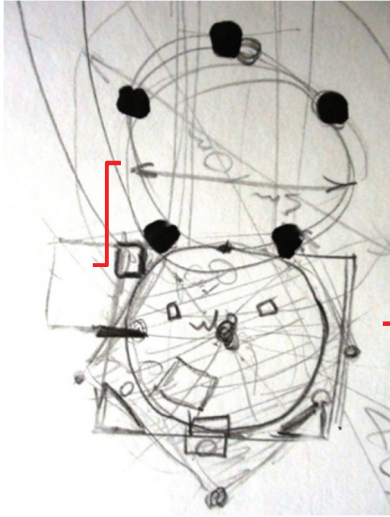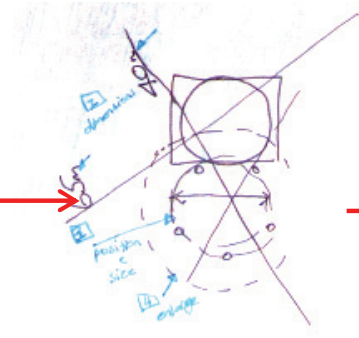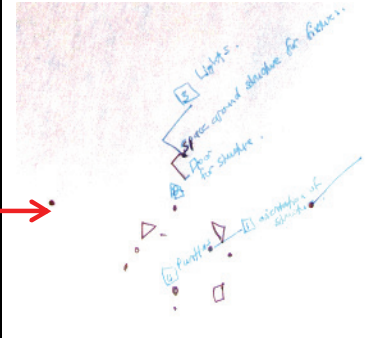
Photograph 6.21, 6.22 & 6.23:
Participants P-E's transformation through construction and manipulation of sketches

Following on their interpretation of the brief, Participants P-E generated a case-based sketch captured in Photograph 6.5 (Section 6.2.2), which they apparently sourced from their LTM. The case refers to a modern existing performance idea with the stage on one side and the audience seated in a half circle in the front. It is possible to recognise the structural similarities between Photograph 6.5 and 6.21.

In my view the repeated use of the shape and structure, as depicted in Photograph 6.5 and 6.21, suggests that the particular recollected theatre, called 'Musaion' amphitheatre (Photograph 6.5), played an important role in Participants P-E's choices represented in later sketches. It could therefore be argued that Participants P-E's memory of this particular theatre may have played a role in generating the concept sketch in Photograph 6.21 (see p.272). In turn, it could also be argued that the memory of the structure and shape depicted in Photograph 6.5 could have influenced the concept depicted in 6.21. The sketch in Photograph 6.23 seems to be a lateral transformation of an idea that was surfacing from LTM through the idea in Photograph 6.21. Apart from the participants being enthused by the visual stimulation of the existing sculpture on the site, it was not possible for me to ascertain what exactly the underlying processes were, and the exact computational sequence in which the process of recall and generating new ideas were by using Goel's (1995) method of analysing the direction of transformation.

I found that Participants P-E used both ideas captured in Photograph 6.21 and 6.23 (see p.272) as structural concepts in which they embedded the development of their rotational platform design. Photograph 6.21 suggests a vertical transformation of the concept captured in Photograph 6.20 (see p.271), while Photograph 6.22 suggests a lateral development of the circular area at the centre of Photograph 6.21. Participants P-E generated two alternative ideas ((a) and (b)) in one sketch. Idea (a) signifies their idea to place the platform inside the existing sculpture, while (b) implies the platform to be loose standing, mobile and able to fit into any possible structure the architects would require.

Tracing the lateral and vertical movements in the thought processes represented in Photograph 6.21 to 6.23 was challenging and I relied on the video material and verbal utterances of the participants to guide my interpretation. I found that the sketch captured in Photograph 6.24 represented a complex process during which Participants P-E simultaneously developed two lateral transformations vertically on one sketch. Participants P-E focused on both a vertical development of the platform inside the sculpture, by adding surrounding additional elements such as a sound system and lighting system, as well as lateral transformation of their idea of separating the platform from the sculpture. The latter idea was in turn developed vertically by adding detail such as pillars and a removable canopy, and adopting a lighting and sound systems as for (b).

Photograph 6.24	Photograph 6.25	Photograph 6.26
Participants P-E: 01:03:16 Sketch 6A 01:30:16 **Lateral and Vertical transformation:** developing two slightly different ideas and adding detail to the initial sketches (Photograph 6.23)	**Participants P-E** Sketch 6A 01:10:56 Simulation of layered detail development **Vertical transformation:** adding detail to the initial sketches in layers (Photograph 6.23)	**Participants P-E** Sketch 6A 01:10:56 Simulation of layered detail development **Vertical transformation:** developed vertically by adding detail to the initial sketches in layers (Photograph 6.23)
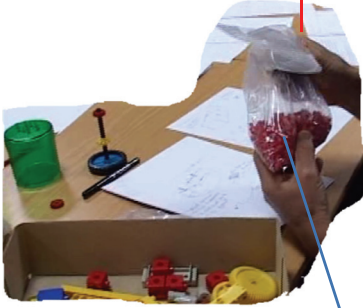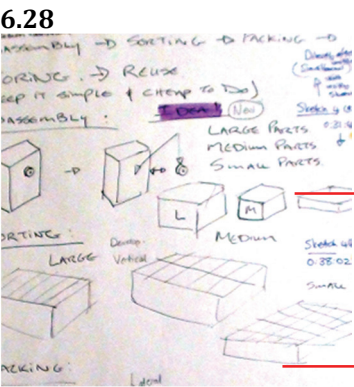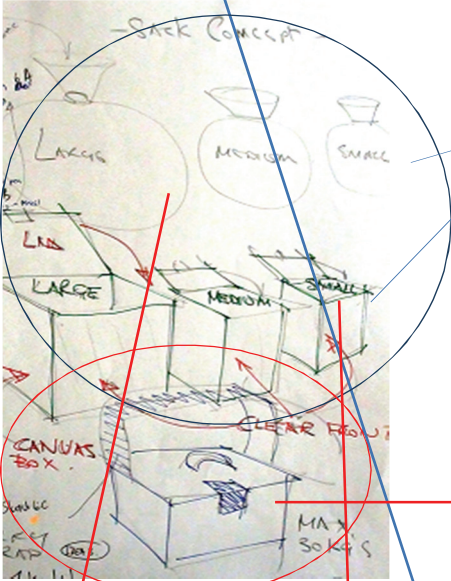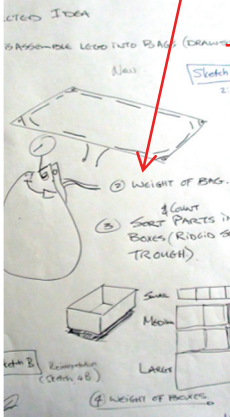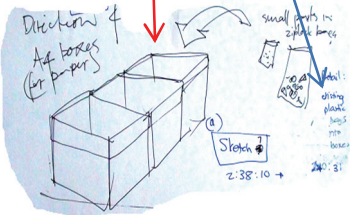
Photograph 6.24, 6.25 & 6.26:
Participants P-E's simultaneous lateral and vertical transformation of ideas

6.6.3 PARTICIPANTS P-I: TRANSFORMATIONS, CONSTRUCTING AND MANIPULATING MODELS

As Participants P-I's team consisted of three members, who all preferred to work on their own when constructing and manipulating their sketches, they generated a relatively high number of sketches on the whole. The implication of their sketch procedure was that the participants were not only exposed to the materiality of the Lego™, and its current storage system in the venue, but that they were constantly in the presence of each other's sketches. The possibility exists that Participants P-I's individual team members could be influenced by each other's sketches. Therefore, when I mapped the development process and the transformations that their ideas had undergone, tracing the origins of each individual sketch accurately and with certainty was not possible. The complexity of this situation was that transformations became transformations from other participants' transformations. I therefore treated all the sketches combined as one large process, as illustrated in Photograph 6.27 to 6.31 (see p.275).

From Participants P-I's sketch behaviour, I inferred a combined progression of thought processes that encompassed all team members throughout the combined protocol. While giving consideration to an aspect specified in their design brief, they would start making a series of sketches that represented their understanding of the brief's intentions, while immediately including written evaluation of the ideas implied by their sketches. As such, Photograph 6.27 to

6.31 is a summary of the semantic connections between the different sketches that indicated the lateral and vertical transformations in their collective design process.

6.27 **6.28**	**Photograph 6.27 and 6.28** External resources (boxes, plastic bags, Lego™ blocks **Participants P-I: Adrian 00:31:45** Source: Reacting on different sizes of Lego™ and existing boxes perceived. **New** Participants P-I: Adrian 00:38:02 Source: Previous sketch **Vertical:** reiterates and transforms idea vertically by adding detail (compartments) for Lego™
6.29	**Photograph 6.29** **Participants P-I Clint: 01:00:22** **Source**: Previous sketch (Addendum G) **Lateral movement**: Making distinctly different sketches; moves syntactically and semantically from bag as low cost container to box as low cost container. **Participants P-I Clint: 00:03:54** Source: Previous sketch (6.27). **Vertical** movement: reiterates and reinforces box drawing through explication and detailing handle, lid and closing mechanism.
6.30 **6.31**	**Photograph 6.30** **Participants P-I Adrian: 02:39:02** Source: Previous sketch (6.28). **Lateral** movement, by changing initial broad idea of bags containing Lego into a bag that can unfold **Photograph 6.31** **Participants P-I Brian: 02:38:10** Source: Previous sketches – whole team. Reacting on different sizes of Lego™ and existing boxes perceived. **Lateral** movement in the context of the whole team's combined ideas by changing the initial broad 'box' idea to different boxes for different size objects. **Vertical** transformation by adding idea of Lego in small transparent bags

Photograph 6.27 to 6.31:   Participants P-I transformation of ideas

In conclusion, I found no logical connection between the intentions, commitments and direction of the participants' thoughts in the sketches of all the participants, but rather found contingent relations. This means that the participants' decisions to develop and transform particular ideas were not logically connected to their design tasks, but were dependent upon the design aspects that they prioritised which resulted from their domain specific knowledge, the functional intentions and the information emerging from the external environment.

Following from my observations of the transformation directions in the sketches of all the participants, I could not deduce any logic patterns amongst the participants. This might be ascribed to the contingency described above, which implies that context plays a determining role in the design process. The importance of the internal-external context in determining what designers attend to and how they react on information is currently widely acknowledged in interactive design cognition studies (Gero & Yan, 1994; Kirsh, 2009), as well as ecological psychology in general (Shani, 2012). From an internal perspective, differences between the strategies of individual participants or teams involved in directional changes have been ascribed to individual design styles and professional preferences (Cross, 1997, 2007a) and unpredictable individual reactions to external design contexts (Schön & Wiggins, 1992). Such reactions in this study included knowing when to do what, meaning knowing when to sketch, when to read the brief, when to talk, when to observe the environment and when to reflect on a sketch. In addition, the expert participants' fast flowing external reactions to their internal knowledge was observed in the way they 'read' their sketches and manipulated them. These actions and reactions represented their procedural knowledge that have become automated metacognition in the case of the participants (Arnheim, 1993; Gero, 1999).

In spite of individual patterns in the sequence of their actions, I found patterns in all the participants' transformation of direction that I inferred from their sketches, which I connected with their making and propagating commitments. I namely found patterns in the cognitive processes surrounding their commitment making. The first pattern that I identified was a moment in the sequence when the participants identified or recognised 'the problem' amidst their initial uncertainty due to a lack of situational information. This moment of recognition tied to their articulation of their goal intentions as discussed in the previous section. This pattern of 'finding' or 'seeing' the 'problem' resonates with the Gestalt psychology's conceptualisation of problem solving (Wertheimer, 1900). The second pattern relates to the participants' strategy to consciously centre their actions and ideas around subjectively selected domain specific design principles or subjective philosophies which determined the commitments that they made. This pattern also resonates with Gestalt theory, which claims that there are important and frequent

mental processes and states which exist over and above their elements since they possess the property of transferability (Arnheim, 1986).[40]

The third pattern that I observed across participants relates to embodiment theory of the role of visual cueing and emergence in which sketches, as external objects, played a significant role. Although this concept is not new in situated design cognition studies (Gero & Yan, 1994; Oxman, 2002), I link the visual sensory exposure of the participants to their sketches and other visual resources (including being on the problem site, objects such as Lego™, aerial photographs) to their dynamic integration in the formation and articulation of their implementation intentions. I base this conceptual link on the dynamic systems theory of Smith (2005) that the formation and maintenance of 'a reaching plan' (implementation intention) by designers could be explained by closely integrating time, space and strength of activation drivers in the perception-action cycles, as explained by embodiment theory.

In the context of my study, this means that three external conditions were needed to formulate implementation intentions. First, the constant presence of the sensory activation (sketches and other visual resources) could become a driving activator. The second condition was the 'hidden' problem and underspecified requirements for the artifact that could solve the problem due to the ill-structured nature of design problems, which automatically resulted in the delay of the rate at which a solution or implementation plan would be reached. The third condition required of the participants to commit to their intentions. Being experts, all the participants in all the groups involved in this study's problem space contained all three of these conditions. Determining the strength of their commitments, Goel (1995) theorises in his *Sketches of Thought* that it is possible to determine levels of commitment by studying the different grades of ambiguity and vagueness of syntactic structures and semantics of pictorial outputs.

6.7   CONCLUSION

The aim of this chapter was to discuss my findings related to the relationship between the participants' external and internal cognitive activities. Building on the statistical results of my study, as presented in Chapter 5, I structured my discussion around an in-depth exploration of the role of intentions. I did this in order to further characterise the design problem solving space. I furthermore explored the role of intentions as a potential cognitive bridge between higher order goal intentions and participants' consideration of lower order external elements encountered in their design task environments. I approached my interpretations from a computational (information processing) as well as embodiment perspective in an integrative

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[40]This is considered as a Gestalt's descriptive thesis. The dynamic thesis explains mental processes as constitutive of distinctive wholes that cannot be accounted for by the properties of individual parts (Wiegner, 2005).

manner. From a computational point of view, I associated cognitive activities with internal information processing. From an embodiment perspective, I linked cognitive activities with external perception of visual information as perceived by participants. Due to the central role that intentions play in design work, I examined the nature of intentions in the participants' design thinking strategies. As such, I demonstrated through evidence from verbal data (vocal utterances), as well as visual data (design sketches) that two types of intentions played a significant role in answering my research questions.

In the next, and final, chapter of this thesis, I summarise Chapters 1 to 6. I reach final conclusions by reflecting on my research questions in terms of cumulative findings, which result from this chapter. I thereafter conclude my study with recommendations for future research, training and practice.

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CHAPTER SEVEN

Conclusion and Recommendations

EXISTING LITERATURE

RESULTS OF MY STUDY

FINDINGS

THEORETICAL RESEARCH QUESTIONS

How can a combination of IPS and ecological elements explain dynamic cognitive processes of expert designers in the early phases of the design process?
AND
Why is it necessary (or not) to combine computational-related theories with ecological theories in order to understand the dynamics involved in design processes?

METHODOLOGICAL RESEARCH QUESTION

How can applying mixed methodology strategies contribute to the validity of protocol studies in a design context?

CONTRIBUTIONS

THEORETICAL CONTRIBUTION

- Construct the concept 'leaky phases'
- Identify abstract design principles as possible driver for design decision taking
- Add to the existing body of knowledge on design cognition

METHODOLOGICAL CONTRIBUTION

- Adapt conventional laboratory design experiments and implement real life elements
- Mixing methods allow complex interrelationships between variables

REFLECTIONS

FUTURE RESEARCH

FUTURE PRACTICE

FUTURE TEACHING

7.1 INTRODUCTION

In Chapter 5 and 6, I presented the findings of my study against the background of existing literature on expert design cognition in the early phases of the design process, IP and situational approaches. The research draws primarily on philosophical literature that focuses on extended design behaviour from an IPS perspective as well as from a situational point of view. The aim of this study was to unravel the complex interactions between the inner and outer worlds of design experts when progressing through the early phases of the design process in order to map the relations between internal intentional driving forces and external physical elements.

In this chapter, I provide a summary of Chapters 1 to 6, followed by a final synopsis of my findings and conclusions in terms of the research questions, as formulated in Chapter 1. After final discussions of my findings, I reflect on the contributions, strengths and challenges of my study. In addition, I reflect on my own qualifications and preparedness in entering the research field. I conclude the thesis by making recommendations for future research, training and practice.

7.2 SUMMARY OF THE RESEARCH QUESTIONS

The **first central research question** has a methodological foundation and concerns the possible contribution of the application of mixed methodology strategies to the validity of protocol studies in a design context. The question was operationalised by the specific sub-question 1: *To what extent does the interaction between the embodiment principles of affordance, perception-action, intention-attention and specification, and psychological characteristics contribute to the dynamics of the problem solving space of expert designers?* Chapters 4 and 5 addressed and informed this research question.

The **second central research question** has a theoretical basis and involves the necessity to combine computational-related theories with ecological theories in order to understand the dynamics involved in the design processes. The question was operationalized by a combination of the following specific sub-questions:

Sub-question 2: *Which kinds of thinking in the early phases of the design process mechanises interactivity between the inner and outer worlds of the participants?*
Sub-question 3: *How does the internal-external interactivity influence the control of the vertical direction of participants' thought processes?*
Sub-question 4:
What is the nature of the relationship between embodiment principles and continued attention to thoughts?

Sub-question 5: *How does a theory of interactivity influence symbol systems theory in a design context?*

Chapter 6 addressed these sub-questions.

The **third central research question** has a theoretical basis and involves the value of combining computational-related theories with ecological theories in order to contribute to the development of novice designers' problem solving abilities. The question was operationalised by sub-question 6: *How might an integrated framework contribute to the development of novice designers?*

Chapters 4, 5 and 6, informed this sub-question.

7.3 OVERVIEW OF THE PRECEDING CHAPTERS

The primary focus of **CHAPTER 1** was to contextualise my study's rationale. I related my decision to work within the context of expert design cognition to the relevance and need for research in the area of expert design cognition in the early phases of the design process. I justified my decision to focus on 'cognitive dynamics' in terms of the cognitive demands of design education and my concern as to how current teacher training trends prepare pre-service TE teachers to transfer some expert design abilities in order to enhance their design thinking.

In **CHAPTER 2** I explored existing literature as partial background to my study. Through examination of the historical background of research in design cognition, I provided a theoretical backdrop to my study. I explained how conventional computational theories of cognition and representation on its own may fail to explain the complex phenomenon of design cognition and the particular role that representation plays therein. I discussed how conventional problem space theory could allow for combinations of ecological theories, such as embodiment of interactive representation. I also emphasised the unique nature of design task environments that form part of designers' internal mental ecology.

In **CHAPTER 3** I further contemplated the possibilities of combining two seemingly opposite approaches to cognition, namely IP and embodiment. In the first part of Chapter 3, I discussed interrelationships between the socio-technological things that designers think about and consider when talking and using multiple symbol systems to represent their thoughts. I examined how design task environments underlie the psychological characteristics of participants' design problem solving space. In the second part of the chapter, I presented an overview of embodiment principles as explained in current situated cognition literature on representation. I concluded this chapter by presenting my conceptual framework.

CHAPTER 4 includes my discussions and justification of the methodological choices I made in designing and conducting empirical research, based on my selected critical realist approach and assumptions. I discussed the data collection procedures which resulted in think-aloud protocols and design sketches made concurrently. Together with the video recording of these protocols and the sketches, my research diary formed part of the data sources. I furthermore described the procedure followed in each of the protocols, I described the manner in which I conducted thematic data analysis and interpretations using *a priori* categories provided by the theory of my conceptual framework. I also described how I processed data quantitatively. This enabled me to simplify the analysis of the qualitative data (words and sketches). I concluded Chapter 4 with a discussion on the ethical guidelines that I adhered to whilst conducting my research and the way in which I endeavoured to enhance the quality of research in terms of mixed methods quality criteria.

In CHAPTER 5, I presented the quantitative results I obtained, providing an overview of the structure of the participants' thought processes. I described the research processes in terms of the mechanisms involved in the close couplings between internal and external processes when the participants structured and solved their design tasks. I presented the quantitative results in terms of *a priori* theory on the structure of design problem solving space. The four main trends that I identified relate to the distinct overlapping cognitive phases in the early phases of the design process; the interactive use of external resources and the interaction between intentions; application of conceptual knowledge; and personal stopping rules and evaluation functions.

CHAPTER 6 entails the second part of my report on the results and is based on the qualitative data analysis that I completed. I provided an account of the process of designing artifacts and the way that symbol systems may serve as carriers of mental states (intentions) and of transformation (external structural elements). I accounted for cognitive processes by describing the close relationship between design aspects, functional intentions and physical objects, which resulted in implementation intentions. The four main themes that I identified were the types of thoughts that the participants had and their relations with intentions; intentions and their dependence relations with external elements; making commitments; and transforming ideas. I interpreted these results in terms of the design theory modelled by Goel and Pirolli (1992) and interactive theories (Shani, 2012), coupling embodiment principles (Anderson, 2003). In support of my discussion, I presented sketches of the participants, verbatim quotations, statistical information in the form of tables and extracts from my research diary.

7.4   CONCLUSIONS IN TERMS OF THE SECONDARY RESEARCH QUESTIONS

I henceforth come to conclusions by relating my findings to the secondary research questions. In this way, I indirectly address my central research questions.

7.4.1   SECONDARY RESEARCH QUESTION 1

To what extent does the interaction between the embodiment principles of affordance, perception-action, intention-attention and specification, and psychological characteristics contribute to the dynamics of the problem solving space of expert designers?

To answer my first primary research question, 'how may the application of mixed methodology strategies contribute to preserving the cognitive complexity embedded in protocol studies in a design context?' I reflect on the contribution of combining QUAL and quan elements in this study. I established validity of the protocol studies through sound construct individuation, coding, decoding and interpretations of the verbal and visual data in terms of *a priori* theory. Mixed methods contributed to the unveiling of individual instances of cognitive activity while at the same time preserving the complexity of the interactive processes involved. I found internal and external sources of thoughts, triggers of actions, external activities, and the things the participants thought about. Subsequently I drew inferences from statistically determined sequences and distributions of embodiment principles that intersected with internal psychological characteristics in the early phases of the participants' design process. I further found that the multiple interconnections between the various psychological characteristics contributed to and confirmed the complexity in the dynamics of the process. I now discuss the salient psychological characteristics around which 'clusters' of interactivity and interrelationships are grouped.

The first psychological cluster was *abstraction hierarchies.* Pattern recognition by the participants was commonly associated with the internal process of formulating aspectual intentions, whereas perceiving objects in the external environment triggered internal pattern recognition. This association primarily occurred during the problem structuring phase. I observed this in the way that the participants drew conceptual and physical associations between similar cases that they recalled from their LTM. They perceptually recognised external primitives such as shapes, size, lines, materials, surface properties, scale and proportion, and connected these with previously experienced cases that bore similarities with what they perceived. In turn, this alludes to various knowledge types that could be connected with such case immersion, which in itself suggests complexity. The implication is that while an internal state, such as 'intention', could serve as a driving force for subsequent cognitive activities, external elements functioned as triggers for external perception-action cycles represented in the various procedural activities.

The second cluster was *reversal of transformation direction*. I found that this psychological characteristic of the problem solving space was primarily driven by the internal intentional state while interacting with the application of conduct controlling mechanisms, including application

of personal stopping rules, control strategies and evaluation functions while they decomposed the problems. In two of the participating groups' protocols reversal of transformation occurred predominantly during their problem solving phase, while the third group, the architects, reversed the direction mostly during the problem structuring phase. There were no correlations among the three groups regarding the total number reversal instances during the entire protocols. The implication is that reversing direction of transformation is a context dependent process. When the participants disagreed with the intentions of the client, they formulated their own intentions which they based on their personal and domain specific knowledge. Confirming this inference is the interrelationships that I found between reversal, and the psychological characteristics of applying personal stopping rules and evaluation functions.

Participants used their knowledge and personal bias and preferences of what they believed to be a proper fit to what they interpreted as the problem in order to evaluate the client's ideas as well as their own. The predominant embodiment principle that intersected with all the participants' reversal of transformation direction was perception-action. Perception on its own occurred when the participants explored the sites, during their problem structuring phase, while they perceived much when they were involved in constructing and manipulating models visually during their problem solving phase. The implication of this is that the participants judged and evaluated the client's and their own interpretation of the problem primarily based on what they visually experienced in combination with their knowledge of concepts, normativity and effectivity and by implication that of visualisation.

The third psychological cluster that I found significant was the *loose control structures* of the participants. The cognitive implication of loose control structures is that the participants delayed the decision taken and the making of commitments in order to prevent premature commitment. It furthermore implied their ability to automatically change the direction of their thoughts. I found that all the participants, although they incrementally developed their artifacts, delayed many of the sub-problems that they encountered right until the end of their protocols. The verbal protocols indicated that even then, they remarked on the fact that their ideas generated during the sessions were only conceptual of nature, and in real life could change even further. I found that normative knowledge and the application of evaluation functions interacted with control structures. However, the fact that the participants succeeded in delaying commitment implies that normative judgement and evaluation were not instrumental in making premature commitments.

I found that the participants' control structures were not influenced *per se* by external elements, but rather that the co-occurrences of embodiment emphasised how loose these structures were. This could be seen in the numerous perception-action instances that intersect with the participants' internal processes. Table 7.1 summarises instances of internal processing that took

place, intersected by particular embodiment principles as reaction to external resources which the participants accessed through perception.

Table 7.1:   **External triggers across the phases of the design process for all the participants**

Trigger	Sketch	Other external aids
Embodiment principle	Affordance + Perception-action + Specificity + Intention-attention	Affordance + Perception-action + Specificity + Intention-attention
Participants P-A	**103**	**93**
Participants P-E	**69**	**8**
Participants P-I	**77**	**94**

7.4.2   SECONDARY RESEARCH QUESTION 2

Which kinds of thinking in the early phases of the design process mechanises interactivity between the inner and outer worlds of the participants?

I found that interactivity materialised through an intricate process of establishing hierarchies of thought by all the participants when structuring and solving their design problems. I found instances of abstraction levels in the participants' problem structuring and solution phases. I furthermore found that the participants' hierarchical thinking was directly related to the interaction between their inner and outer worlds. As such, my theorising about hierarchical thinking in a design context, which I explained by closely coupling internal and external processes and sources, is an extension of existing information processing theory (Goel, 1995) and ecological (Clark, 2006) theories of design cognition.

I learned that a general pattern of hierarchical thinking existed in the participants' thinking, starting during the problem structuring phase and continuing during the entire problem solving phase. The hierarchical pattern was derived from the semantics of the participants' symbol systems which represented the things that they thought about. The four levels in the hierarchy were as such characterised by the types of information, the level of generality or specificity of information and the source(s) of the information, as captured in Figure 7.1.
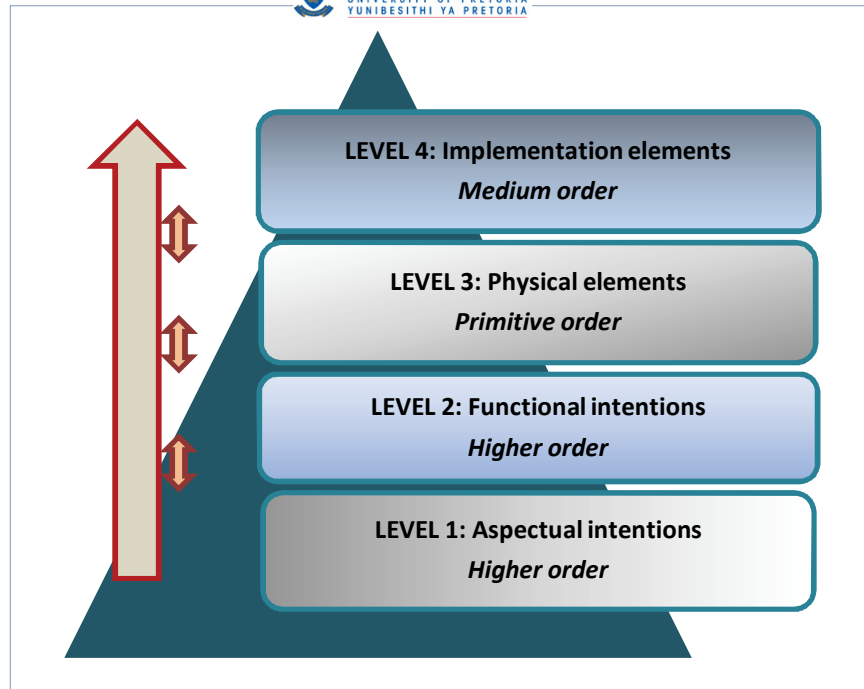
Figure 7.1: Hierarchy of thinking in the early phases of the design process

I found that there was limited linear order to the hierarchy and observed that, although there was a distinguishable starting point in Level 1, and to a limited extent a movement towards Level 2, the order between Level 2 and 3 was multi-directional as it could originate in either the internal processes and sources of thoughts or in the external environment that embodies information, giving rise to top-down and bottom-up processes. This implies a dependency relationship between the different levels, the findings of which I discuss in more detail in secondary research question 3 further on.

Level 1 relates to the internal abstract thinking about design aspects, which I connect to Dooyeweerd's (Basden, 2000) modality theory. Although not all abstract thoughts of the participants necessarily counted as design aspects, all design aspects were abstract thoughts. I found that it was the design aspects that gave meaning and direction to the way that they selected and developed their ideas as they moved on in the process. I found that these aspects were vaguely articulated, and contained implicit internal domain specific knowledge. I discerned the important role that pattern recognition played in participants' recall of specific cases which were conceptually or visually connected with their current design tasks. The implication is that it was the design aspects and process of subsequent connections with the other levels that provided the participants' thought processes a sense of coherence or Gestalt, not only to me as the researcher, but also to themselves.

Level 2 relates to thinking about the functional intentions and where they meet with the participants' preferred design aspects. I found that functional thoughts materialised from a combination of the participants' interaction with internal and external sources. Internal sources

included domain specific knowledge, general design experience, personal stopping rules, professional bias and preferences (Appendix D). External sources included their design briefs, the client (researcher), objects in their environment, and information and opportunities that emerged from their sketches. The implication is that functional intentions provided criteria for satisfaction or fit for the purpose which directed intent to pay attention to physical elements that could meet the criteria. I linked the participants' ability to connect aspectual and functional intentions with internal knowledge and perceivable elements. The implication is that functional intentions do not reside only in the inner world of the participants, but could be extended to existing or envisaged external artifacts themselves. I found that the participants had the superior ability to connect aspectual and functional intentions, which resulted in the addition of specificity in the information in their verbal and visual representations as well as their perceptiveness. The implication is that perceivable information becomes useful in a design context only when it is integrated with internal processes and resources by connecting existing recalled internal knowledge and personal and professional aspectual preferences.

Level 3 entails thinking about how to concretise abstract aspectual and conceptual functional thoughts through a process of negotiating suitable physical elements to fit the purpose by working effectively in a particular context. Such alignment and seeking fit implied the application of normative knowledge. This finding extends the conventional thinking about normativity which links functional intentions with physical elements, to include aspectual intentions. I found that connecting intentions with physical elements, however, also connected with normative thinking when the participants decided what to pay attention to and what not. The implication was a close connection between the meeting of intentions and physical elements with attention. I ascribe such commitment to the participants' need for coherent Gestalt (Kieran, 2011).

Some internal design cognition literature (Eastman, 2001) reports on designers who primarily react on information which they consider relevant to their design tasks, and some external theories (Anderson, 2003) focus on human problem solvers' automatic intention-attention reaction to relevant externally perceived information. Eastman's (2001)statements are based on his studies from a 'recall of information' perspective, which focus on internal processing, and do not take into account the external factors that may influence the designers' thought processes. However, accounting for the participants' consideration of information from an extended point of view, my data indicated that the participants considered both relevant and non-relevant information for varying lengths of time. There might be different explanations for each such instance, including a fixation on the visual stimulation presented by an external object, as was the case with the engineers' preoccupation with the sculpture that offered visual information on the site. In contrast, the industrial designers as well as the architects were at times upset about

personal experiences which they recalled from internally stored information. This behaviour might be explained by the participants' need for internal cognitive relief. By considering the utterance of non-relevant thoughts externally, it is possible that the participants 'bought time' in order to process unfinished thoughts that preceded such utterances. These incidences provided evidence of the important and necessary interaction between internal processing and external elements. Cross (2001b) confirms expert designers' need to consider seemingly irrelevant information. He accounts for this in terms of designers' continuing search for relevance, which prevents them from prematurely ignoring irrelevant information.

Level 4 relates to the implementation intentions of the participants and where they met with aspectual and functional intentions and physical elements. Implementation intentions refer to those intentions that the participants articulated and intended to apply the physical elements to in order to meet their functional and aspectual intentions. Implementation intentions are closely coupled with procedural knowledge. Adding this fourth level is an extension to conventional functional intention-physical elements, a notion found in current engineering design (Kroes, 2002) and technology (Mitcham, 2002) literature. In conclusion, I connected the kinds of things the participants thought about, and the order in which they thought about them as they emerged from the representations and the context in which each were implicitly or explicitly used. I found that the participants' conceptualisation of their intentions not only depended upon their own internalised knowledge and ideas about artifacts, but equally depended upon their perception of external elements in their environment (Figure 6.3, p.244). I also found that the participants used case sketches to represent their recall of similar cases which triggered a process of connecting with their current design tasks. They tended to use these sketches to visualise abstract design principles which they intended to apply in an adapted form in their current tasks. In this manner, their external representations formed a bridge between their internal and external worlds. In Table 7.2, I summarise the salient cognitive functions of the different levels of thinking.

Table 7.2:   **Cognitive mechanisms and functions in the design process**

COGNITIVE MECHANISMS	COGNITIVE FUNCTIONS
• **Aspectual intentions**	• Provide meaning and coherence • (Gestalt) • Bearer of abstract patterns
• **Functional intentions**	• Provide social and technical purpose to artefacts • Bearer of conceptual knowledge
• **Physical elements**	• Provide concretisation of ideas • Intermediary between aspects, functions and implementation intentions

COGNITIVE MECHANISMS	COGNITIVE FUNCTIONS
• **Implementation intentions**	• Facilitate making and propagating commitments • Bearer of procedural knowledge • Bearer of conceptual knowledge

7.4.3   SECONDARY RESEARCH QUESTION 3

How does the internal-external interactivity influence the control of the vertical direction of participants' thought processes?

In this research question I build on what I found regarding the participants' hierarchical thinking. As such, the answer I arrived at is an extension of Goel's (1995) characterising of designers' loose control structures. I extended the idea of conducting control to identify driving forces of such control. The correlation between the participants' sketches and their verbal outputs revealed vertical couplings among their intention-driven and emergent-driven events on multiple timescales. I found vertical direction of thoughts including top-down and bottom-up in all the participants' thought processes. However, I furthermore learned that the direction of their thoughts changed at various, but unpredictable stages of their design process. Therefore verticality does not imply computation linearity, as is evident from Chapter 6, Figure 6.3 to 6.5 [p.244, p.247, p.250].

I found that the participants' top-down processes were triggered by their internal intentional states. However, not all intentions resided in their inner worlds, but some, such as the clients' intentions, were contained in the design brief, which is an external object. However, all the participants at some stage rejected some of the clients' intentions. The implication is that they reversed the direction of the process from a bottom-up to a top-down process by internalising their own intentions. I also found that the participants reacted automatically on various external triggers, which prompted their thought processes in a bottom-up direction. The external sources of these triggers included the brief, client, partners, sketches and perceivable objects in the environment. I found that they swiftly and internally connected the information afforded by the external sources with existing knowledge. The implication is that expertise in design work is characterised by the swift and automatic changing of direction and making of connections.

However, apart from the observation that intentions drove actions from the top while external elements that emerged from the situation (including their sketches) drove their actions from the bottom, I found no overall pattern that encompassed all of the participants' protocols. Yet, I detected individual patterns amongst the participants which imply unpredictability and context dependency. The participants' frequent revisiting of their design brief acted as bridge between their inner and outer worlds.

7.4.4   SECONDARY RESEARCH QUESTION 4

What is the nature of the relationship between embodiment principles and continued attention to thoughts?

The fundamental information for answering this question lies in the individuation of the origin of the participants' thoughts, establishing the number of times a particular theme (represented by 'modules' in the coding sheets) was addressed and the length in time the participants spent on a theme, as explained in Chapter 6. The participants' long chunks were primarily present during the problem solving phase, while they developed their artifacts, whereas their short chunks mostly occurred during the problem structuring phase, when they were structuring problems (Appendix I).

The fact that some long chunks originated during the problem structuring phase and continued into the problem solving phase is also significant. I found that these long chunks could be traced to the participants' aspectual intentions. I furthermore found that long chunks inevitably consisted of a combination of aspectual, functional and implementation intentions, whereas short chunks often lacked implementation intentions (Table 6.1 [p.223], 6.3 [p.227], and 6.5 [p.231]). In this way, I extend existing theory about the shifts in attention (Suwa, Purcell, et al., 1998) of designers that provide an explanation of the duration of attention to particular content in experts' early processes. The models for vertical thinking (Chapter 6, Figure 6.3, 6.4 and 6.5 [p.244, p.249, p. 250]), and the horizontal loops that connect the semantics in their sketches, however, could not reveal any logic connection between the particular vertical direction of thoughts and the duration thereof.

What these models demonstrated, was that the more connection existed between the various intentions and a particular representation(s), the more time was spent on the themes embedded in the thoughts of the participants. Yet, it is not clear if any causal relationship between long and short chunks or between top-down and bottom-up thinking *per se* exists. This may be considered in future research.

I conclude that the participants' long chunks could be attributed to their ability to make internal connections between the suitability of their combined choices of physical elements and how they intended to manipulate these to solve problems. Although their connection making seemed like a viable explanation for long chunks, I could not find a satisfactory explanation for some chunks being short. In assuming that making connections is a cognitive ability, I can not argue that the participants 'lost' this internal ability when heeding content in short chunks, but rather that other factors, such as a lack of time to revisit chunks or external perceivable elements distracted them.

The participants invariably acted in cycles of connecting aspectual and functional intentions with physical elements, which gave meaning to their actions as well as providing coherence. These connections subsequently lead to the participants visualising (internally and externally) implementation through construction, recombination and manipulation of physical elements. Consequently, other cycles emerged when the implementation intentions gave rise to the participants 'seeing' other possible solutions emerging unexpectedly. This means that physical elements acted as intermediaries between aspectual and functional intentions and implementation intentions. Embedded in the participants' cycles were sub-cycles of coherent meaning making and exhaustion of functional intentions that constituted the incremental solving of sub-problems. Their constant active engagement with physical objects enabled them to manipulate their sketches which in turn contributed through instantiation (and represented) their solutions through transformation.

The participants' extensive conceptual and procedural knowledge, including references to objects, people, context and interactions (Appendix D) correlated with their implementation intentions, which confirmed their commitment to the ideas that they expressed. Together with their verbal statements, which increased with detail and specificity, the participants' sketches played a particularly important instantive and transformative role in the problem solving space of the participants, the particulars of which is summarised in secondary research question 5.

7.4.5   SECONDARY RESEARCH QUESTION 5

How does a theory of interactivity influence symbol systems theory in a design context?

The notion central to answering this secondary research question is my view that intentional states constitute the core or prototypical case of representation in the context of design cognition. Although various aspects of my findings contain overlaps with arguments emanating from the work of Goel (1995), Goodman (1975) as well as Newell and Simon (1972), the reconciliatory intention of this study required of me to balance the internal-external counterparts that characterise the division of mental labour when involved in design work.

I found that the participants all used the same symbol systems schemes which consisted of universal systems, namely verbal (normal) language and graphic marks strung together to form pictorial images. Their scheme domains consisted of verbal and pictorial symbol systems. This suggests extended mental states and implies a development of traditional computation symbol systems theory to allow for extended cognitive processing (Shani, 2012). The implication is that the participants' realm domain can be explained in terms of an inner and outer world, whereas traditional symbol systems theory only considered internal processes, as visualised in Figure 7.2 p.2933.

As such, I found that the inner world of the participants consisted of mental states, including the intention that they aimed to achieve, the client's (researcher) instructions to comply with, problems and sub-problems to solve, domain specific and generic design knowledge as a resource and personal bias. Their outer worlds consisted of perceivable physical objects and elements which included three dimensional objects and surface elements in their external task environment. Their outer worlds furthermore included 'hard-wired' external activities such as reading, writing, designating, replicating and erasing, mathematical entities such as numbers and formulae, and external contextual states of affairs. There was evidence of the top-down and bottom-up interactive processes (Chapter 6, Figure 6.3-6.5 [p.244, p.247, p.250) during which the participants' mental processes extended beyond the cranium (Shani, 2012). The implication is that the interactive activity of making sketches, as well as their material embodiment of physical information, requires an extended theory of symbol systems as visualised in Figure 7.2 (p.293).
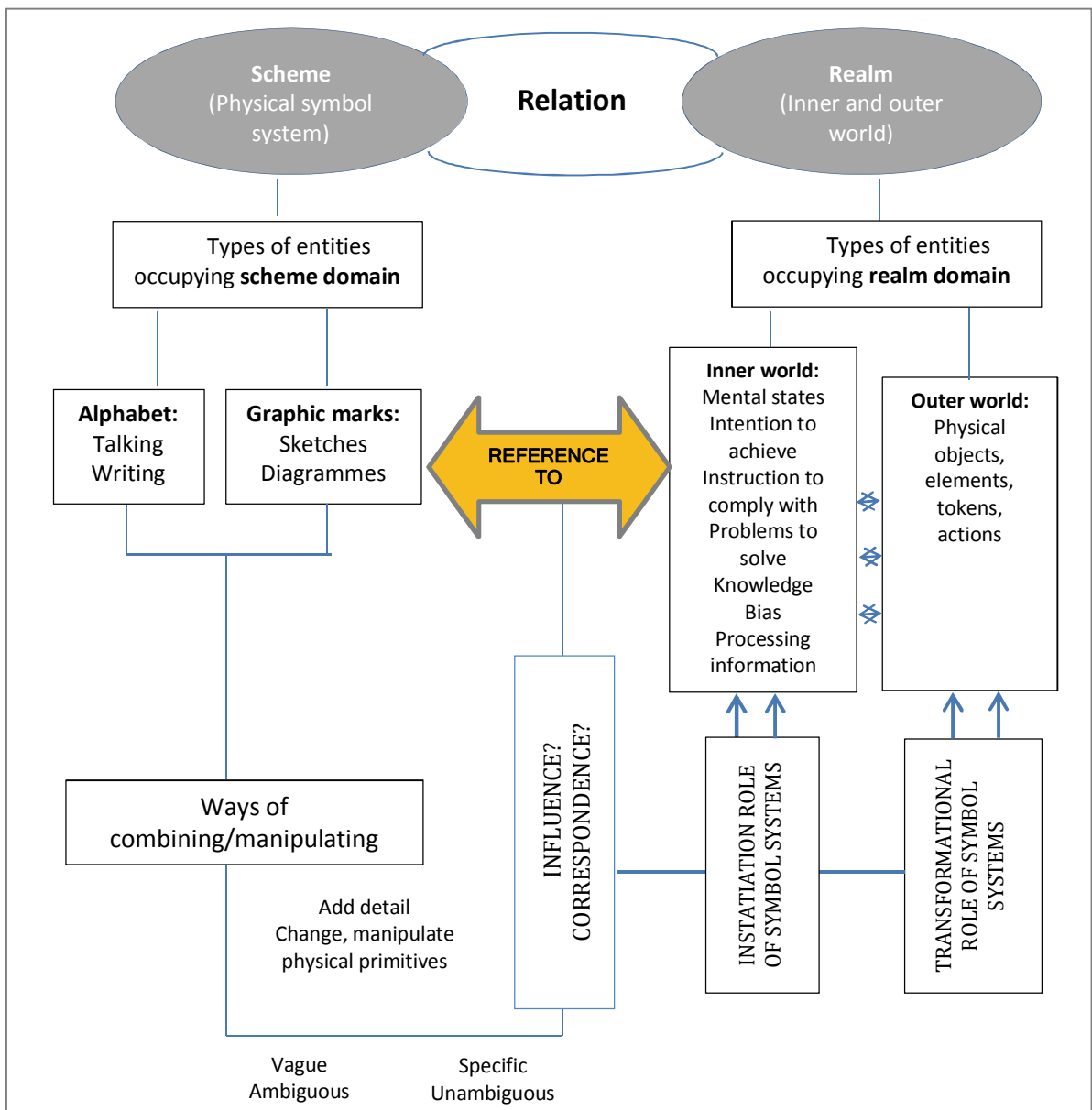

Figure 7.2: **Information processing in an extended symbol system**

I found that the symbol systems used by the participants could be explained by using the metaphor of 'bearers' of content of the participants' internal and external realm domains and as such instantiating intrinsic content. As such, the semantics of their sketches expressed their mental states including intentions, instructions, bias and knowledge as vehicle for intrinsic content. The implication is that the participants' external symbol systems acted as vehicles of their mental states.

The participants' symbol systems bore marks of the cognitive phases of the design process as they proceeded from problem structuring to the various phases of problem solving. These marks encompassed instances of solution decomposition into leaky phases. This suggests that when the participants were structuring their problems their processes simultaneously involved a preliminary search for suitable solutions. The semantic properties of the participants' symbol systems thus depended on the amount of detail and specificity in the syntactic organisation of individual tokens they chose to express and exemplify their thoughts with (Goel, 1995).

An interesting observation was the ability of symbol systems to signify the participants' limited-commitment-mode strategies. This means that the symbol systems the participants used did not require them to complete a particular theme before beginning another, an insight that corresponds with Goel's theory of symbol systems (Goel, 1995). The implication is that an extended theory of symbol systems should allow explanation of designers' need for unrestricted sequences of attending and committing to intersecting ideas.

In contrast to instantiative vehicles of content, I found that the participants' symbol systems also acted as transformative vehicles of content that implied 'any enduring material aspect of a cognitive process which plays a special role in enabling or facilitating the occurrence of a given instantiative vehicle' (Shani, 2012, p.17). I observed that physically transforming their sketches implied that the participants developed their ideas laterally or vertically by manipulating or deleting forms, lines, shapes, textures and proportions. As such, a theory of symbol systems that designers use require a vocabulary that accounts for the way that sketches facilitate changes in the participants' mental states of intent to one of satisfaction, problem solving or fulfilment.

7.4.6   SECONDARY RESEARCH QUESTION 6

How might an integrated framework contribute to the development of novice designers?

Answering my **first primary research question**, *how can a combination of IPS and ecological elements explain dynamic cognitive processes of expert designers in the early phases of the design process?* and **second primary research question**, *why is it necessary (or not) to combine computational-related theories with ecological theories in order to understand the dynamics*

involved in design processes?, necessitates a reflective synthesis of all the previous secondary questions. In order to develop complex and dynamic thinking skills of novices that mirror those of expert designers, one sided approaches of teaching and learning designing, which are promoted by separating computational and ecological theories, should be prevented. I believe that it is more productive to rather integrate these theories. On the one hand abstractions and generalisation with its subsequent disregard for concrete situational influences on individuating problem solving (Kirsh, 2009), which is typical of computational theory, limit the learning experience. On the other hand, overemphasis of situational theories to provide guidance for educational programmes constitutes a narrow focus on the detail of a specific design situation without considering typical design situations. This implies that teaching programmes that by nature rely on generalised models that guide uniform and regimented computational criteria for successful learning output might benefit from a unified theory of design cognition which is amenable to generalisation without compromising individual creativity and the personal design styles of learners. Conscious planning and instilling a balanced and synergetic use of both internal resources and external information could contribute to educators keeping track through formal and informal assessment of where the dominant control for particular cognitive activities are situated.

Such a balance could be struck by considering the conscious nurturing of hierarchical thinking by accessing internal resources of intentional states, developing psychological characteristics typical of design behaviour, applying various knowledge types and including authentic external elements which contextualise design projects of novices. Amongst other things, it implies that authentic ill-structured design tasks with authentic external elements should be integrated with the development of mental skills and resources. This could be achieved by mapping a balanced set of learning and design experiences, by considering the following:

- How much control might be found in students' internal processes, directed by internal resources?
- How much control might be found in the learning and design task environment?
- How is students' perceptual sensitivity for external influences through affordances, cues and contextual constraints built up over time?
- How is students' mental and physical flow of movement between their inner and outer world developed?
- How central is students' use of a variety of symbol systems?
- How sensitive are teachers for the instantiative and transformative role of students' various modes of output to inform them about the particular cognitive phase in which learners are at particular points in time?

In section 7.6.3 I provide practical guidelines for implementing such an integrated approach in design education.

7.5 FINAL REFLECTIONS

In this section I first reflect on the potential theoretical contributions of the study to the existing knowledge base of design cognition, with specific focus on the interactive approach detailed in Chapter 2 and 3. Secondly, I confirm the potential methodological contributions with regard to possible adaptation of conventional think-aloud protocol studies embedded in a mixed methods research design, as discussed in Chapter 4. Finally, I refer to the potential profession-related and education-related contributions of the study.

7.5.1 THEORETICAL CONTRIBUTION

The first primary research question, namely *how can a combination of IPS and ecological elements explain dynamic cognitive processes of expert designers in the early phases of the design process?* implies potential theoretical contributions to design cognition theory. Secondary research questions 2, 3, 4 and 5 contributed towards attaining this aim. I discuss each of their contributions in separate sections.

7.5.1.1 Hierarchy of thoughts

In secondary question 2, I attempted to account for the kinds of thinking in the early phases of the design process that mechanised interactivity between the inner and outer worlds of the participants. I discovered a pattern of hierarchical thinking that encompassed all three participants across their entire protocols, and serve as extensions of Goel's (1995) information processing account of abstract hierarchies and pattern recognition in the problem solving space of designers. As such, I developed a four level model of hierarchical thinking (Figure 7.1, p.287) for design cognition in which I merged information processing theory with intentionality theory. The data suggested that designers need to draw a logic and conscious alignment of aspectual intentions, functional intentions, physical elements and implementation intentions in order to achieve direction of fit and subsequently realise coherent Gestalt. This merger adds 'dual nature' theories in design methodology that currently only distinguish between functional intentions and physical properties of artifacts when designing (Kroes, 2002) and that do not align with aspectual and implementation intentions in order to achieve coherent Gestalt.

I found that the participants incrementally, but not linearly, developed their ideas by starting with formulating abstract aspectual intentions, functional intentions, and physical properties to achieve their intentions with, and by concluding with implementation actions. The central role of

pattern recognition and visualisation was highlighted, which implied making cognitive connections between internal and external sources of knowledge. The theoretical implications of this addition is that information processing models of the design task environments and problem solving space are extended to include the external environment that allow for interactive accounts of cognitive engagements of designers. In this way, accounts of direction of fit (in the mental states) could include generalised explanations in terms of external information accessed through affordance, intention-attention behaviour, perception-action cycles and specificity of information. In this regard, one of the limitations of the study was that I did not conduct a one-to-one mapping of all the knowledge types associated with each of the hierarchical levels. I consider this as a possible extension of the study.

Based on my findings of the dominant role of the participants' awareness of intentions and their subsequent alignment of decisions, activities and objects in expert design behaviour in the early stages of the design processes, I now construct the concept 'intention-permeation'. Intention-permeation builds a conceptual and practical bridge between the internal and external worlds of designers. Intention-permeation can be defined as the penetration of objectively, subjectively or opportunistically selected intentions and their alignment with designers' subsequent behaviour. The implication is that intention-permeation is a forceful, yet subtle cognitive mechanism that enables dynamics in the thought processes of designers. This implies that designers' decisions and actions are driven by their intentions, which leak through chunks of thoughts connected thematically. It follows that any change in direction of thought processes are brought about by realignment of the behaviour to form a coherent unity with selected intentions.

I view intention-permeation as a dynamic psychological strategy of structuring and solving design problems. The possibility of connecting intention-attention with psychological characteristics identified by Goel and Pirolli (1992) is indicated by my coding system (Appendix D and Appendix E). As such, mental state inclusion in information processing theories may serve as productive building blocks to reveal the inevitable inclusion of internal and external realm domains (task environments) of designers in real life design situations. The close coupling of internal and external worlds of designers might possibly contribute to construct a unifying theory in which interactivity between the inner and outer worlds are put at the centre. I consider the embodiment principle of intention-attention amenable to close coupling with IPS theories. However, although existing literature on embodiment refers to intention-attention, and psychological studies of decision behaviour in turn refer to goal-directed processes, the concept intention-permeation has not yet been formally introduced in the context of design studies. For this reason, I consider the outcome of my study in terms of associating concepts as innovative and as such, adding to the knowledge base on both IP and embodiment in an interactive design context.

7.5.1.2 Vertical processes and patterns

In secondary research question 3, the focus was on the role that internal-external interactivity played in the control of the vertical development of the participants' thought processes. I integrated Goel's (1995) notion of vertical transformations with theories that are concerned with top-down and bottom-up thought processes. The contribution to Goel's (1995) theory is in essence one of showing how conceptual sketches may be used to determine vertical couplings among their intention-driven and emergent-driven events on multiple timescales of designers.

The data from my study, which I modelled into visual presentations of the vertical transformation of expert designers' thought processes, indicated to me that participants' dynamically and constantly moved in and out of their internal and external task environments during the early phases of the design processes. In secondary research question 2, I uncovered instances where directional changes took place on an anatomical level. Whereas the complexity of design thinking is widely acknowledged (Blessing, 2000; Cross, 2007a; Visser, 2004), this study demonstrated how to untangle the complexity and find some kind of structure in the often dense and overlapping mental activities involved in design behaviour.

I discovered that designers' aspectual intentions served as the driving force needed to complete a coherent line of design reasoning in the wake of many intersecting external and internal distracting stimuli. By bringing aspectual reasoning into the equation, I could account for the cycles of coherent meaning making of the participants which could be generalised across the design domains involved in the study. These cycles of meaning making indicated dependency relations. This insight confirms my earlier proposition that designers need to consciously consider design aspects and connect these automatically with functional intentions and external elements in order to attain Gestalt. The participants engaged in cyclical thinking which extended in multiple sub-cycles until the functional intentions were exhaustively considered and achieved. During these cycles, there were multiple instances of overlap and repetitive interaction with the same physical elements. These elements were referred to in various combinations and recombinations, which confirm the centrality of Gestalt in theories of extended cognition.

In addition, the importance of implementation intentions was suggested by the participants' relatively frequent use thereof as means of self-regulation. I found that the embodiment notions of perception and conception could be interpreted as implementation intentions. This was evident in instances when participants engaged in interactive perception-action cycles. The participants, while or after perceiving opportunities of using physical elements, acted by referring to how a particular implementation activity would ensure achievement of a specific functional or aspectorial intention. This confirmed my intuition about the designers' need to consider both aspectual and implementation intentions in order to satisfy their coherent Gestalt.

In turn, satisfying Gestalt implied adherence to the functional intentions by using physical elements. The significance of this insight is that the need for Gestalt can be seen as encompassing all intentions and interacting with ecological factors. This insight is an extension of Gero and Fuji'si (2002) model.

I consider the addition of implementation intentions as an extension of existing design cognition theory as it provides a refined calibration of the development of intentional thinking, which in turn sheds light on the incremental transformation of mental states. Although implementation is often implied in functional intentions reported on (Goel, 1995; Suwa, Purcell, et al., 1998), its cognitive role has not been defined in terms of computation or of interaction. I regard its individuation away from functional intention as an important addition to current design cognition theories that tend to focus exclusively on functional intentions of artifacts when reporting on design methodology (Kroes, 2002). I consider the articulation, either visual or verbal, of implementation intentions as an important indicator of commitment, which designers need to refine their solutions.

The data furthermore highlight the significance of the notion of a multi-directional dependency in extended design reasoning theory. The interactive use of physical elements to satisfy intentions emphasises the dependence of higher order intention satisfaction on lower order physical elements (Figure 6.2, p.241). Similarly, physical elements in isolation were meaningless in the context of the study and depended on intentions to become meaningful. The implication of this is that intensions and physical elements each have distinctive strategic roles in the design process. Whereas intentions, from a top-down position, drove the purposeful search for appropriate physical elements to use as concretisation of the participants' intentions, the same cannot be said of physical elements. Therefore, the data suggested that physical elements depend on being perceived externally or visualised internally. Physical elements become consequential only when their emergence from the environment and potential usefulness is connected to an intention. In this manner, I draw theories of vertical reasoning processes (Figures 6.3,.6.4 and 6.5) and their links with extended cognition into the current debate around extended theory being able to account for the dynamics involved in design processes of expert designers.

Although I could point to significant theoretical contributions of an expanded theory of vertical transformation, some limitations in the secondary research questions are evident. The first limitation is that it was not possible to generalise across patterns of vertical processes in a way that could serve a predictive purpose, due to the centrality of context. However, it was possible to generalise across the overall necessity of both internal and external sources of information to mechanise vertical directional change in thoughts. The second limitation is that, although lateral transformation could be inferred from the data, separate and independent maps are needed to

connect the lateral developments to internal and external resources, apart from what is discussed in secondary research question 5.

7.5.1.3   Attention span

In secondary research question 4, I investigated the role that internal-external interactivity played in pursuing (or not) ideas. This question's aim was to take existing theories on what designers think about one step further. The theoretical contribution of this question is twofold. Firstly, my study confirms Suwa and Tversky's (1997) notion of designers' shift in attention and their subsequent classification of attention span into long and short chunks. In addition, I take these authors' theory one step further by adding aspectual and implementation intentions and considering visual and verbal data integratively as part of long and short chunks..

It is further evident that when the participants made sketches, the modules they related to, consisted of long chunks. This implied that external visualisation prolonged their attention to a particular theme. In this way I could connect long chunks with multiple modes of output, increased information, specificity and level of commitment. The longer participants spent time heeding a particular idea, and the more modes of output they were engaged in simultaneously, the more detail and specificity were included, which all pointed to increased commitment. It is at this point where I extend Goel's (1995) theory of commitment in which he connects multiple modes of output with increased commitment.

A limitation of the study in this regard was that I could not find a satisfactory explanation for the reasons for short chunks being short, other than attributing this to limited time. A further study could possibly shed more light on this issue by connecting long and short chunks with top-down and bottom-up thinking.

7.5.1.4   Making and propagating commitments

In secondary **question 5,** I expanded on Goel and Pirolli's (1992) notion of making and propagating commitments by exploring the semantics of verbal and visual representations and connecting it to internal and external influences. My investigations in this regard lead to two contributions in commitment theories. The first is an expansion of information processing theory of symbol systems on a metaphysical level. My theory of interactive cognition fits comfortably within existing schema used by Goel (1995) as basis for his own theory of notational systems, as illustrated and explained further on (Figure 7.2, p.293).

Whereas Goel theorises about sketches (external objects), when they are made while talking (external activities), as signs of commitment, I argue that implementation intentions are also

signifiers of commitment, although they occur in verbal or visual representations. As intimated in secondary research question 4, I inferred this signifying power of intentional commitments from the relative late stage in the design process it typically emerges from its connections with long attention spans and from its co-occurrence with sketch making instances (Figure 6.2 [p.241], 6.3 [p.244], 6.4 [p.247], Addendum D). The implication of this observation is that I could extend Goel's (1995) metaphysical interpretation of symbol systems.

Goel (1995) explains symbol systems as the relation between scheme and realm. The scheme domain consists of equivalence classes of physical states to which computational states are assigned. The realm domain consists of sets or classes of: (a) tokens or instantiations of other computational states, (b) external actions, (c) mathematical entities, and (d) objects, states of affairs and events in the world external to the systems. I take his theory further, not on the level of the scheme, but on the level of the realm domain and explanations of the relation between scheme and realm. I include both internal and external elements. Although Goel's 'realm' also includes internal and external elements, his account for the relation between scheme and realm merely focuses on the materiality of sketches and does not include explanations of the interaction between other physical objects in the environment, sketches and internal mental states. It is at this level of interactive explanation where I extend Goel's (1995) theory of symbol systems in a design context. I argue that design cognition can be described as a coordinated effort of designers to achieve internal and external coherence — a process that is partly facilitated by making sketches. As such, I propose a novel model of extended information processing, as visualised in Figure 7.2 (p.293).

By viewing the symbol system in the way visualised in Figure 7.2, direction of fit was apparently determined by the participants' inner worlds of intentions that they wanted to achieve, and instructions from the client that they wanted to comply with. The conditions of satisfaction and achievement of these inner mental states were in turn determined by the synergetic interaction between the inner and outer realms. As such, the theoretical issue at stake in my model is essentially about explaining two aspects of the processing of information in an extended cognitive process where internal and external elements are integrated. The first aspect involves the relationship between the particular (symbol system) scheme used by the participants and the realm or part of the external world in which their symbol systems were situated. I expand Goel's (1995) metaphysical interpretation of the concept of symbol systems by dividing the realm domain in two sections, whereas the realm according to Goel's (1995) interpretation consists of one whole section in which no separation between internal and external elements are made. However, in order to account for interactivity, in my model I separate these two extremes. On the one extreme lies the internal domain of mental states, knowledge, personal preferences and information processes, while the second extreme comprises the external world of

physicality and materiality including objects and activities. The data presented in Chapters 5 and 6, as well as the answer to secondary research question 5 indicated that it was possible to draw causal relations between the scheme and the realm. This implied that the participants' references were the function of their constitutive symbols and the composition of the symbol systems they used (Goel, 1995).

The second aspect in my model (Figure 7.2, p.293) that adds to expansion of the theory of symbol systems (Goel, 1995) involves the insight that the dual nature of sketches makes them amenable to instantiate and transform content and structure. The implication is that this theory of mine accounts for the correlation between the syntactic structure of sketches made during various stages in the design process and the corresponding mental states by judging the constitutive nature of the internal and external processes. I allege that the vague and ambiguous nature of conceptual sketches in the early phases of the design process is not only indicative of the cognitive phase, but also bears information regarding the mental state and how close or distanced designers are from direction of fit.

I furthermore extend Goel's (1995) theory of vertical transformation through constructing and manipulating models by explaining them in terms of the metaphysical account of transformation (Shani, 2012). I posit that developing design sketches is a complex process of externally representing multiple internal semantic changes. I furthermore theorise that making design sketches is dependent upon internal visualisation interacting with external visualisation. Such visualisations imply the ability to distinguish and change structural relationships in images, a skill that is closely linked to the operations involved in perceptions (Arnheim, 1969). Transformation can thus be defined as designers' ability to interactively visualise internally and externally, and to make conceptual connections between spatial configurations of physical elements in their sketches with their mental states. Sketches are thus vehicles of both lateral and vertical transformation. However, vertical transformation does not merely entail a singular linear top-down or bottom-up process, but rather implies multi-directional processes where top-down and bottom-up are often unpredictably interchanged according to contextual variables that influence designers' perception-action cycles.

7.5.2   METHODOLOGICAL CONTRIBUTION

The third primary research question, namely *how can applying mixed methodology strategies contribute to the validity of protocol studies in a design context?,* implies the potential methodological contributions of my study. The **first** methodological contribution of this study materialised in secondary research question 1, focusing on establishing the extent to which embodiment principles interacted with participants' ability to approach and complete the early phases of the design process. I adapted Goel and Pirolli's (1992) concept of thoughts leaking

from one module to another into the notion of leaky phases. The data suggested that two pairs of the designers spent the same time on problem structuring than problem solving, while one team spent more time on problem solving than problem structuring (Table 5.1). Within these broad temporal patterns, I traced the distribution of interconnections between instances of embodiment principles and the following variables (Addendum D): the use of internal knowledge types, psychological characteristics, modes of output, direction of thought, and cognitive phase.

I can subsequently theorise about the complex, non-linear and unpredictable nature of the cogntive movements between the various phases. This lead to insight regarding the importance of context and the limitation of non-generalisability in studies in which ecological principles are assumed. Although the methodology I applied can be repeated, the sequence of the participants' movements could not be guaranteed as being repeatable. The complexity of design behaviour is confirmed by the co-occurrences of multiple internal and external processes. The results contributed to my computational mapping of participants' constant but complex movement between the inner and outer worlds.

The quantitative findings that presented the extent of internal-external interaction confirm the importance of taking all the sources of information into consideration, as alluded to by extended cognition theorists such as Kirsh (2009), and Shani (2012). However, a limitation of the study was its narrow focus to the role of intentions as driving force of design behaviour. What it subsequently failed to show was a detailed quantitative account of all the possible associations between all embodiment principles[41] with all the various knowledge types. However, as the data for such associations were captured in a coding system (Appendix D) and statistically calculated (Appendix E), it is possible to extend the current study in follow-up research.

The **second methodological** contribution came from answering secondary research question 2. The participants' computational maps (Addendum D) revealed sequence and semantic composition of their thoughts. This assisted me to categorise the types of things they thought about into four categories, namely aspectual intentions, functional intentions, physical elements and implementation intentions. From refined maps (Addendum I), I derived an incremental increase in information, which I in turn connected with the cognitive hierarchy in which these four categories appeared in the protocols, as visualised in Figure 7.1 (see p. 287). In turn, an analysis of things designers think about could be connected to their internal and external thought processes.

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[41] I failed to describe connections between the embodiment principles, affordance, perception-action and specificity and all the various knowledge types.

The **third** methodological contribution of the study can be found in the secondary research question 3, which built on secondary question 2. As such, the methodology of computationally tracing the origins of the participants' thoughts and the progression of their thoughts allowed me to infer the control mechanism behind actions and trace it to an internal or external source. This contributed to my theory that thoughts either originate in mental states including obligations to follow brief instructions, attaining aspectual and functional intentions or internal knowledge accessed through LTM. Alternatively, thoughts may originate in external information afforded by the external task environment. Once I individuated the driving force behind thoughts, I was able to tail the vertical trajectory of a module, which in turn resulted in the connections I made between the internal/external origins of thought and their direction. This contributed to my theory of the multi-directional nature of designers' thought processes that entailed top-down and bottom-up patterns. Top-down processes originated in internal sources including instructions, intentions and knowledge, while bottom-up processes originated in external information afforded by physical elements.

The **fourth** methodological contribution of my study relates to secondary research question 4, which focused on the role of internal-external interactivity in pursuing ideas. This question confirms Suwa and Tversky's (1997) model for analysing sketches in order to determine where shifts in attention of architects occur. I used their methodology but extended its use to involve not only analysing architects' sketches, but to analyse both verbal and visual data from three different design disciplines. I extended Suwa and Tversky's (1997) model by closely coupling long durations and internally determined aspectual intention while I associated short durations with thoughts originating in information that emerged from external elements. However, when the participants connected emerging information with internal knowledge that is stored in their LTM and with their aspectual intentions, embodiment contributed to longer chunks of attention. Although I could infer that such connections contributed to longer chunks, there was no reason to believe that the absence of such connection contributed to chunks being short.

The **fifth methodological** contribution of my study relates to secondary research question 5, which entails the structural analysis of the participants' visual representations. I primarily relied on qualitative analysis of the external structure and physical character of the participants' sketches in terms of ambiguity, density and vagueness to address this question. The structural properties of sketches contributed to their ability to represent lateral and vertical transformations, whereas their dual nature allowed them to instantiate mental states and to facilitate transformation. Degrees of specificity and transparency in their physical content thus informed me about sketches' correlation with cognitive phases. Their distribution in the sequence of thoughts and their contents confirmed the role of sketches as external driving force in the development of ideas, and their mechanistic role in changing vertical direction of thought

processes. I subsequently argued that a theory of design cognition cannot be balanced without acknowledging both external and internal aspects involved in information processing when engaging in design problem solving activities.

7.5.3   PROFESSION-RELATED CONTRIBUTION

In the current competitive and developing worlds, all demanding suitable and efficient products to be used within particular contexts, an alignment between intentions in the start states, transformation states and goal states of designers is necessary. In this section I focus on the potential contribution of my study to professional designers across domains.

7.5.3.1   Reversing the direction of transformation and intentions

During the various sub-phases of problem solving, the central role of interaction between the internal and external worlds of the designers was evident. The study emphasised the importance of reversing the direction of transformation as part of their internal worlds, driving their design processes. Although the assumption in professional design work is that the primary driver of decision making and commitment is the instructions and requirements of the client, I found that experts question the intentions and implied solutions of the client based on their superior knowledge of aspectual intentions and domain specific knowledge. Meta-cognition of the source of their thoughts might explain to professionals where directional faults or suitable solutions originate. Such knowledge could in turn contribute to adapting subsequent behaviour by changing the direction of thoughts or developing what is currently on the table incrementally according to the best fit. The multiple vertical changes in direction, from top-down to bottom-up and vice versa, emphasised the importance of being open to internal as well as external triggers of ideas.

7.5.3.2   Hierarchical thinking and Gestalt

I found a hierarchical structure in the things that the participants thought about. A general pattern across all the protocols, consisting of a four-level hierarchy, ranging from abstract aspectual intentions, functional intentions, physical elements and implementation intentions, emerged. Considering these levels consciously, and using it as an instrument to ensure coherent Gestalt could benefit the thinking process of professional designers. They could constantly draw interrelations between their intentions and instructions on all four levels, ensuring that they create self-regulating perception-action feedback loops in their thinking to ensure direction of fit. By interactively or retrospectively individuating instances in their own and other design processes when intentions are being explicitly articulated, it might be possible for other

designers in practice to infer what the implicit indicators of the selection of their intentions are and judge the suitability of their choices.

7.5.3.3 Vertical interaction–patterns of development

While it is widely acknowledged that the design process does not imply a linear structure, this study indicated patterns of vertical processes. However, vertical in this sense implied the direction of thoughts and not a linear sequence. The data furthermore suggested the central role of identifying the source of particular thoughts in order to determine whether the control of the transformation direction lies with internal or external sources. Knowing where the control lies means that professional designers can revisit such a source at a later stage to investigate its appropriateness in detail, as opposed to merely reacting on driving forces without connecting the information it provides (or not), with the direction of fit. Conscious revisiting of resources does, however, not imply that designers should fixate on them as this might limit their perceptiveness for emerging information from unexpected sources, internal or external.

7.5.3.4 Value of conceptual sketches

Whereas current design practises suggest an increased use of digital methods of sketching and drawing, this study emphasised the necessity to sketch manually, as it is the act of sketching in combination with perception that seem to generate different kinds of thinking, rather than digital methods of sketching. It is in particular the structural properties of the marks made by hand that are significantly unique and beneficial to accommodate the loose control structures of creative designers. While it is easy to be seduced into early commitment to clear and unambiguous sketches that are primarily the end products of digital methods, it seems to be the vagueness and ambiguity of conceptual hand sketches that contribute to designers' propagation of ideas and gradual commitment to them. Hand sketches furthermore allow for much lateral and vertical transformation, which might not necessarily be the case with some digital material.

Learning from the value of making and using free hand sketches in my study might contribute to professional designers' consideration of the choice of visualisation strategy in the early phases of their design processes. The sketches of the participants showed evidence of their physical description of basic formal primitives. By engaging with the external nature of their visualisations instead of using digital media to externalise, professional designers may connect with the physical world and the concretisation of their ideas without indulging in more imaginative primitives. Although much effort is currently put into the development of digital sketch software (Dillon, 2010), professional designers should be aware of the different ways of thinking it elicits and at what stage of their design process it is conducive and appropriate to use.

7.5.4   EDUCATION-RELATED CONTRIBUTION

In this study, I described design practices of expert designers which revealed some evidence of a unique intellectual culture with its own 'designerly ways of knowing, thinking and acting' (Cross, 2001b). By drawing on what has been shown as examples of expert design behaviour, design educators might benefit from applying teaching and training strategies that could enhance such a culture. The way in which I designed and implemented the TAPS might therefore serve as an example of a possible way of facilitating novice designers in developing design thinking skills that mirror those of experts. By implementing the requirements for ill-structured problems that include both internal and external components, they might aid the potential development of some psychological processes characteristic of expert design problem solving spaces. It is in particular learning the skill of unpacking an ill-structured problem, identifying what information is given and what is not given that seems essential in understanding and structuring design problems.

Hierarchical thinking, based on intentional states coupling with physical elements was highlighted by this study as a psychological characteristic of experts' design thinking. By consciously introducing the various levels of intentions in hierarchical order, understanding to differentiate between them through conceptual knowledge acquisition and practical perceptual explorations of existing artifacts, design educators may contribute to the development of students' Gestalt alignment of intentions and solutions to problems. This study further showed that experts possess knowledge of how to use these physical elements to concretise their abstract design aspectual, functional intentions and implementation when planning a new artifact. Connecting these with appropriate physical elements allowed the designers to concretise their internal states of intentions. This demonstrated the importance of progressing through the levels of abstraction to concretisation. Design educators may gain useful information to guide them in their engagements with novice designers in training by copying the strategies the experts employed, focusing on the dual nature of artifacts, namely the physical and the functional, and aligning these with their knowledge of design aspects.

What the current study in particular demonstrates is the conceptual knowledge that experts seemingly possess of the external world of artifacts that is relevant to their design domains, their physical components and properties that achieve their functionality. Their exceptional ability to link this and other conceptual knowledge to their internal and external visualisation abilities was clear. A major part of their design strategies was the experts' making connections between domain specific knowledge of efficiency and effectivity, and normative thinking when they applied evaluation functions and personal stopping rules. Effective design education should include opportunities for students to develop such thinking skills.

Design educators might further gain from the study by heeding the structure of expert designers' task environments and the way it may influence their problem solving spaces. This study presents evidence of the necessity of having access to internal as well as external sources of information in order to allow for productive internal processing of information. The study emphasises the critical value of procedural knowledge to enable students to find their way in ill-structured task environments. Such procedural knowledge was shown to be founded on multiple cognitive activities. These include inquiring, perceiving information afforded by external environments, acting on it and heeding internal intentions. Students' procedural knowledge might therefore be developed by purposefully and perceptually paying critical attention to relevant physical elements that may lead to direction of fit and attend to increasing specificity of internal and external information. It is in particular the ways in which the expert designers manoeuvre between their internal and external worlds that seemingly allow them to swiftly and efficiently reach satisfaction of their intentions and compliance with instructions.

This study can further contribute to design educators' facilitation of external visualisation skills and choice of media. This implies that educators should become acquainted with the different ways of thinking required by different media. Their teaching could also benefit from considering the instantiative and transformative role that hand sketches may play in both the problem structuring and problem solving phases of students' design processes. By learning about the cognitive value of making rough, ambiguous sketches, educators may encourage the use of free hand sketches. By restricting the participants in this study to the use of free hand sketching, the types of cognitive activities the experts were involved in during the early phases of their design processes might benefit design educators if they were to adapt their teaching and learning programmes accordingly. As in the case of professional designers, design and TE has also been confronted by a shift in the focus to digital media instead of traditional free hand conventions. This shift poses problems for the development of internal cognitive manipulations necessary to connect with physical form depiction.

7.6 GENERAL STRENGTHS OF THE STUDY

I consider the methodological choices I made, and which were based on the quality requirements of representation and legitimation, as a strength of my study. Representation in this context refers to the way in which I extracted adequate information from the underlying data and how I analysed it. Legitimation refers to the validity of my interpretations, as discussed in more detail in Chapter 5. I was able to represent complex, real-life design problem solving activities by examining participants' mental processes when involved in the early phases of the design process. The concurrent protocols conducted in the design experiments allowed me to

study the mechanisms involved in verbal and visual representations that impacted on a characterisation of typical expert design behaviour.

I approached this study employing a parallel mixed methods approach collecting and analysing quantitative and qualitative data. The decision to apply mixed methods was effective as it allowed me to collect different forms of data (quantitative and qualitative, verbal and visual) and integrate them. This added value to the study and its findings, and was achieved through linking temporal measurements, incident counts, proportions, relations with qualitative words, and sketches. Linking the data allowed me to employ iterative bidirectional analysis. Not only was I able to move iteratively between verbal protocols and sketches to confirm the inferences I made, I was also able to confirm the quantitative findings with the qualitative findings moving backwards and forwards between the data until I was sure that the research questions had been addressed.

A mixed methods approach also allowed me to apply and confirm design problem solving theory, while at the same time enabling me to expand the DPS theory. I expanded the DPS theory by associating it with embodiment theory. This resulted in my understanding of research in design cognition as a continuum consisting of a range of options. It furthermore revealed where weaknesses and strengths of different options could be purposefully selected in order to attain balance and compromise, instead of viewing this as a set of dichotomies that would limit what we could learn from research.

I manipulated the traditional laboratory type design experiment in the sense that I controlled the design problems that the participants were required to solve. I adapted the conventional experimental notion of protocol studies to allow the participants to work in pairs and small teams. This enhanced the flow of their thoughts and subsequently generated a large amount of cognitive instances which I used as units of analysis. The adapted experiments furthermore allowed me to consider the complex theory underlying the study. The study, therefore, was variable oriented and not case-oriented. I used the opportunity to generate multiple variables relevant to existing theory.

Through counting, measuring time, determining distributions and proportions, and drawing networks of associations, I could infer patterns of generic expert design behaviour as well as some cognitive mechanisms. I derived patterns of interactivity between internal and external resources, hierarchical thinking mechanising synergetic achievement of direction of fit, and coherent Gestalt and vertical transformations. The syntactic and semantic analysis of the visual data furthermore provided information regarding the instantiative and transformative role of conceptual sketches in the early phases of the design process. By employing quantitative and qualitative confirmatory data analytical techniques, and using variables from two different

cognitive theories, I was able to confirm the ability of Goel and Pirolli's (1992) problem solving space theory to integrate ecological cognition theories (Bickhard, 2008) and subsequently contribute theoretically by proposing an alternative expanded theory of design cognition.

In conclusion, the strengths of the current study can be found in the multiple models proposed for various theoretical and philosophical inferences demonstrated by empirical evidence. These models include vertical mapping (Figures 6.3 to 6.5 [p.244, p.247, p.250]); hierarchical thinking (Figure 7.1, p.289); cognitive mechanisms and the functions in the design process (Figure 7.2, p.296); and the role of symbol systems in extended cognitive design theory (Figure 7.3, p.318). Finally, I could map the South African Department of Basic Education's model of the design process with the cognitive characteristics of expert behaviour in the design process, as found in this study (Figure 7.3).

7.7 POTENTIAL LIMITATIONS OF THE STUDY

The first limitation of this study relates to the inherent inability of design experiments to provide a true life design task environment. This weakness is vested in one of the aspects generally present in real life design tasks, namely the 'penalty for being wrong'. In my adapted experiment no 'real time' was used. Furthermore, no 'real resources' were consumed or wasted and the decisions and actions taken by the participants had no real consequences. As I (as researcher) was no 'real' client who would normally set penalties for erroneous decisions, the participants could potentially neglect thinking through and anticipating as many as possible consequences of their decisions. I attempted to prevent this possibility by selecting experts who were reportedly in the habit of always considering as many consequences as possible.

A second potential limitation was the inability of a concurrent TAPS-protocol study as data collecting instrument to allow the participants to externalise every thought they had during the protocols. It was thus not possible to provide visible evidence of everything that the participants thought about, which necessitated my reliance on inferences of some of their cognitive behaviour. On the one hand, I attempted to compensate for this potential weakness by using multiple forms of data, namely video material, verbal utterances and concurrent sketches countering or confirming each other. On the other hand, the advantage of this research strategy in a design context was that I was able to keep track, trace and map many processes and sub-processes that were captured in the recordings of the protocols. This enabled me to infer cognitive processes, which underlie the actual concurrent sequences of thought.

Thirdly, the manner in which I designed the data collection through TAPS, during which talking and sketching took place concurrently, posed challenges of its own. One such challenge was that it resulted in the cognitive process to be slowed down. This means that participants slowed

down their normal processes in order to synchronise their verbal thoughts with visualisation. The result of this phenomenon was that the group of industrial designers, consisting of three members compared to two in each of the other protocols, used three hours, compared to two hours, to complete their task. In countering this problem, I allowed the industrial designers more time than the other participants to reach the stage of generating a solution that everybody in the group was satisfied with. In general though, allowing the participants to talk aloud to a team member, compensated for this slowdown in their processes.

Next, the size of the sample, did not allow me to generalise my findings and the danger of non-representativeness therefore exists. The implication for representation is that the possibility of subjectivity of participants was possible in terms of particular individual idiosyncratic behaviour skewing the findings. I attempted to counter the challenge of non-representativeness by involving three different design domains. I assumed that, because my sample was purposefully selected from a cross section of expert design disciplines, and natural existing groupings within the selected participants existed, the findings could be considered as typical. Viewing my sample in this manner, I take the view that 'ideographic' and 'nomethic' approaches are not mutually exclusive, and that it is possible to have both rich and intensive descriptions and typifying at the same time. The reason for limiting the number of domains in a single study can be attributed to the large amount of information that is generally generated, which makes reporting on all of this impractical. In addition, the majority of cognitive studies engage in domain specifics and not in the generic processes, as this study attempted to do.

The fifth challenge I experienced was that of countering the possible effect of experts' individual personal design styles, priorities, motivation and personal psychological aptitudes on the objectivity of the data. Although Newell and Simon (1972) aver that it is not possible to eliminate idiosyncratic behaviour completely from design experiments, I attempted to neutralise its effect by purposefully selecting expert designers who met general expertise criteria.

Next, the relatively large amount of data posed a challenge. In spite of the small sample, the pool of generated data was relatively large (Goel, 1995). I considered the meaning of each word uttered and each mark made on paper, as well as the structure of both types of symbol systems, as relevant during data analysis. As each cognitive instance counted as a unit of analysis, the combined protocols contributed to the challenge of analysing, coding and cleaning up the data. Prior to conducting the TAPS, I examined the categories and themes of my conceptual framework. I found that integrating the various theoretical frames in one framework challenged me as it was time consuming and labour intensive. In addition, each cognitive component in my conceptual framework implied multiple interrelated and interconnected variables, which had to be coded as such, yet allow for retracing of individual variables. I combined verbal protocols with concurrently produced sketches, which added to the labour intensiveness of the process.

The seventh challenge I experienced relates to entering the transcripts on EXCEL data sheets. Although EXCEL made it possible to accommodate the information in a systematic and orderly manner, the large pool of data made it difficult to report in detail on all the categories and themes. My integrated conceptual framework permeated multiple and complex potential interrelationships. I ensured valid analysis through multiple iterations and repeated readings of all the data sources. I separated the analysis of verbal data from the visual data, which assisted me to order and retrace information. Cross references in the coding system aided me in drawing cross-correlations between the two sets of data. The benefits I gained from these strategies were that I was able to triangulate my analysis. I was also able to correlate inferences by comparing verbal data with visual data and could in this way strive to obtain credible findings.

The next challenge of this study involves the decision to employ a mixed methods research design. In spite of my efforts to use the benefits of the QUAL and quan methods, it nonetheless posed certain limitations. Coding the complex set of qualitative data in a manner that was practical and meaningful to the statisticians, who were divorced from the rest of the research process, required multiple visitations. In addition, modelling design problem solving spaces that encompassed internal as well as external processes and elements that sufficiently captured the nature of my study's explanatory target was challenging. However, my conceptual framework provided a secure structure for the statistical procedures. I furthermore made use of a technical statistical assistant who assisted me in structuring the coding process. As a result, I was able to expand on the existing typology development of generic design behaviour.

7.8   REFLECTING ON MY ROLE AS RESEARCHER

In my view, I was relatively well-prepared to conduct this study. Based on my ongoing work in professional design work and design education as a lecturer at a tertiary institution since 1995, I had established an extensive network of professional designers and academia in design education. I was sufficiently positioned to approach these connections when accessing expert designers in my purposefully selected domains as potential participants of my study.

My participating role in the TAPS, acting as client, posed some challenges during the data collecting phase. During the protocols, I had to guard myself from not taking part in any choices, selections, judgements or evaluation functions that could influence the direction and pace of the participants' cognitive processes. However, being a lecturer in design education for many years provided me with sufficient insight to withhold my own views and ideas, and only participate by providing necessary information and monitoring think-aloud procedures.

I experienced the data analysis as tiresome. In order to stay mentally alert, I constantly made field notes on EXCEL sheets that enabled me to keep track of the conceptual links between the

various categories and subcategories as I progressed. The implication is that my coding sheets overlapped in field notes which I carried over from one category to another. I found that overlapping notes supported my understanding of the complexity of the multiple interrelationships between all the themes and sub-themes. Furthermore, I faced personal bias during the analysis phase. Due to my own academic and professional foundations in visual arts, I was naturally more familiar and at home with the data generated by the architecture participants. Mentally, this bias might have strained me when analysing the engineers' and industrial designers' data. These compelled me to read and re-read material, and constantly engage in discussions with colleagues and contacts in these fields informing me about the conceptual and procedural nature of the two domains.

7.9   EFFECTS OF THE STUDY

The following effects have already been initiated as a result of this study:

- Establishment and implementation of a curriculum for undergraduate TE teacher training at the Faculty of Education of the University of Pretoria.
- Development and incremental implementation of a curriculum in interactive design thinking for undergraduate students specialising in Engineering Graphics and Design in the Further Education and Training phase at the Faculty of Education of the University of Pretoria.
- Development and implementation of a curriculum for postgraduate design students (including architecture, landscape architecture and interior architecture students) enrolled for teacher training courses specialising in Engineering Graphics and Design at the Faculty of Education of the University of Pretoria.
- Development and incremental implementation of a fourth year course in ill-structured problem solving strategies at the Department of Mining Engineering of the University of Pretoria.
- Development and implementation of philosophy of design workshops for Higher Education across design domains, including fashion design, at the Faculty of Fine Arts, Design and Architecture of the University of Johannesburg.
- Election to serve on the advisory board of the Technical University of Tshwane's department of Industrial Design in the capacity of design education specialist.

7.10   RECOMMENDATIONS

Based on the findings of my study, I make recommendations with regard to further research, practice and training of TE teachers.

7.10.1 RECOMMENDATIONS FOR FUTURE RESEARCH

An interactive approach to expert design cognition identifies intentional attention to particular external physical things as a core principle of cognition and external representation. Based on the complexity of the interactive processing of information in the early phases of the design process by experts found in this study, I recommend the following forth-flowing studies:

- A case study exploring the push and pull role of different types of intentions, namely aspectual, functional intentions and implementation intentions versus instructions of expert designers across design domains.
- Comparative studies exploring how the different types of intentions bridge internal and external processes.
- Exploratory quantitative studies across design domains focusing on the procedural knowledge and its relations to implementation intentions and the quality of their end products of experts across the design domains.

I recommend the following studies with novice designers in the various professional design domains:

- Evaluation studies that explore the potential effect of interventions focusing on conscious articulation and application of types of intentions in students' design projects on the quality of end products.
- Case studies that explore the process of alignment between the various intentions and physical elements to determine the role that Gestalt plays in novice designers.

Content analysis of local and international design and technology education curricula to establish the following might be considered:

- Opportunities provided to develop naive designers' goal-directed strategies.

I furthermore recommend the following studies on TE teaching practice:

- Exploratory quantitative studies exploring how teachers develop students' hierarchical thought processes including contextualised abstract thinking and concretisation.
- Case studies on how teachers may guide students to connect design aspects with real life contexts of design problems that they are required to solve.

In addition, potential studies on the learning practices of TE students may include:

- Exploratory quantitative studies on the use and role that externally perceived objects in the learning environments may play in design projects.
- Case studies on the perceptual skills of students and the possible influence on their cognitive processes in design projects.

7.10.2 RECOMMENDATIONS FOR DESIGN PRACTICE

Based on the outcome of my study, I recommend that novice designers gain practical experience in intentionally moving between their internal and external worlds when structuring and solving design problems. This implies the development of contextualised hierarchical thinking, making connections between abstractions and concrete physical elements. The process of moving between inner and outer worlds assumes linking external information with abstract domain specific knowledge, where conscious transfer of knowledge to new situations might result in better quality solutions to problems. To facilitate quality solutions in turn requires greater internal flexibility in adapting to situations. Flexibility thus entails the ability to adjust thinking in multiple directions, including top-down, bottom-up, lateral and vertical thought processes, as the situation requires. This implies the prevention of designers to fixate on a course of thinking or particular ideas prematurely, in order to delay early commitment to ideas and encourage them to consider multiple alternative solutions before committing to one.

I found that using symbols systems allowed the participants to construct and manipulate models on paper by making marks that physically represent surface properties, which in turn encouraged visual cueing and multiple cognitive actions. Novice designers may gain cognitive expertise by using methods of representation that promote externalised visual thinking in the early phases of the design process. I furthermore determined that experts produce fast flowing thoughts in the early phases of the design process that need to be represented by symbol systems that do not slow down their thought processes or overstimulate them visually.

7.10.3 RECOMMENDATIONS FOR FUTURE TRAINING IN DESIGN AND TECHNOLOGY (D&T) EDUCATION

Considering the potential contributions discussed in section 7.5.4, I recommend an extended cognitive approach to be implemented in the future training in D&T education. This implies a focus on the conscious implementation of a programme that facilitates a synergetic movement of students between their inner and outer worlds. The findings and outcomes of the interactive nature of design cognition might thus be transferred to the development of design education courses in general and to technology education in particular.

Design projects could facilitate expanded cognition by formulating design problems that are truly ill-structured. From a school-based teaching and learning point of view, this implies that teachers should not formulate project problems that imply or explicate the solution. It further means that teachers should provide learners with sufficient opportunities to be confronted with a lack of information in all three states in design problem spaces, namely the start state, the goal state and the transformation state. Instead of providing all the information regarding the physical context of problem situations during the start state, learners should rather be guided to

find out what they do not know about the context through enquiry. Subsequently, they could then search and find the relevant information. Similarly insufficient information regarding the goal state means that teachers should not prescribe solutions to problems in order to allow for rich and real world related design behaviour during their transformation states. They should rather consider ways of facilitating search processes through questioning and critical thinking exercises that could lead to learners identifying and finding relevant missing information.

D&T training can draw from the rich interrelationships between the variables that influence design reasoning, namely abstract internal processes and the specificity and concreteness of particular design task environments. I found concrete elements in the participants' use of and reliance on physical elements in their environments (Appendix D) while actively engaging in internal processes. Facilitating students to acquire knowledge of physical elements and a concrete understanding of how to engage with these may benefit from the following considerations:

- Conceptual knowledge of the physical properties and potential uses of alternative artifacts.

- Consideration of connections between the kinds of aspects, including the required behaviour of the intended artifact, required functional and physical properties of the intended artifact.

- Implementation intentions and their knowledge of the physical and functional nature of the artifacts they designed.

- A drive to achieve goal intentions by using domain specific knowledge, as well as expert knowledge of the physical and structural aspects of artifacts.

- Intentionally selecting physical elements that may lead to achieving planned functions of artifacts or activities.

Training programmes could consider facilitating the understanding of the reliance of intentions on physical elements in environments by leading students to:

- Interact with external resources such as their sketches and physical objects.

- Construct and manipulate their sketches.

- Actively engage in their internal and external task environments to facilitate their search for structure in their individual design tasks.

- Exploit the physical environment to help them reason and solve problems.

The findings of this study may furthermore guide training programmes in designing activities which could enhance students' ability to draw cognitive links between aspectual and functional intentions. Such programmes are required to nurture a consciousness amongst students of their internal resources. However, conceptual knowledge in isolation is meaningless. Students should therefore be trained to purposefully link their intentions and instructions to physical elements

of artifacts. In this manner, they might develop the cognitive skills necessary to achieve direction of fit and coherent Gestalt through a process of moving from higher order abstraction to lower order concretisation.

D&T programmes may also benefit from emphasising the cognitive role of using various symbol systems, in particular sketches, to instantiate and transform mental states and ideas of learners. Closely coupled with this recommendation is the development of perceptual, internal and external visualisation skills through active engagement with the physical environment, as well as the conceptual and practical implications of the design tasks. Learning activities should include sensitisation and conscious practicing of systemic action that involves reaction on external information afforded by physical elements, intentionally paying attention to things that are relevant to intentions, and looking for specificity of external information. Being flexible between their internal and external worlds may improve students' automatic moving in top-down and bottom-up ways driven by abstractions and concrete things. Furthermore, a focus on the cognitive role of sketches may subsequently lead to teachers guiding students to use their sketches consciously in order to delay decision making and to generate and develop ideas through lateral and vertical thinking processes.

In conclusion, I mapped the cognitive processes of the participants in this study onto that of the South African Department of Basic Education's (CAPS 2012) generic model of the design process. The purpose of this mapping is to present a visual model (Figure 7.3) of the design process that mirrors the cognitive activities of expert designers.
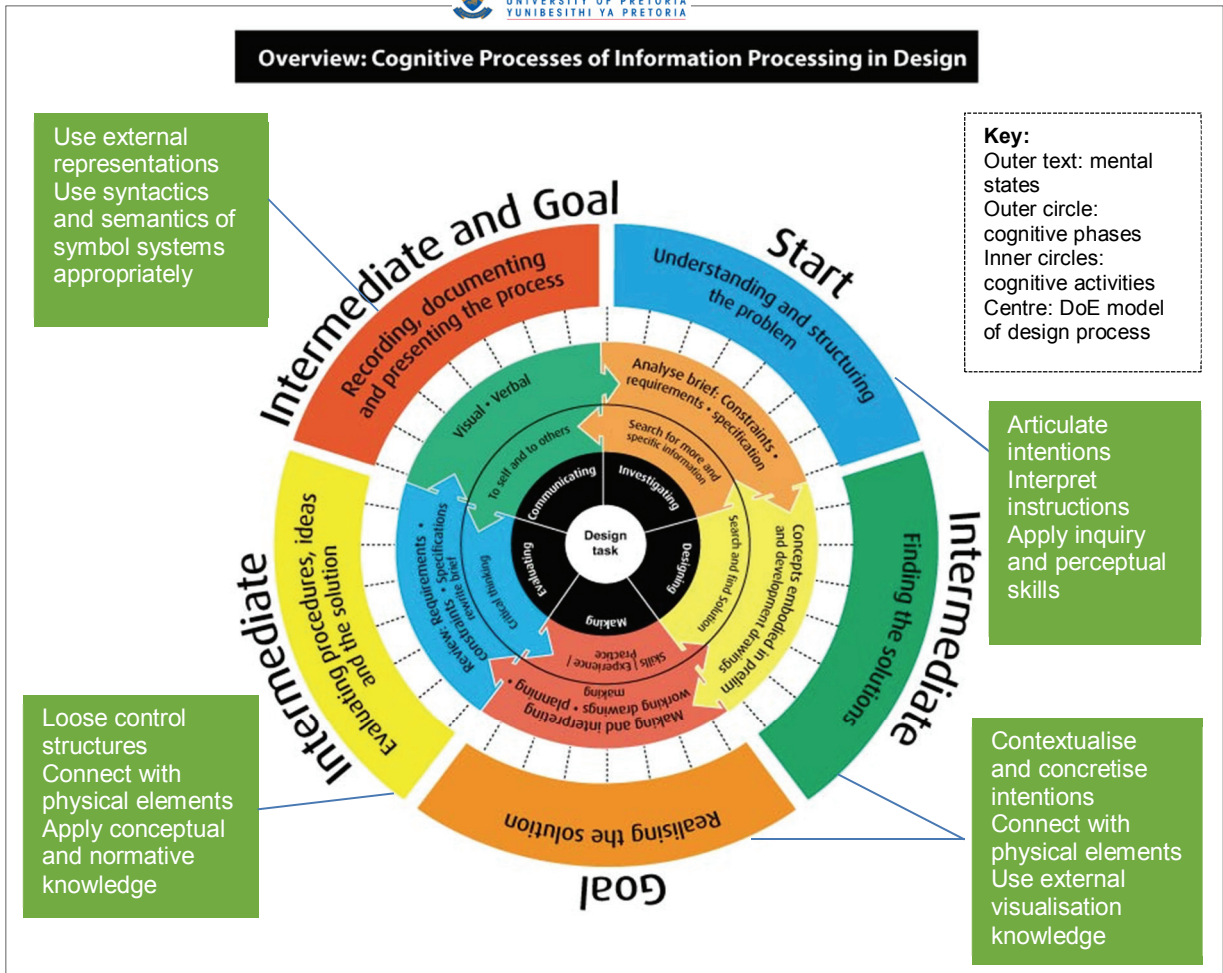
Figure 7.3: Mapping the cognitive processes of expert designers onto the DoE model for novices

7.11 IN CLOSING

In a world that is constantly changing in terms of social and technological development, designers are challenged to design efficient, functional artifacts that fulfil socially and technologically contextualised needs. This requires generic types of design knowledge and domain specific knowledge. To do this, designers need to adapt their behaviour appropriately in order to design efficient and functional artifacts that may address changes like these. Such adaptations require knowledge of the world as a socio-technological system, knowledge of design procedures including interaction with the external world, knowledge of visualisation methods and its power to support design thinking. It further requires knowledge of when an artifact is functional and efficient by selecting appropriate and adequate physical elements.

My study demonstrated the necessity for designers to recognise what they need to know in order to solve design problems and apply effective strategies to find relevant information by linking external information to existing internal knowledge. This means that in a design context one should start with what you do not know, find what you need and build with what you have and know. I aimed to learn from both verbal and visual data. It was important to keep in mind

that interpreting design cognition data assumed that different symbol systems (representations) correlate with different design phases and cognitive processes. Meaningful segments of verbal and visual data were clustered by similar themes, enabling me to identify information in the relevant early cognitive phases.

It is my conviction that the perspective which I advocate here is both novel and worth voicing. No doubt, various components of the view I present share significant degrees of overlap with previous arguments that emanate from the work of major figures in design research. My argument as a whole presents a picture which, despite its plausibility, has not, to my knowledge, received the attention it deserves. One possible reason for the fact that the view I present has not been championed earlier may be anchored in the apparent absence of a crucial conceptual distinction – namely, the distinction between instantiative and transformative vehicles of content in the early phases of the design process.

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APPENDIX A	Participants' detail	CD only
APPENDIX B	Instructions to the participants	CD only
APPENDIX C	Design briefs	CD only
APPENDIX D	Qualitative coding of transcripts [modules & phases, psychological characteristics, direction, ecology)	CD only
APPENDIX E	Statistical treatment of data	CD only
APPENDIX F	Caps document intermediate phase and senior phase	CD only
APPENDIX G	Original sketches in sequence	CD only
APPENDIX H	Sketches coding	CD only
APPENDIX I	Coding duration of modules and intentions	CD only
APPENDIX J	Vertical maps	CD only
APPENDIX K	Field notes	CD only
APPENDIX L	Ethical clearance certificate	Hard copy only
APPENDIX M	Language clearance certificate	Hard copy only

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Faculty of Education

RESEARCH ETHICS COMMITTEE

CLEARANCE CERTIFICATE	CLEARANCE NUMBER :	EP 10/03/01
DEGREE AND PROJECT	PhD
	The cognitive dynamics of socio-technological thinking in the early phases of expert designers' design process.
INVESTIGATOR(S)	Maria Margaretha Catherina Haupt
DEPARTMENT	Educational Psychology
DATE CONSIDERED	26 February 2013
DECISION OF THE COMMITTEE	APPROVED

Please note:

For Masters applications, ethical clearance is valid for 2 years

For PhD applications, ethical clearnace is valid for 3 years.

CHAIRPERSON OF ETHICS COMMITTEE	Prof L Ebersohn
DATE	26 February 2013
CC	Jeannie Beukes
	Liesel Ebersohn
	Ronel Ferreira
	Prof MJ de Vries

To whom it may concern,

The editing and proof reading of the thesis entitled "The cognitive dynamics of socio-technological thinking in the early phases of expert designers' design process" were completed on 6 March 2013. I verify that it is ready for publication and/or public viewing as it is up to the expected standard.

Kind regards,

Melissa Labuschagne

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Melissa Labuschagne trading as Exclamation Translations.
072 995 8740
info@exclamationtranslations.co.za
www.exclamationtranslations.co.za