Design Science

Towards a shared ontology: A generic classification of cognitive processes in conceptual design

Laura Hay[1], Alex H. B. Duffy[1], Chris McTeague[1], Laura M. Pidgeon[2], Tijana Vuletic[1] and Madeleine Grealy[2]

1 *Department of Design, Manufacture and Engineering Management, University of Strathclyde, Glasgow G1 1XJ, UK*
2 *School of Psychological Sciences and Health, University of Strathclyde, Glasgow G1 1QE, UK*

Abstract

Towards addressing ontological issues in design cognition research, this paper presents the first generic classification of cognitive processes investigated in protocol studies on conceptual design cognition. The classification is based on a systematic review of 47 studies published over the past 30 years. Three viewpoints on the nature of design cognition are outlined (search, exploration and design activities), highlighting considerable differences in the concepts and terminology applied to describe cognition. To provide a more unified view of the cognitive processes fundamentally under study, we map specific descriptions of cognitive processes provided in protocol studies to more generic, established definitions in the cognitive psychology literature. This reveals a set of 6 categories of cognitive process that appear to be commonly studied and are therefore likely to be prevalent in conceptual design: (1) long-term memory; (2) semantic processing; (3) visual perception; (4) mental imagery processing; (5) creative output production and (6) executive functions. The categories and their constituent processes are formalised in the generic classification. The classification provides the basis for a generic, shared ontology of cognitive processes in design that is conceptually and terminologically consistent with the ontology of cognitive psychology and neuroscience. In addition, the work highlights 6 key avenues for future empirical research: (1) the role of episodic and semantic memory; (2) consistent definitions of semantic processes; (3) the role of sketching from alternative theoretical perspectives on perception and mental imagery; (4) the role of working memory; (5) the meaning and nature of synthesis and (6) unidentified cognitive processes implicated in conceptual design elsewhere in the literature.

Key words: cognitive processes, conceptual design, design cognition, protocol analysis, psychology

Received 13 July 2016
Revised 18 April 2017
Accepted 18 April 2017

Corresponding author
L. Hay
laura.hay@strath.ac.uk

Published by Cambridge University Press

Des. Sci., vol. 3, e7
journals.cambridge.org/dsj
DOI: 10.1017/dsj.2017.6

1. Introduction

The majority of empirical design cognition studies published over the past 25 years have focused on the early, relatively ambiguous stages of the design process known as *conceptual design* (McNeill *et al.* 1998; Goel 2014; Dinar *et al.* 2015). Generating a high number of ideas during conceptual design is believed to result in lower cost and higher quality products (Jin & Benami 2010). Furthermore, conceptual design tasks are typically associated with creativity and the generation of novel ideas, which are considered fundamental to innovation and societal progress (Li *et al.* 2007). Thus, conceptual design may have a significant impact upon design performance later in the design process, as well as broader social and economic processes and systems. However, in spite of the relative importance of conceptual design and the considerable body of empirical work on the topic, there remains a lack of clarity regarding the nature of the cognitive processes involved in conceptual design tasks (Jin & Benami 2010). Kim & Ryu (2014, p. 519) point to the involvement of 'perception, problem solving, reasoning and thinking about the design', but acknowledge that there is a need for thorough research 'to better understand designers' internal cognitive processes'. More generally, Dorst & Cross (2001, p. 425) note that the internal mechanisms involved in creative idea generation are 'mysterious (and often mystified)'.

A range of methods may be applied in the study of conceptual design cognition. These include case studies, involving in-depth study of individual design projects (e.g. Taborda *et al.* 2012; Buys & Mulder 2014) and controlled tests of cognitive performance during predefined design tasks (e.g. McKoy *et al.* 2001; Viswanathan & Linsey 2012), as well as interviews and questionnaires (Dinar *et al.* 2015). However, the method of protocol analysis may be viewed as the most prolific. In protocol analysis, the nature of a designer's cognitive processing at various points during a design task is inferred from verbal self-reports gathered during or following task performance, as well as design outputs produced and observations of physical behaviours such as gestures and other motor actions (Ericsson & Simon 1984; van Someren *et al.* 1994; Gero & Tang 2001). Whilst protocol analysis has been widely criticised with respect to issues of subjectivity and reliability (Ericsson & Simon 1984; Lloyd *et al.* 1995; Suwa & Tversky 1997; Sarkar & Chakrabarti 2014), it has nonetheless become regarded as 'the most likely method (perhaps the only method) to bring out into the open the somewhat mysterious cognitive abilities of designers' (Cross 2001, p. 80). This view is shared by several authors in the literature, including e.g. van Someren *et al.* (1994), Lloyd *et al.* (1995) and Sarkar & Chakrabarti (2014).

To address the need for greater clarity regarding the nature of the cognitive processes that may be involved in conceptual design, we carried out a systematic review of 47 protocol studies on conceptual design cognition published over the past 30 years (Hay *et al.* under review). A key finding of this review is that although broad commonalities may be detected, protocol studies vary considerably with respect to the concepts and terminology applied to describe cognition. To some degree, these differences may be explained by variations in the major paradigms underlying design cognition research generally, i.e. the problem solving and reflective paradigms as discussed at length by Dorst & Dijkhuis (1995). Nonetheless, the inconsistencies make it difficult to rationalise the range of cognitive processes investigated in protocol studies on conceptual design. In turn, this obscures the fundamental nature of the processes under study, making it difficult to provide a unified view of the field and to identify general avenues for future work. The use of terms that are virtually meaningless in cognitive psychology further adds to these difficulties, e.g. *seeing as* (Goldschmidt 1991), *unexpected discovery* (Suwa *et al.* 2000) and *cognitive action* (Suwa *et al.* 1998). Overall, these observations may be considered to highlight a lack of common models and theories of design cognition, a view that is supported to an extent by Dinar *et al.* (2015). More fundamentally, however, we suggest that the review findings raise important ontological questions for design cognition research: what cognitive processes actually exist within this domain, and how should they be defined and organised for study?

In this paper, we explore the ontological challenges highlighted by our systematic review, and present the first generic classification of cognitive processes investigated in protocol studies on conceptual design cognition. To develop this classification, we mapped specific descriptions of cognitive processes studied by authors in our systematic review sample to more generic, established definitions provided in the cognitive psychology literature. This exercise revealed 6 categories of cognitive process that appear to be commonly investigated and are therefore likely to be prevalent in conceptual design: (1) long-term memory; (2) semantic processing; (3) visual perception; (4) mental imagery processing; (5) creative output production and (6) executive functions. Each category is comprised of several processes, which are elaborated in Section 4. In addition, the classification and its development highlight 6 key avenues for future empirical work on cognitive processes in conceptual design:

1. clarifying the nature and role of episodic and semantic memory in conceptual design;
2. developing more consistent definitions of the types of semantic processes involved in conceptual design;
3. considering and critiquing alternative perspectives on the similarities between visual perception and mental imagery processing, and in turn investigating the role of sketching from multiple theoretical perspectives to arrive at a more definitive position;
4. investigating the role of working memory in conceptual design, including the use of both the visuo-spatial sketchpad for mental imagery and the phonological loop for verbal design information;
5. clarifying the meaning of the term 'synthesis' in conceptual design and the nature of the process(es) it denotes;
6. expanding the classification as a whole to include any cognitive processes not identified from the reviewed studies, but implicated in conceptual design elsewhere in the literature (e.g. learning).

The classification may be considered to provide a more unified view of conceptual design cognition and the key avenues for future research on cognitive processes in this area. In addition, we suggest that it provides a starting point for the development of a generic, shared ontology of cognitive processes in design (discussed at length in Section 5). The remainder of the paper is organised as follows. An overview of the systematic review approach and sample characteristics is firstly provided in Section 2. In Section 3, we summarise the range of cognitive processes identified through the review in terms of three viewpoints on design cognition emerging from our sample: search (V1), exploration (V2) and activities (V3). In Section 4, descriptions of cognitive processes associated with each viewpoint are mapped to the cognitive psychology literature, before the generic classification is presented and elaborated. In Section 5, we discuss the implications of the work for the broader design cognition community and areas for future research. The paper concludes with a summary of the work in Section 6.

Table 1. Search terms applied in the systematic review (Hay *et al.* under review), under review)

		← AND →	
Domain	**Participants**	**Conceptual design**	**Cognition**
Design	Architect OR	Creativ* OR	Cognit* OR
	Architects OR	Designing OR	Idea OR
	Designer OR	Drafting OR	Ideas OR
	Designers OR	Drawing OR	Mental OR
	Engineer OR	Ideat* OR	Percept OR
	Engineers OR	Imagery OR	Visual*
	Engineering	Sketch*	

2. Systematic review approach and sample

As noted in Section 1, the work reported herein is based on the findings of a systematic review of 47 protocol studies on conceptual design cognition, guided by the following research question (Hay *et al.* under review): *What is our current understanding of the cognitive processes involved in conceptual design tasks carried out by individual designers?* We covered the domains of architectural design, engineering design and product design engineering. The review was conducted by two design researchers (RDes1 and RDes2) with expertise in product design engineering, receiving input from a cognitive neuroscience researcher (RCog) as required. Our approach was informed by the PRISMA statement (outlined in Moher *et al.* 2009), providing generic guidance with respect to recommended activities for a rigorous and transparent systematic review. An overview of the article selection process, inclusion criteria, sample characteristics and synthesis process is provided below.

Firstly, to identify candidate articles for inclusion, we searched major engineering/design and psychology databases (Compendex, Design and Applied Arts Index, Technology Research Database, Embase, PsycINFO and PubMed) between 27th March 2015 and 3rd April 2015. These searches returned a total of 6796 articles, reduced to 4996 through removal of duplicates. Search terms are presented in Table 1, and were applied largely across the title and abstract fields. The broadest time frame permitted by each database was applied. Following de-duplication, we screened the abstracts of the remaining articles for relevance with respect to the research question. At this stage, we decided to focus the review on protocol studies alone, excluding other types of research such as case studies, controlled experiments and surveys. This was largely motivated by the view that protocol analysis is the most capable method for revealing cognitive processes in design (Section 1). To maximise coverage, further candidate articles were then identified by searching protocol study reference lists and conducting follow-up database searches with additional terms relating to protocol analysis (9th October 2015). A total of 103 protocol studies were carried forward.

Next, we assessed the fitness of each study for answering our research question with respect to 6 inclusion criteria: (1) must be published in English;

(2) conference papers must be published post-2005; (3) must report original research; (4) must focus on individual designers rather than group-based design tasks; (5) must focus on a conceptual design task in the domains of architectural design, engineering design or product design engineering and (6) must identify cognitive processes involved in conceptual design (Hay *et al.* under review). Note that articles obtained through initial, reference list and follow-up searches were all consistently assessed. A total of 47 articles were included in the final sample (denoted by * in the reference list at the end of this paper), with the following characteristics (Hay *et al.* under review):

- *Publication year:* 1979 (Akin 1979) to 2015 (e.g. Yu *et al.* 2015), with 52.3% of studies published in the last decade.
- *Study type:* full protocol studies (76.6%) and analyses of existing protocol data (23.4%).
- *Sample size:* 1 to 36 participants (∼350 overall), with an average of 7 and a median of 6 per study (SD = 6.30).
- *Participants:* practicing designers and undergraduate, Master's and PhD design students with experience levels of 0 to 38 years.
- *Design tasks:* 45 distinct tasks, with 44.4% architectural design, 42.2% product design engineering and 13.3% engineering design.
- *Types of data gathered:* concurrent verbalisations (68.1%); retrospective verbalisations (23.4%); combined concurrent and retrospective verbalisations (8.5%); video of behaviour (84.4%) and physical sketches (51.1%).
- *Length of verbal protocols:* 15 to 600 minutes.

Following consolidation of the review sample, the full text of each article was reviewed by RDes1 and RDes2 in order to extract and synthesise descriptions of cognitive processes provided by authors. This was conducted in an iterative fashion, with categories and processes being continually refined through discussion (with RCog) and classification in a common synthesis matrix as they emerged from the review sample. Our interpretation of what constitutes a cognitive process is based on the following definition provided by Poldrack *et al.* (2011, p. 3) in the cognitive science literature: cognitive processes are 'entities that transform or operate on mental representations'. *Mental representations* are defined as 'mental entities that stand in relation to some physical entity [. . .] or abstract concept (which could be another mental entity)'. The synthesis process also revealed persistent differences in the way that cognition is described and formalised across different studies, which were interpreted as reflecting the viewpoints of search (V1), exploration (V2) and design activities (V3) introduced in Section 1. As a means to structure the review findings, we assigned each article to one of these viewpoints based on relevant keywords and interpretation of the work against the broader literature on search, exploration and activities.

3. Viewpoints on conceptual design cognition

Three major viewpoints on design cognition were found to emerge from our systematic review sample: (V1) *design as search*; (V2) *design as exploration* and

(V3) *design activities*. V1 and V2 are explored in detail in Hay *et al.* (under review), whilst V3 is briefly conveyed. We identified a range of cognitive processes investigated in studies associated with each viewpoint. In this respect, the viewpoints overlap to some degree; that is, certain processes may be studied by authors aligning with different viewpoints (an observation that shall become clearer in Section 4). To provide a basis for mapping descriptions of cognitive processes provided in design protocol studies to the cognitive psychology literature in Section 4, each of the viewpoints is outlined in the following sub-sections. Whilst the key points are covered, interested readers are referred to Hay *et al.* (under review) for a considerably more in-depth exploration and discussion of V1 and V2 in particular.

The full set of 35 cognitive processes identified from our review sample is summarised in Table 3 in Appendix A. It should be noted that several of these processes are described by authors as involving multiple related sub-processes, which may also be viewed as cognitive in nature. Throughout the following sub-sections, the 35 processes listed in Table 3 are *italicised* and followed by a discussion on any sub-processes that may contribute to their execution. The key elements of this discussion are also summarised in Table 3. Note that the comprehensiveness of the identified processes and our resulting classification is discussed in Section 5.2.5.

3.1. Design as search

The first viewpoint on design cognition (V1) considers designing to constitute a goal-directed search process transforming knowledge states in a problem space. In the context of design as search, the designer is typically viewed as an information processing system (IPS) operating within some objective reality (Chan 1990; Stauffer & Ullman 1991; Dorst & Dijkhuis 1995). During designing, information is retrieved from *long-term memory* and activated in *working memory* (Chan 1990; Stauffer & Ullman 1991), where it is then transformed from input to output states via the execution of elementary information processes termed *operators* (Stauffer & Ullman 1991). Operators are argued to be stored within schemas in long-term memory, i.e. networks of knowledge units encompassing both declarative and procedural knowledge about design problems (Chan 1990; Ball *et al.* 2004). The design state may be transformed laterally, i.e. from one idea to a different idea, or vertically, i.e. from one idea to a more detailed version of the same idea (Goel 1995; Chen & Zhao 2006).

A *search process* may be viewed as a sequence of state transformations effected by the execution of operators. The search begins with a problem state, i.e. knowledge of some problem to be solved, and proceeds through intermediate design states until the goal (i.e. desired) state is reached and the problem is solved (Chan 1990; Stauffer & Ullman 1991). The search process is delimited by a problem space, constituting a representation of the designer's task environment. In addition to knowledge of the problem and goal state, the problem space encompasses knowledge of all possible intermediate design states (Newell & Simon 1972; Chan 1990; Stauffer & Ullman 1991; Goel 1995).

Design problems are generally considered to have a large problem space owing to their ill-defined nature; however, implementing constraints can reduce the size of the space to be searched (Chan 1990; Goel 1995). The search process is further managed through the definition and implementation of design goals, specifying desired states to be attained (Akin 1979; Chan 1990; Stauffer & Ullman 1991). In this respect, several authors suggest that the search process may be preceded by, and/or interrupted by, another process known as *problem structuring*. During problem structuring, information about the problem is gathered, requirements are formulated, goals are set and prioritised, and constraints are established (Akin 1984; Chan 1990; Goel 1995). Restructuring the problem results in changes to the nature and/or structure of goals, constraints and requirements (Chan 1990). Related processes include: *problem decomposition*, i.e. the process of breaking down a design problem into sub-problems through the specification of sub-goals (Lloyd & Scott 1994; Liikkanen & Perttula 2009; Lee *et al.* 2014); and *problem reframing*, i.e. the process of identifying restrictive frames of reference and specifying new frames conducive to solving the design problem (Akin & Akin 1996).

Several authors may also be observed to study reasoning processes in a search context. For instance, Eckersley (1988) and Lloyd & Scott (1994) highlight the role of *deductive and inductive inference* in design problem solving, i.e. the process by which a logical judgement is made on the basis of pre-existing information (e.g. prior knowledge or previous judgements) rather than direct observations. In addition, Ball *et al.* (2004) examined the use of *analogical and case-based reasoning* in design problem solving, where information about known concepts and past design problems is used to understand newly encountered concepts and problems, respectively.

3.2. Design as exploration

In addition to a search process operating within a single knowledge space, designing may also be viewed as an exploratory process operating between a problem and a solution space. During design as exploration (V2), actions taken in the solution space (e.g. idea generation) are considered to influence actions taken in the problem space (e.g. problem structuring) and vice versa. Interactions between the two spaces may add new variables into each (e.g. new design requirements and potential solutions). In this way, design problems are considered to evolve alongside solutions (Maher & Tang 2003; Jin & Chusilp 2006; Yu *et al.* 2014). This view is formalised in the co-evolution model of design (Dorst & Cross 2001; Maher & Tang 2003; Yu *et al.* 2014), where design is described as a *co-evolutionary process* that 'explores the spaces of problem requirements and design solutions iteratively'. Design concepts in the solution space are evaluated and evolved on the basis of requirements in the problem space, and vice versa.

A significant number of protocol studies on exploratory design focus on what may be termed sketch-based design exploration. Here, a designer's understanding of a problem is considered to be affected by what they draw, perceive and interpret in their sketches, and vice versa. This may also be described as situatedness (Gero & Kannengiesser 2004). The concept of situatedness is reflected in studies on the process of visual reasoning, an area largely pioneered by Goldschmidt (1991). Goldschmidt argues that during sketching tasks, designers continually switch between two modes of reasoning: (i) *seeing as* (SA), i.e. the process of proposing properties and attributes that a design could possess based on analogies between sketch elements and mental representations (e.g. concepts and past experiences); and (ii) *seeing that* (ST), i.e. the process of reasoning about design decisions relating to these proposals and how they might affect design requirements. Suwa *et al.* (1998) study a process that appears similar to SA, termed *re-interpretation*. That is, assigning new functions to parts of a design through the interpretation of visuo-spatial elements and relations in sketches. More recently, visual reasoning was modelled as the continual interaction of drawing, seeing (i.e. perceptual) and imagining (i.e. mental imagery) processes by Park & Kim (2007).

The concept of situatedness is also reflected in the work of Suwa *et al.* (1998, 2000), who examine the *cognitive actions* of architects. Cognitive actions may be viewed as a set of interdependent cognitive processes argued to be involved in sketching, spanning three different levels of information processing: *physical actions* at the sensory level, *perceptual actions* at the perceptual level, and *functional* and *conceptual actions* at the semantic level. Suwa *et al.* (2000) suggest that during sketching, designers may execute a particular type of perceptual action termed *unexpected discovery*, where a designer perceives a previously unseen feature, relation, or space in their sketches. Instances of unexpected discovery were found to be correlated with a process termed *situated requirements invention*, where new design goals are set up, generalised and carried through the design process as new design requirements. Thus, the designer's understanding of the problem is considered to be affected by changes in perceptual input during sketching.

3.3. Design activities

A final viewpoint that may be adopted on design cognition is that of design activities (V3), with several authors examining activity patterns and relationships in addition to the nature of design activities *per se*. Note that the former is beyond the scope of this paper and therefore not discussed here. In design research, an activity may be generally defined as a goal-directed action, where an action is the act of transforming some entity from an input state to an output state (Sim & Duffy 2003; Boyle *et al.* 2009). Design activities may involve physical actions transforming external entities (e.g. motor actions of the arms and hands transforming sketches), and/or cognitive processes transforming internal entities (e.g. mental imagery processes transforming mental images, ideas, etc.). The design activities discussed in this section are considered from a cognitive perspective, i.e. focusing on the cognitive processes involved rather than physical actions. Five key design activities were identified from our review sample: problem analysis, concept generation, synthesis, concept evaluation and decision making.

Firstly, *problem analysis* involves understanding the design problem, setting goals, and defining constraints and requirements (Jin & Chusilp 2006; Kruger & Cross 2006; Jin & Benami 2010). Jin & Chusilp (2006, p. 30) suggest that when designing, 'the problem definition may be elaborated or revised', resulting in changes to constraints and requirements'. Problem analysis may be viewed as analogous to the process of problem structuring discussed in the context of design as search in Section 3.1 (Liikkanen & Perttula 2009), and is examined by several authors in the context of studies on design activity patterns (e.g. McNeill *et al.* 1998; Kruger & Cross 2006; Jin & Benami 2010; Lee *et al.* 2014). The related processes of *identifying, exploring, clarifying, and prioritising constraints and requirements* – that is, the *management of constraints and requirements* – have also received attention from numerous authors (Kim *et al.* 2005, 2006; Lane & Seery 2011; Daly *et al.* 2012).

Secondly, we found *concept generation* to be interpreted in two different ways by authors: the generation of ideas or partial solutions followed by the *synthesis* of these into more mature or complete concepts (Jin & Chusilp 2006); or simply the generation of ideas, with synthesis treated as a separate process (Jin & Chusilp 2006; Kruger & Cross 2006). Concept generation appears to involve the *retrieval of representations from memory* as a basic process (Jin & Chusilp 2006; Jin & Benami 2010; Lane & Seery 2011), which may occur in response to 'perceptual stimulation' (Jin & Chusilp 2006, p. 30). The *association of representations* is also positioned as a basic process by Jin & Benami (2010), and evidence supporting the involvement of associative reasoning processes in concept generation and synthesis (e.g. analogical and case-based reasoning as discussed in Section 3.1) has been identified by a number of other authors (e.g. Chiu 2003; Kim *et al.* 2010; Daly *et al.* 2012; Kim & Ryu 2014; Yu & Gero 2015). The *transformation of internal representations* (e.g. images and concepts) during concept generation is also considered by Jin & Benami (2010), Lane & Seery (2011) and Leblebici-Basar & Altarriba (2013).

Finally, *concept evaluation* refers to the process of assessing concepts against constraints, criteria and design requirements defined during problem analysis (McNeill *et al.* 1998; Jin & Chusilp 2006; Kruger & Cross 2006; Jin & Benami 2010; Lee *et al.* 2014). Evaluation serves to ensure that a concept is 'relevant, useful and good', with relevance and usefulness determined against 'design requirements and constraints', and goodness against 'design criteria' (Jin & Chusilp 2006, p. 31). Kim & Ryu (2014) were additionally found to investigate the closely related process of *decision making*, i.e. the process of selecting a concept to be taken forward for further development from a range of evaluated alternatives. Two sub-processes involved in evaluation were also considered by several authors: (i) *comparing*, e.g. comparing two concepts, comparing concepts against criteria, etc. (Kim & Ryu 2014) and (ii) *judging*, where judgements may be based on subjective aspects such as value (Kruger & Cross 2006), aesthetics (Chandrasekera *et al.* 2013) and affect (Kim & Ryu 2014), or objective criteria (Chiu 2003; Kruger & Cross 2006; Lee *et al.* 2014).

4. A generic classification of cognitive processes

It may be seen from the material covered in Section 3 that protocol studies vary considerably with respect to the concepts and terminology used to describe design cognition. This makes it difficult to rationalise the range of cognitive processes fundamentally under investigation across different protocol studies. To gain a clearer view in this respect, we mapped specific descriptions of cognitive processes provided by authors in our sample to more generic, established definitions provided in the cognitive psychology literature in a bottom-up fashion. That is, by interpreting the key characteristics of cognitive processes described by design authors, and then identifying processes with similar characteristics in the cognitive psychology literature. We then grouped the latter into 6 categories according to ontological conventions conveyed in psychology articles, books, and formal frameworks (e.g., Poldrack 2009; Poldrack *et al.* 2011): (1) long-term memory; (2) semantic processing; (3) visual perception; (4) mental imagery processing; (5) executive functions and (6) creative output production. These categories, and the processes they are comprised of (Table 2), are formalised in a generic classification of cognitive processes in conceptual design presented in

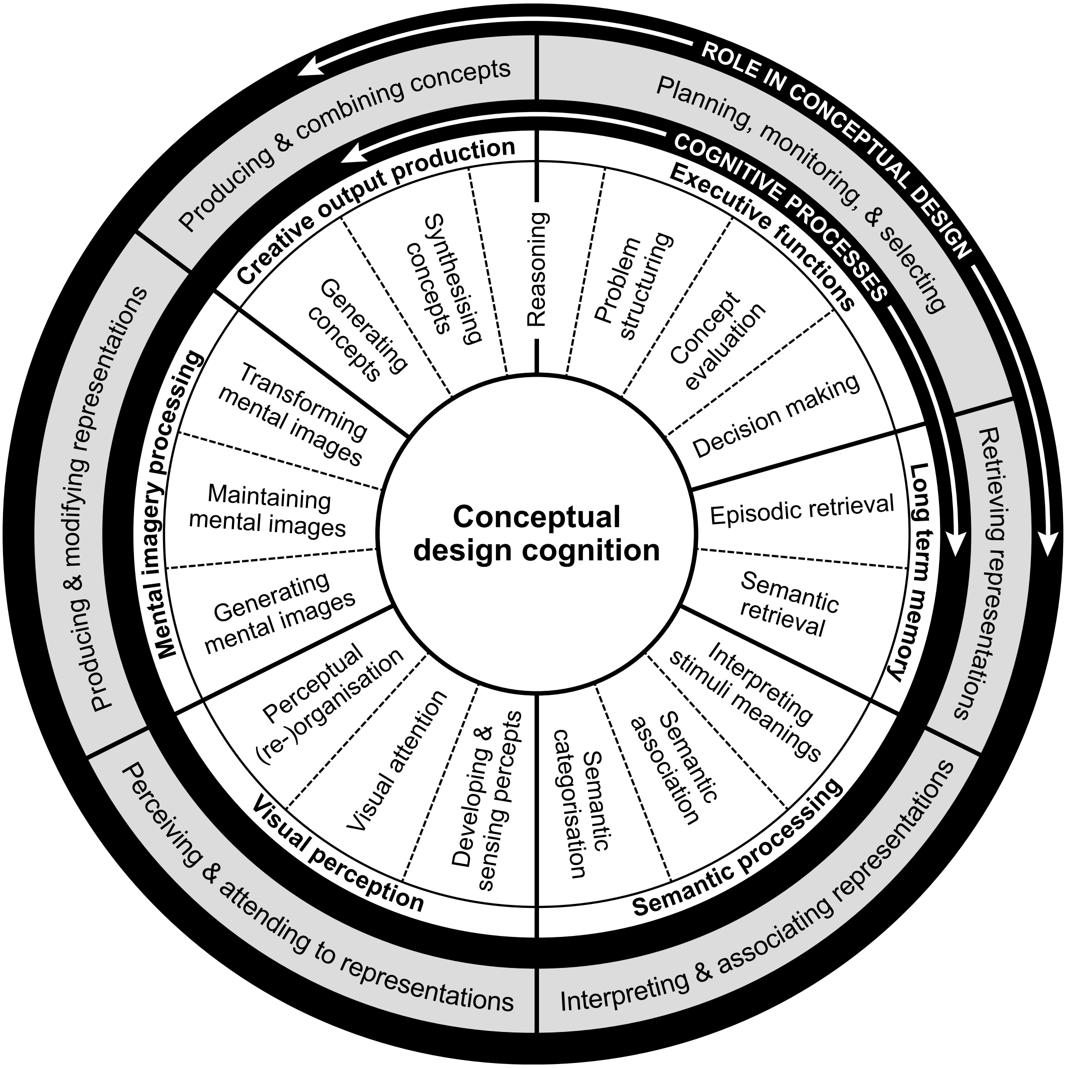

Figure 1. Generic classification of cognitive processes involved in conceptual design.

Figure 1. As shown in Table 2, the 6 categories appear to be commonly investigated across multiple viewpoints and are therefore likely to be prevalent in conceptual design.

Drawing from the psychology literature, the cognitive processes included in the classification and their role in conceptual design tasks are outlined in the subsections below as follows: (i) long-term memory and semantic processing (Section 4.1); (ii) visual perception and mental imagery (Section 4.2) and (iii) higher-order processes involved in creative output production and executive functioning (Section 4.3). Note that future work relating to individual processes is discussed in Section 5.

Table 2. Commonly investigated processes in the review sample

Cognitive process category	Cognitive processes	Examples of process descriptions from reviewed studies	ID [1]	Role in conceptual design
Long-term memory	Retrieval generally	Retrieval of operators and other information from long-term memory.	$V1_{P6}$	Retrieving representations
		Retrieving knowledge (conceptual cognitive action).	$V2_{P12}$	
		Retrieval of representations from memory.	$V3_{P5}$	
	Episodic retrieval	Retrieval of previously encountered design problems in case-based reasoning (Ball *et al.* 2004).	$V1_{P10}/V3_{P9}$	
	Semantic retrieval	Retrieval of types of product and function during concept generation (Jin & Benami 2010).	$V1_{P9}/V3_{P8}$	
Semantic processing	Interpreting meanings conveyed by stimuli	Seeing as, i.e. the process of proposing properties/attributes that a design could possess based on metaphors and analogies.	$V2_{P3}$	Interpreting and associating representations
		Re-interpretation, i.e. the process of assigning new functions to parts of a design through the interpretation of visuo-spatial elements and relations in sketches.	$V2_{P4}$	
	Semantic association	Inference operator, i.e. an elementary information process that hypothesises new relations between symbols (Akin 1979).	$V1_{P5}$	
		Association of representations, i.e. forming mental relations between representations retrieved from memory.	$V3_{P6}$	

(continued on next page)

Table 2. (continued)

	Semantic categorisation	Generalisation operator, i.e. an elementary information process that associates attributes with supra-symbols (Akin 1979).	$V1_{P5}$	
		The analysis and interpretation stages in the process of seeing, i.e. identifying the attributes of a perceived object, and using this information to categorise the perceived object based on information stored in memory.	$V2_{P5}$	
Visual perception	Visual perception generally	Data input operator, i.e. an elementary information process dealing with afferent sensory information from the external world (Chan 1990).	$V1_{P5}$	Perceiving and attending to representations
	Developing and sensing percepts	The perceiving stage in the process of seeing, i.e. identifying and combining primitive visual elements, and consciously sensing the resulting visuo-spatial representation.	$V2_{P5}$	
	Visual attention	Attending to visual features of sketch elements (perceptual cognitive action).	$V2_{P10}$	
		Attending to spatial relations among sketch elements (perceptual cognitive action).		
	Perceptual organisation	Organising or comparing sketch elements (perceptual cognitive action).	$V2_{P10}$	
	Perceptual re-organisation	Unexpected discovery, i.e. the process of perceiving a visuo-spatial feature/relation in a sketch that was not intentionally created and is therefore unexpected. This includes the discovery of: (i) the shape, size, or texture of a sketch element; (ii) a spatial or organisational relation among elements; and (iii) a space that exists in between elements (figure-ground reversal).	$V2_{P13}$	

(continued on next page)

Table 2. (continued)

Mental imagery processing	Generating images	The generation stage in the process of imagining during visual reasoning.	$V2_{P6}$	Producing and modifying representations
	Maintaining images	The maintenance stage in the process of imagining during visual reasoning.		
	Transforming images	The transformation stage in the process of imagining during visual reasoning.		
		Transformation of representations, i.e. the process of altering mental representations retrieved from long-term memory to produce new representations.	$V3_{P7}$	
Executive functions	Problem structuring	The process of defining the design problem prior to or during the search for a solution.	$V1_{P2}$	Planning, monitoring, and selecting
		Decomposition, i.e. the process of breaking a design problem down into sub-problems through the specification of sub-goals.	$V1_{P3}$	
		Goal definition operator, i.e. an elementary information process defining goals or sub-goals.	$V1_{P5}$	
		Structuring/restructuring a problem based on the outcomes of actions taken to develop and evaluate a solution during co-evolutionary design.	$V2_{P1}$	
		Setting up goals (conceptual cognitive action).	$V2_{P12}$	
		Situated invention of design requirements, i.e. the process of developing new design requirements based on what is perceived in sketches.	$V2_{P14}$	
		Problem analysis, i.e. the process of characterising and structuring the design problem by setting goals and defining constraints and requirements.	$V3_{P1}$	

(continued on next page)

Table 2. (continued)

		Identifying, exploring, clarifying, and prioritising constraints and requirements.	$V3_{P2}$
	Evaluating concepts	Compare operator, i.e. an elementary information process determining the compatibility of proposals against constraints (Stauffer & Ullman 1991).	$V1_{P5}$
		Evaluating solutions against problem requirements during co-evolutionary design.	$V2_{P1}$
		Preferential and aesthetic evaluation (conceptual cognitive action).	$V2_{P12}$
		Concept evaluation, i.e. the process of assessing concepts against design requirements, constraints, and other criteria to determine the extent to which the concepts fulfil the criteria.	$V3_{P10}$
		Comparing, i.e. the process of comparing concepts against design criteria or other concepts.	$V3_{P11}$
		Judging, i.e. the process of making judgements about concepts on the basis of value, aesthetics, affect, or objective criteria.	$V3_{P12}$
	Decision making	Accept operator, i.e. an elementary information process adding new information to the solution state (Akin 1984; Goel 1995).	$V1_{P5}$
		Reject operator, i.e. an elementary information process determining proposal to be unsatisfactory (Stauffer & Ullman 1991; Goel 1995).	$V1_{P5}$
		Select information operator, i.e. an elementary information process that selects one source of information from a range of several sources (Stauffer & Ullman 1991).	$V1_{P5}$
		Suspend operator, i.e. an elementary information process terminating a decision without a definite conclusion (Stauffer & Ullman 1991).	$V1_{P5}$

(continued on next page)

Table 2. (continued)

		Decision making, i.e. the process of determining what concept(s) should be taken forward for further development from a range of alternatives.	$V3_{P13}$	
Executive functions/ Creative output production	Reasoning	Rule application operator, i.e. an elementary information process applying arithmetical rules and making assertions and logical deductions (Chan 1990).	$V1_{P5}$	Planning, monitoring, and selecting/ Producing and combining concepts
		Calculate operator, i.e. an elementary information process inferring new information by combining existing information (Stauffer & Ullman 1991).	$V1_{P5}$	
		Patch operator, i.e. an elementary information process that adds or combines information without making it less abstract (Stauffer & Ullman 1991).	$V1_{P5}$	
		Refine operator, i.e. an elementary information process that makes information more specific and less abstract (Stauffer & Ullman 1991).	$V1_{P5}$	
		Simulate operator, i.e. an elementary information process that represents information at the proper level of abstraction in order to relate it (Stauffer & Ullman 1991).	$V1_{P5}$	
		Inference, i.e. the process of making logical judgements on the basis of pre-existing information.	$V1_{P8}$	
		Seeing that, i.e. the process of developing a rationale for design decisions pertaining to proposals made during the process of seeing as.	$V2_{P3}$	

(continued on next page)

Table 2. (continued)

		Analogical reasoning, i.e. the process of using information about known semantic concepts to understand newly presented semantic concepts, e.g. those contained within a design problem.	$V3_{P8}$/ $V1_{P9}$	
		Case-based reasoning, i.e. the process of consciously mapping knowledge of previously encountered problems onto a current problem.	$V3_{P9}$/ $V1_{P10}$	
Creative output production	Generating concepts	Create operator, i.e. an elementary information process generating information that appears spontaneously (Stauffer & Ullman 1991).	$V1_{P5}$	Producing and combining concepts
		Specification operator, i.e. an elementary information process producing a partial solution or partial specification (Akin 1979).	$V1_{P5}$	
		Concept generation, i.e. the process of generating ideas for solutions/partial solutions to design problems.	$V3_{P3}$	
	Synthesising concepts	Integration operator, i.e. an elementary information process further specifying the current solution state (Akin 1979).	$V1_{P5}$	
		Developing a solution based on the outcomes of actions taken to structure/restructure the problem during co-evolutionary design.	$V2_{P1}$	
		Synthesis, i.e. the process of combining and/or developing previously generated ideas to produce more mature concepts.	$V3_{P4}$	

[1]Code identifier (ID) elements: V = viewpoint number; P = process number. Please refer to Table 3, Appendix A for a list of authors investigating each process.

4.1. Long-term memory and semantic processing

As shown in Table 2, long-term memory retrieval and semantic processing have received attention across all three viewpoints. These processes may be considered to relate. Firstly, long-term memory can be subdivided into (i) episodic and (ii) semantic memory, dealing with (i) past events/experiences bound with context and (ii) conceptual knowledge that is not tied to specific events/experiences (Tulving 1983; Squire & Zola 1998). Semantic processing refers to the interpretation of meanings conveyed by stimuli (Martin & Chao 2001). Semantic processing may involve what is termed semantic association, i.e. the process of forming mental relationships between meaningful representations (Federmeier *et al.* 2002). Sets of related representations are termed semantic networks, and exist within semantic memory. Thus, semantic association is intricately related to semantic memory (Martin & Chao 2001).

4.1.1. Long-term memory

Based on the review sample, it seems that both episodic and semantic memory are involved in conceptual design. For example, the retrieval of previously encountered design problems in case-based reasoning (Section 4.3) may be viewed as an instance of episodic retrieval (Ball *et al.* 2004; Bilda *et al.* 2006), whilst the retrieval of semantic concepts such as types of product and function during concept generation is an instance of semantic retrieval (Jin & Benami 2010). Both episodic and semantic memory are argued to play an important role in creative ideation (broadly analogous with concept generation, discussed in Section 4.3) in the broader psychology and neuroscience literature (e.g. Runco & Chand 1995; Benedek *et al.* 2013; Abraham & Bubic 2015). However, whilst the involvement of long-term memory in design concept generation has been investigated by a number of authors in the sample, these studies do not clearly distinguish between episodic and semantic memory (Jin & Benami 2010; Lane & Seery 2011).

In addition to concept generation, Ball *et al.* (2004, p. 495) also consider the role of long-term memory retrieval in design reasoning, specifically analogical and case-based reasoning. They suggest that analogical reasoning involves the retrieval and application of 'abstract experiential knowledge', whilst case-based reasoning is driven by knowledge about 'a concrete prior problem whose solution can be mapped systematically onto the current problem'. Whilst the latter clearly pertains to episodic memory, the nature of the former is unclear; the term 'abstract' is suggestive of conceptual knowledge recalled from semantic memory, but the term 'experiential' pertains to episodic memory.

4.1.2. Semantic processing

Instances of semantic processing identifiable in the sample (Table 2) include both (i) interpreting meanings conveyed by representations and (ii) forming relationships between meaningful representations, i.e. semantic association as noted above. In studies on design as exploration (V2), the process of *seeing as* proposed by Goldschmidt (1991), and the closely related process of *re-interpretation* considered by Suwa *et al.* (1998), both involve interpreting meanings conveyed by visuo-spatial features and relations in sketches. That is, potential design properties and attributes, and new functions, respectively. *Seeing as* in particular appears to involve analogical reasoning, where inferences are made about a situation based on similarities with other situations (analogies).

Analogical reasoning, and the related process of case-based reasoning, are typically treated as effortful, higher-order processes (discussed in Section 4.3). In contrast, semantic association may be viewed as a largely automatic, implicit process (Jin & Benami 2010). The *association of mental representations* (Table 2) appears to be a fundamental process involved in concept generation (Jin & Benami 2010), and is also identifiable among the operators involved in design as search, e.g. the *inference operator* proposed by Akin (1984) (Table 2). Another form of semantic processing identifiable in the sample is what may be termed semantic categorisation. That is, the process of assigning stimuli to conceptual categories stored in memory based on their properties and attributes (Martin & Chao 2001). Examples of semantic categorisation include the *generalisation operator* proposed by Akin (1984), and the analysis and interpretation stages of the *seeing* process proposed by Park & Kim (2007) (Table 2).

4.2. Visual perception and mental imagery processing

As shown in Table 2, we found visual perception to be investigated primarily in studies on design as search (V1) and exploration (V2), and mental imagery processing in studies on design as exploration and design activities (V3). Visual perception is the process by which a human constructs and consciously senses internal (visual) representations of the external world (Bruce *et al.* 2003; Milner & Goodale 2008; Gobet *et al.* 2011). Internal representations produced through perception may be termed percepts (Fish & Scrivener 1990; Finke 1996). The process is primarily driven by afferent sensory information pertaining to external visuo-spatial representations (Eysenck & Keane 2005). Closely related to visual perception is visual mental imagery processing, involving the generation, maintenance and transformation of visual mental images (Kosslyn 1995). Mental imagery may be considered to mimic the experience of visual perception by generating and sustaining internal visual representations that may be inspected, but without necessarily using perceptual input and relying heavily on information retrieved from memory (Kosslyn 1995). However, the degree to which the two processes may be considered to be similar remains a matter for debate in the psychology and neuroscience literature (Ganis 2013). Note also that percepts are typically distinguished from mental images (Fish & Scrivener 1990; Finke 1996).

4.2.1. Visual perception

Authors studying design as search were found to investigate processes that may be interpreted as perception, e.g. the *data input operator* considered by Chan (1990) (Table 2). In these studies, perception is largely treated as a process providing the designer with external information when information retrieved from memory is not sufficient to progress the search process. The basic mechanisms of perception are typically not conceptualised or studied in depth, perhaps owing to the perspective that design is a rational search process and the consequent focus on higher-order processes such as reasoning and decision making (Section 4.3).

In contrast with the above, several studies on design as exploration were found to investigate more specific visual perceptual processes. This may be expected given the considerable focus on sketch-based (i.e. visual) design tasks in these studies (Section 3.3). For instance, Park & Kim (2007, p. 3) include a process termed 'perception' as part of the broader process of *seeing* in their model of visual reasoning in conceptual design. That is, based on their description, developing and consciously sensing percepts (Table 2). The *perceptual cognitive actions* proposed by Suwa *et al.* (1998) may be considered to reflect the following processes to some extent: (i) visual attention, where the designer selects and focuses on a particular part of a sketch (Zhang & Lin 2013); and (ii) perceptual organisation, referring to the process of organising visual information to form coherent visuo-spatial representations (Bruce *et al.* 2003) (Table 2). With respect to the latter, the process of *unexpected discovery* studied by Suwa *et al.* (2000) may be viewed as an instance of perceptual re-organisation (Table 2). That is, the process of re-organising visual information to reveal previously unseen features and relations of visuo-spatial representations (Bruce *et al.* 2003; Tversky 2014). Indeed, in a later paper published in a psychology journal, Suwa (2003) refers to unexpected discovery as perceptual re-organisation. Three types of re-organisation process were identified by Suwa *et al.* (2000), namely re-organisation to reveal a previously unseen (i) visual feature, (ii) organisational or spatial relation and (iii) space in between previously drawn elements.

4.2.2. Visual mental imagery processing

The processing of visual mental imagery is argued to be centrally involved in the generation of concepts by numerous authors in the sample (Goldschmidt 1991; Athavankar 1997; Kavakli & Gero 2001; Bilda & Gero 2007; Park & Kim 2007; Jin & Benami 2010). We found that mental imagery has received considerable attention in studies on design as exploration (V2), but virtually none in studies on design as search (V1). This may again be owing to a focus on higher-order processes in studies on design as search as suggested above, and/or the perspective that the designer can be reduced to an information processing system in an objective reality. In contrast, studies on design as exploration tend to view the designer as a person constructing their own reality, in line with the notions of situatedness (Gero & Kannengiesser 2004) and reflection-in-action (Dorst & Dijkhuis 1995).

Kosslyn (1995) describes four kinds of mental imagery process:

- image generation, i.e. forming mental images by either maintaining perceptual input or retrieving information from long-term memory;
- image inspection, i.e. interpreting the features and relations of mental images;
- image maintenance, i.e. retaining the features and relations of mental images;
- image transformation, i.e. rotating, re-sizing, and manipulating the structure of mental images.

As shown in Table 2, studies in the sample were found to report all of the above processes except image inspection. Bilda & Gero (2007) draw parallels between mental imagery processing and visual perception (discussed further in Section 5.2.2), suggesting that designers may inspect their mental images in the same way that they inspect external sketches, i.e. by focusing attention on different visuo-spatial features and relations. The authors code a blindfolded designer's imagery-based protocol using perceptual cognitive action codes pertaining to visual attention (*attending to visuo-spatial features and relations*, Table 2). However, it is unclear from the findings reported whether evidence supporting this process was identified or not.

4.3. Higher-order processes

A distinction may be made between the cognitive processes discussed in Sections 4.1 and 4.2 and what are termed higher-order processes in this paper. That is, processes that are largely mediated by the frontal lobes of the brain and may involve the interaction of several other processes. As conveyed by Table 2, we found higher-order processes to be studied across all viewpoints (in varying degrees). Whilst the processes may be described in different terms by different authors, it may be seen in Table 2 that these descriptions can be interpreted as describing the same fundamental process. In summary, it seems that the following higher-order processes may be central to conceptual design (presented in order of discussion below):

- *Problem structuring* (e.g. Goel 1995; Suwa *et al.* 2000; Liikkanen & Perttula 2009), i.e. defining and relating the goals, constraints and requirements to be addressed by the designer. Design problems may be restructured during designing, i.e. the definition of and/or relationships between goals, constraints and requirements may be altered.
- *Evaluating concepts* (e.g. Stauffer & Ullman 1991; Maher & Tang 2003; Jin & Chusilp 2006), i.e. assessing the goodness of a concept on the basis of value, aesthetics, affect or objective criteria.
- *Decision making* (e.g. Stauffer & Ullman 1991; Kim & Ryu 2014), i.e. deliberately selecting (or not selecting) one option (e.g. a concept or a course of action) over another.
- *Reasoning* (e.g. Chan 1990; Goldschmidt 1991; Ball *et al.* 2004), i.e. thinking and drawing conclusions in accordance with some system of logic. Instances of both deductive and inductive reasoning were identified. Two specific forms of inductive reasoning that appear to be important are: (i) analogical reasoning, where a newly encountered concept/situation is compared with previously encountered concepts/situations to infer an understanding of the former (discussed at length by Goel (1997)) and (ii) case-based reasoning, where a newly encountered problem is compared with previously encountered problems to infer a solution and/or solution procedure for the former (conceptualised and discussed in depth by Maher *et al.* (1995)).
- *Generating concepts* (e.g. Akin 1984; Jin & Benami 2010), i.e. producing new ideas for solutions or partial solutions to design problems.
- *Synthesising concepts* (e.g. Akin 1984; McNeill *et al.* 1998; Jin & Chusilp 2006), i.e. combining and developing previously generated ideas to produce more mature ideas.

Executive functions are a type of higher-order cognitive process involved in the planning, selection and monitoring of human behaviour to facilitate the achievement of goals (Rabbitt 2004; Chan *et al.* 2008). Executive functions in psychology research typically include processes such as goal setting, selective attention, decision making and problem solving, although there are several different models of executive functioning (Chan *et al.* 2008). Based on the review sample, it seems that the following processes may be viewed as executive functions in conceptual design (Table 2): (i) problem structuring; (ii) concept evaluation and (iii) decision making. It is these processes that appear to facilitate: (i) planning, in the form of identifying and structuring goals (specifying desired design outputs), constraints (specifying limitations on design outputs) and requirements (specifying criteria design outputs should meet); (ii) monitoring, in the form of assessing the goodness of design outputs against goals, constraints and requirements and (iii) selection, in the form of decision making at various points during design tasks (e.g. a decision to reject a concept based on the outcome of evaluation, followed by a decision to restructure the problem by defining new goals or altering existing goals). With the exception of decision making, which we did not identify in studies on design as exploration (V2), all of these processes have received attention across the three viewpoints covered by the review as shown in Table 2. This is not to say that decision making is not involved in design as exploration; rather, it was not identified in the studies included in the review sample. Having said this, several authors focusing on design as exploration mention decision making generally in their discourse (e.g. Goldschmidt 1991; Suwa *et al.* 1998).

The remaining higher-order processes identified from the sample – that is, reasoning, generating and synthesising, as listed above – appear to be higher-order processes involved primarily in the production of creative outputs. That is, in a conceptual design context, concepts – i.e. ideas for solutions or partial solutions to design problems. Having said this, it seems that reasoning is also involved in executive functioning to some extent (as indicated in Table 2), e.g. Stauffer & Ullman (1991) suggest that the *simulate* and *calculate* operators listed in Table 2 are involved in evaluation. As discussed in Section 4.1, there appear to be relationships between concept generation and lower-order memory and semantic processes. However, whilst understanding the nature of these relationships is important for the development of models and theories of design cognition, exploration of these relationships is beyond the scope of this paper.

5. Discussion

As discussed in Section 1, the generic classification elaborated in Section 4 (Figure 1) is based on a set of 35 cognitive processes identified through a systematic review of 47 protocol studies on conceptual design. The classification was motivated by observed differences in the way that cognition is described across different studies, leading us to pose the following ontological question: what cognitive processes actually exist within this domain, and how should they be defined and organised for study? In the following sub-sections, we firstly discuss the implications of the classification with respect to this question (Section 5.1). We then outline future empirical work required to clarify and expand the classification *per se* (Section 5.2).

5.1. Towards a shared ontology

Questions regarding the nature of design cognition ontology may be seen to mirror ontological debates in the cognitive psychology and neuroscience literature, where efforts are currently under way to develop a shared ontology of cognitive processes, representations and tasks (Poldrack *et al.* 2011). In this respect, several design researchers have proposed ontologies to describe the phenomenon of design (e.g. Gero 1990; Sim & Duffy 2003; Gero & Kannengiesser 2004, 2007). However, these are not always intended to describe design at the cognitive level, and those that do describe cognitive processes are not necessarily comprehensive. For example, Gero's situated FBS ontology describes design in terms of general interpretation, transformation and focusing processes operating on functional, behavioural and structural design variables (Gero & Kannengiesser 2004, 2007). However, these processes are positioned as encompassing a range of more specific cognitive processes, examples of which are only briefly mentioned. Whilst the ontology is intentionally general so that it may be applied to describe any instance of designing (Gero *et al.* 2014), it cannot be viewed as comprehensive at the cognitive level.

A generic, shared ontology of cognitive processes in design cognition research would not only provide a common basis for developing theories and models, but would also increase the comparability of findings from different protocol studies and promote a more integrated body of knowledge on design cognition. Two key limitations of protocol analysis are: (i) its reliance upon subjective inferences from verbal self-reports and (ii) its focus on small samples (owing to the resource-intensive nature of qualitative data processing), which may increase the uncertainty associated with results (Hay *et al.* under review). As suggested in Hay *et al.* (under review) and Dinar *et al.* (2015), controlled experiments using cognitive tests and metrics could provide a means to test the findings of protocol studies using a more objective approach and larger samples. In this respect, a shared ontology would provide a consistent basis for selecting and/or developing standard tests of the cognitive abilities contributing to design, an area that has thus far received relatively little attention in the literature (with the notable exception of work by Shah *et al.* (2012, 2013) and Khorshidi *et al.* (2014)). In addition, the development of a generic ontology that is conceptually and terminologically consistent with that of cognitive psychology and neuroscience would facilitate comparisons between design cognition studies and cognitive studies of related activities such as artistic and musical composition. This would also increase the capability of design cognition researchers to contribute to the broader body of knowledge on human cognition, and vice versa, for psychologists to contribute to knowledge on design cognition.

The classification presented in Figure 1 is based on a sample of 47 protocol studies. As such, the cognitive processes included are necessarily limited to those that were identifiable in the reviewed studies. Nonetheless, given its basis in both the design cognition and cognitive psychology literature, we suggest that the classification provides a starting point for developing the kind of ontology characterised above. As conveyed in Section 4, we have begun to map the cognitive processes in the classification to different tasks and activities involved in the design process. It may also be possible to map the processes to existing design ontologies such as those cited above, potentially highlighting further processes that are currently overlooked as well as avenues for resolving competing ontological perspectives. The classification may additionally provide a basis for identifying what ontological categories, if any, are particular to the different kinds of designing reflected in the three viewpoints outlined in Section 3. We suggest that future work to expand and develop the classification towards an ontology should adopt a triangulated approach, combining induction from empirical data with deduction from models and theories of conceptual design to ensure comprehensive coverage of the cognitive processes involved. As highlighted by Poldrack *et al.* (2011, p. 3), continued efforts in this respect must involve the broader design cognition community; an emergent ontology that is 'based on the consensus obtained within a small group of individuals' will be largely useless to those who do not 'share the group's ontological commitments'.

5.2. Future empirical work

In addition to potentially providing a foundation for ontology development, the generic classification elaborated herein also highlights several avenues for future work relating to specific cognitive processes. These are discussed below.

5.2.1. The role of long-term memory and semantic processing

As noted in Section 4.1, both episodic and semantic memory are argued to play an important role in creative ideation in the broader psychology and neuroscience literature (e.g. Runco & Chand 1995; Benedek *et al.* 2013; Abraham & Bubic 2015). Consistent with this view, a number of authors in our sample were found to suggest that episodic and semantic memory retrieval may be involved in concept generation (broadly analogous with creative ideation). However, although we were able to identify potential instances by interpreting descriptions of memory retrieval provided by authors (Section 4.1.1), we found that episodic and semantic memory are rarely explicitly distinguished. Thus, given their potential importance in creativity and ideation, clarifying the nature and role of episodic and semantic memory in conceptual design presents an avenue for future research.

Like long-term memory above, semantic processing – and in particular, semantic association – is argued to play an important role in the generation of creative ideas in the broader psychology and neuroscience literature (e.g. Mednick 1962; Mumford *et al.* 2012; Beaty *et al.* 2014). Furthermore, semantic processing typically involves retrieval of semantic knowledge to some extent and is therefore closely related to semantic memory, which is also argued to be central to creative ideation as discussed above. As such, semantic processing constitutes a salient avenue for research on conceptual design cognition. However, semantic processes are frequently rather poorly and inconsistently conceptualised in the reviewed studies. For example, the processes of both *seeing as* and *re-interpretation* appear to involve semantic processing as discussed above; however, this processing is described in different terms. The term 'seeing as' arguably obfuscates the nature of the processes that it describes, and is not a term that is recognised in the psychology literature. Leblebici-Basar & Altarriba (2013) investigate the transformation of verbal concepts into visual/form-based concepts, which also seems to be a form of semantic processing but is not clearly defined as such. To provide a common basis for future work on semantic processing in conceptual design, there is a need to develop more consistent definitions of the types of semantic processes involved, perhaps using established concepts from the psychology literature.

5.2.2. The role of sketching

Several authors may be seen to suggest that during sketching, visual perception (Section 4.2.1), semantic processes (Section 4.1.2) and mental imagery processing (Section 4.2.2) are intimately related (Goldschmidt 1991; Park & Kim 2007; Jin & Benami 2010). Designers generate mental images by retrieving and associating representations from long-term memory (Goldschmidt 1991; Kavakli & Gero 2001; Jin & Benami 2010), processes that are discussed in Section 4.1. They externalise these images through sketching, perceive the elements of the sketches produced and interpret meanings conveyed by what they perceive e.g. design properties/attributes (*seeing as*, Table 2), functions (*re-interpretation*, Table 2), etc. This drives the generation of new images and/or the transformation of maintained images, which may again be externalised and so on. In addition to supporting processes such as *re-interpretation* and *unexpected discovery*, sketching is argued to be beneficial in offloading the designer's visuo-spatial working memory and freeing up cognitive resources during design tasks. That is, sketches serve as an 'external memory' where visuo-spatial features and relations may be stored, inspected and manipulated as opposed to maintaining them in working memory (Suwa *et al.* 1998; Bilda & Gero 2007).

In spite of the observation that sketching supports key processes involved in conceptual design, there is also evidence in the reviewed studies suggesting that designers can still produce satisfactory design outcomes without sketching (e.g. Athavankar 1997; Bilda & Gero 2007; Athavankar *et al.* 2008). That is, relying on mental imagery alone. For example, Bilda *et al.* (2006) found no significant differences in aspects such as design outcome scores and ideation performance between designers who were blindfolded and unable to sketch, and those who had full access to sketching and visual perception processes. One potential explanation for these observations is that designers may treat mental images in much the same way as they treat percepts of external representations. For instance, Kosslyn (1995) argues that humans inspect and interpret mental images through processes similar to those employed in the inspection and interpretation of external representations. From this perspective, it may be the case that many of the processes conventionally executed on percepts of external sketches in design may equally be executed on mental images. This argument is advanced to some extent in Kavakli & Gero (2001), Kavakli & Gero (2002), Bilda *et al.* (2006), and Bilda & Gero (2007), with Kavakli & Gero (2001) claiming that visual perception and visual mental imagery constitute 'functionally equivalent' processes.

The role of sketching has only been investigated in 5 of the 47 studies included in our review sample (Athavankar 1997; Suwa *et al.* 1998; Bilda *et al.* 2006; Bilda & Gero 2007; Athavankar *et al.* 2008). Furthermore, these studies employed small samples of 1–6 designers. As such, future studies are required to further explore the tentative findings contributed thus far on a larger scale. In addition, there are several issues with existing studies that should be addressed in future work. Virtually all of the work conducted on the role of sketching in the sample is based on the premise that visual perception and mental imagery are similar, or even 'functionally equivalent' processes, and designers therefore treat mental images in much the same way as they treat percepts of external representations as discussed above. In turn, the coding schemes and approaches adopted in these studies are intimately tied to this premise. For instance, similarities between visual perception and mental imagery processing appear to be used as a justification for applying a perception-based coding scheme to code a mental imagery-based protocol in Bilda *et al.* (2006). However, as noted above, the degree to which the two processes can be considered to be equivalent remains a matter for debate in the psychology and neuroscience literature. They are generally considered to overlap both cognitively and neurally, but there are differing perspectives on the extent of this overlap (Ganis 2013). Thus, there is a need to consider and critique these alternative perspectives in a design context, and potentially to investigate the role of sketching from multiple theoretical perspectives in order to arrive at a more definitive position.

5.2.3. Working memory

Stauffer & Ullman (1991, p. 114) refer to a cognitive system termed the 'controller' in the context of design as search, which is included in Newell and Simon's (1972) information processing model and may be seen to essentially 'supervise' the control and execution of cognitive processes. The controller is responsible for sequencing operators (i.e. elementary information processes) in design as search and integrating different kinds of information. This reflects the notion of what may be termed the central executive in psychology research. The central executive is a theoretical cognitive system involved in co-ordinating and regulating cognitive processes, as well as binding different kinds of information to form coherent episodes. The central executive is a key component of working memory models, perhaps most notably Baddeley's multi-component model (Baddeley 1983, 2003). In this model, working memory is proposed to constitute a set of cognitive systems supporting the simultaneous storage and manipulation of visuo-spatial and verbal information. In addition to the central executive, working memory is comprised of: (i) the visuo-spatial sketchpad, supporting storage and manipulation of visuo-spatial information; (ii) the phonological loop, supporting storage and manipulation of verbal information and (iii) the episodic buffer, supporting the integration of visuo-spatial and verbal information into coherent chronologically sequenced units (Baddeley 1983, 2003).

Based on the reviewed studies, working memory appears to be involved in conceptual design. The term is at least briefly mentioned by authors across all three viewpoints, e.g.: V1 – Stauffer & Ullman (1991); V2 – Bilda *et al.* (2006) and V3 – Liikkanen & Perttula (2009). It appears in the information processing models that typically underpin studies on design as search (e.g. Chan 1990; Stauffer & Ullman 1991), as well as in general accounts of designers' cognitive processing (e.g. Liikkanen & Perttula 2009; Leblebici-Basar & Altarriba 2013; Kim & Ryu 2014). The majority of references to working memory appear to focus on the use of the visuo-spatial sketchpad to support mental imagery processing (e.g. Bilda *et al.* 2006; Bilda & Gero 2007; Athavankar *et al.* 2008), which is perhaps unsurprising given the central role that mental imagery appears to play in conceptual design. The view that working memory is involved in conceptual design is consistent with the broader psychology and neuroscience literature, where working memory is implicated in both creative idea generation and evaluation (e.g. Dietrich 2004; Mumford *et al.* 2012). However, other than a study on mental imagery processing and working memory limitations by Bilda & Gero (2007), we found that it has received little investigative attention in the reviewed protocol studies. That is, there is little empirical evidence providing insight into the role of working memory in conceptual design. Consequently, working memory processes are not currently included in the classification presented in Figure 1.

Given the role of working memory in creative ideation and evaluation, investigating its role in conceptual design provides another salient avenue for future research. Work in this area could also contribute to expanding our proposed classification of cognitive processes. In addition to the visuo-spatial sketchpad, future research on working memory should also consider the role of the phonological loop in conceptual design given that designers frequently deal with verbal information from e.g. design briefs and technical documentation in addition to visual information from sketches and models. For future studies, it should also be noted that working memory and short-term memory are generally not considered to be synonymous terms by psychologists, although they appear to be employed as such in several papers in the sample (e.g. Stauffer & Ullman 1991; Bilda & Gero 2007).

5.2.4. The nature of concept generation and synthesis

Regarding creative output production, an area requiring clarification is the nature of synthesis and its relationship with concept generation. Both of the following perspectives may be detected in the sample: (i) synthesis involves combining ideas previously generated through concept generation to form more mature concepts (e.g. Jin & Chusilp 2006); and (ii) synthesis contributes to the process of concept generation (e.g. Lane & Seery 2011). One potential explanation for co-existing interpretations of synthesis may be identified in the work of Finke *et al.* (1992) on creative cognition, which appears to have influenced certain authors in the sample (notably Jin & Benami (2010)). As discussed in Section 4.2.2, the generation, maintenance and transformation of mental images is argued to be centrally involved in the generation of concepts. In this respect, Finke *et al.* (1992) describe two kinds of synthesis: (i) mental synthesis of an image, i.e. assembling the component parts of a mental image and (ii) conceptual combination, i.e. combining concepts with different attributes to produce new concepts. New concepts produced through conceptual combination may inherit certain attributes from the individual concepts, as well as possess emergent attributes different from those of individual concepts.

Given that concept generation appears to fundamentally involve mental imagery processing, it may be the case that authors discussing synthesis as part of the concept generation process are referring to the mental synthesis of an image. In contrast, authors describing synthesis as the process of combining previously generated concepts to produce more mature concepts are more likely referring to conceptual combination. However, it is worth highlighting that neither of these processes maps clearly to the description of synthesis provided in the most recent evolution of Gero's function–behaviour–structure (FBS) framework, which treats synthesis as a two stage process of (i) mapping behavioural design variables to structural variables and (ii) externally representing the structure comprised by these variables (Gero & Kannengiesser 2004). Considering the broader design literature, Sim & Duffy (2003) provide a comprehensive review of design activities. They note the existence of descriptions of synthesis aligning with that provided by Gero & Kannengiesser (2004), e.g. the mapping of dependencies between function, form and behaviour, as well as the perspective that synthesis is a form of abduction. Nonetheless, Sim & Duffy (2003, p. 205) argue that synthesis is 'more than just a mapping of dependencies', suggesting that it may rather be viewed as a process of integrating 'concepts or parts into a whole'. Overall, then, there is a need for future work to clarify what is meant by the term 'synthesis' in conceptual design, and the nature of the process(es) that it denotes.

5.2.5. Unidentified cognitive processes

Finally, as noted in Section 5.1, the cognitive processes included in the classification are necessarily limited to those that were identifiable in the reviewed studies. In this respect, it is possible that there may be cognitive processes considered to play an important role in designing elsewhere in the literature that were not investigated in our sample. A notable example is *learning*, which may be broadly defined as the process of acquiring new skills and knowledge. Sim & Duffy (2004) highlight that learning in design practice has been studied by a number of authors. However, we did not identify learning as a cognitive process explicitly studied in our sample. Sim & Duffy (2004, p. 40) highlight that the 'observation that designers learn [...] is supported by protocol studies in design that [demonstrate] experienced designers can reach satisfactory design solutions more effectively than novice or naïve designers', citing Lloyd & Scott (1994), who are included in our review sample, as an example. A similar example may be found in Ball *et al.* (2004), who conclude that experts are more likely than novices to carry out analogical reasoning in a rapid, automatic fashion based on knowledge schemas. The schematisation of domain knowledge is frequently associated with the development of domain expertise, which may be interpreted as learning. Nonetheless, Ball *et al.* (2004) do not explicitly study learning.

Considering the continual evolution in our understanding of design cognition, identifying and addressing gaps in the proposed classification must be an ongoing endeavour. Given that different methods may provide different views on the same phenomenon, this may entail empirical work using other approaches such as controlled experiments and case studies. In addition to empirical work *per se*, systematic reviews focused on other research methods may also reveal additional cognitive processes.

6. Conclusion

Inconsistencies in the concepts and terminology applied to describe cognition across different viewpoints on designing raise important ontological questions for the field: what cognitive processes actually exist within this domain, and how should they be defined and organised for study? Towards addressing these questions, this paper has presented the first generic classification of cognitive processes investigated in protocol studies on conceptual design cognition. Mapping cognitive processes described by design authors to more generic, established definitions in the cognitive psychology literature has revealed 6 categories of process that appear to be commonly investigated and are therefore likely to be prevalent in conceptual design: (1) long-term memory; (2) semantic processing; (3) visual perception; (4) mental imagery processing; (5) creative output production and (6) executive functions. Each category is comprised of several processes. In addition, the classification and its development highlight 6 key avenues for future empirical work on cognitive processes in conceptual design:

1. clarifying the nature and role of episodic and semantic memory in conceptual design;
2. developing more consistent definitions of the types of semantic processes involved in conceptual design;
3. considering and critiquing alternative perspectives on the similarities between visual perception and mental imagery processing, and in turn investigating the role of sketching from multiple theoretical perspectives to arrive at a more definitive position;
4. investigating the role of working memory in conceptual design, including the use of both the visuo-spatial sketchpad for mental imagery and the phonological loop for verbal design information;
5. clarifying the meaning of the term 'synthesis' in conceptual design and the nature of the process(es) it denotes and
6. expanding the classification as a whole to include any cognitive processes not identified from the reviewed studies, but implicated in conceptual design elsewhere in the literature (e.g. learning).

In addition to providing a more unified view of the field, the classification provides a starting point for the development of a generic, shared ontology of cognitive processes in design. An ontology of this nature that aligns with that of cognitive psychology and neuroscience would have several benefits, including: provision of a common basis for model and theory development; increased comparability of studies, both within design and across related fields such as artistic and musical composition; provision of a consistent basis for defining/selecting standard tests of cognitive design abilities; and increased capability for cross-disciplinary contributions by design cognition researchers and cognitive psychologists. In closing, it is important to highlight that not only should future work on design cognition address gaps in understanding within the design community; it should also contribute to broadening knowledge on design in the fields of cognitive psychology and neuroscience, where the activity remains under-researched in spite of its fundamental importance across multiple contexts and sectors. As such, we hope that our colleagues in both design research and cognitive science will contribute to the future empirical and theoretical work needed to develop a more consistent design cognition ontology.

Acknowledgments

This research is funded by the United Kingdom's Engineering and Physical Sciences Research Council, grant number EP/M012123.

Appendix A. Cognitive processes identified from protocol studies

The 35 cognitive processes identified from studies on design as search, design as exploration and design activities in our systematic review sample are presented in Table 3 below. Each process is assigned a code identifier consisting of

Table 3. Overview of cognitive processes identified from reviewed protocol studies

ID	Cognitive processes investigated [2]	Description	Authors	Domains [1]
VIEWPOINT 1: DESIGN AS SEARCH				
$V1_{P1}$	Solution search	The process of transforming knowledge states within a design problem space through the application of operators ($V1_{P3}$), beginning with the problem state and progressing through intermediate design states until the goal (i.e. solution) state is reached. State transformations may be: (i) lateral, i.e. moving between different ideas; or (ii) vertical, i.e. increasing the level of detail of the same idea.	(Akin 1984; Chan 1990; Stauffer & Ullman 1991; Goel 1995)	AD; ED
$V1_{P2}$	Problem structuring	The process of defining the design problem prior to or during the search for a solution ($V1_{P1}$). Problem structuring involves gathering information, setting goals, and establishing constraints. Restructuring the problem results in changes to the nature and/or structure of goals, constraints, and/or requirements.	(Akin 1984; Chan 1990; Goel 1995)	AD; ED
$V1_{P3}$	Problem decomposition	The process of breaking a design problem down into sub-problems through the specification of sub-goals (involved in problem structuring, $V1_{P2}$).	(Lloyd & Scott 1994; Liikkanen & Perttula 2009; Lee *et al.* 2014)	AD; ED; PDE
$V1_{P4}$	Problem reframing	The process of recognising restrictive frames of reference surrounding a design problem, and specifying new frames of reference that are conducive to solving the problem. Suitable frames of reference are determined using declarative and procedural domain knowledge retrieved from memory ($V1_{P6}$).	(Akin & Akin 1996)	AD

(continued on next page)

Table 3. (continued)

$V1_{P5}$	Operators	Operators are elementary information processes that transform information from input to output states. They are the basic component of problem structuring ($V1_{P1}$) and search processes ($V1_{P2}$). Particular sequences of operators applied to reach a solution and manage the search process are termed search methods and control strategies, respectively. Operators investigated in the reviewed studies may be grouped into 4 categories: information gathering; comprehending, representing, and structuring information; generating and synthesising; and evaluating and decision making.	(Akin, 1984; Chan 1990; Stauffer & Ullman 1991; Goel 1995; Kim *et al.* 2007)	AD; ED; PDE
$V1_{P6}$	Retrieval of operators and other information from long-term memory	Knowledge of operators ($V1_{P5}$) is stored within schemas (i.e. networks of knowledge units) in a designer's long-term memory. During designing, schemata relevant to the problem are retrieved from long-term memory and the operators activated in working memory. The operators then act on other kinds of recalled information, e.g. technical knowledge, knowledge of past solutions, etc., to effect a change in the problem structure or design state (manifested initially as a change in the information content of working memory).	(Akin 1984; Chan 1990; Stauffer & Ullman 1991)	AD; ED
$V1_{P7}$	Activation and manipulation of operators and other information in working memory			

(continued on next page)

Table 3. (continued)

$V1_{P8}$	Inference	The process of making logical judgements on the basis of pre-existing information (e.g. prior knowledge or previous judgements) rather than direct observations. Both inductive and deductive inference are argued to be involved in designing.	(Eckersley 1988; Lloyd & Scott 1994)	ED
$V1_{P9}$/ $V3_{P8}$	Analogical reasoning	The process of using information about known semantic concepts to understand newly presented semantic concepts, e.g. those contained within a design problem. Analogical reasoning may be carried out in a largely subconscious, automatic fashion using schemata retrieved from long-term memory (see $V1_{P6}$). Analogical reasoning may be viewed as a form of inductive reasoning (see $V1_{P8}$).	(Ball *et al.* 2004; Liikkanen & Perttula 2009)	ED; PDE
$V1_{P10}$/$V3_{P9}$	Case-based reasoning	The process of consciously mapping knowledge of previously encountered problems onto a current problem in order to generate concepts for solutions. Like analogical reasoning ($V1_{P9}$), case-based reasoning may be viewed as a form of inductive reasoning (see $V1_{P8}$).	(Ball *et al.* 2004)	AD; ED; PDE
VIEWPOINT 2: DESIGN AS EXPLORATION				
$V2_{P1}$	Co-evolution of design problems and solutions	The process of developing a solution to a design problem whilst simultaneously structuring/restructuring the problem. The designer's task environment is considered to comprise of: (i) a problem space, encompassing knowledge of design requirements; and (ii) a solution space, encompassing knowledge of design solutions. The problem space serves as a basis to evaluate ideas developed in the solution space, whilst the solution space provides the basis to evaluate requirements existing in the problem space. Interactions between the spaces may add new variables to both (e.g. new requirements in the problem space or new solutions in the solution space), thereby changing the focus of designing.	(Dorst & Cross 2001; Maher & Tang 2003; Maher & Kim 2006; Yu *et al.* 2014)	AD; PDE

(continued on next page)

Table 3. (continued)

$V2_{P2}$	Visual reasoning	Broadly speaking, the process of generating and reasoning about ideas whilst engaged in sketching. Visual reasoning is conceptualised in two different ways by authors in the sample, namely as: a process of seeing that and seeing as ($V2_{P3}$); and the interaction of seeing ($V2_{P5}$), imagining ($V2_{P6}$), and drawing ($V2_{P7}$) processes.	(Goldschmidt 1991; Park & Kim 2007)	AD; PDE
$V2_{P3}$	Seeing as and seeing that	Two modes of reasoning that a designer continually shifts between during sketching in the early stages of designing: (i) seeing as, i.e. proposing properties/attributes that a design could possess based on metaphors and analogies; and (ii) seeing that, i.e. developing a rationale for design decisions relating to these proposals. Reasoning is driven by what the designer perceives in their sketches, hence the term visual reasoning ($V2_{P2}$).	(Goldschmidt 1991; Won 2001)	AD; PDE
$V2_{P4}$	Re-interpretation	The process of assigning new functions to parts of a design through the interpretation of visuo-spatial elements and relations in sketches. Re-interpretation is classed as a type of functional cognitive action ($V2_{P8}$).	(Suwa *et al.* 1998, 2000)	AD
$V2_{P5}$	Seeing	The process of perceiving, analysing, and interpreting visual information from external representations during sketching. Seeing is argued to form part of a designer's visual reasoning process, interacting with the processes of imagining ($V2_{P6}$) and drawing ($V2_{P7}$).	(Park & Kim 2007)	PDE
$V2_{P6}$	Imagining	The process of generating new internal images, which may be transformed according to particular schemata (see $V1_{P4}$) and maintained for externalisation via the process of drawing ($V2_{P7}$). Images may be generated using perceptual information generated by the process of seeing ($V2_{P5}$), and/or schemata retrieved from long-term memory.		

(continued on next page)

Table 3. (continued)

$V2_{P7}$	Drawing	The process of evaluating and confirming internal images produced through the process of imagining ($V2_{P6}$), before externalising them (through sketching) to produce an external representation.		
$V2_{P8}$	Cognitive actions during sketching	A set of interdependent processes involved in sketching that pertain to sensory information (physical actions, $V2_{P9}$), perceptual (specifically, visual) information (perceptual actions, $V2_{P10}$), and semantic information (functional and conceptual actions, $V2_{P11}$ and $V2_{P12}$ respectively). The processes are argued to correspond to basic levels of human information processing.	(Suwa *et al.* 1998, 2000; Kavakli & Gero 2001, 2002; Bilda & Demirkan 2003; Sun *et al.* 2013)	AD; PDE
$V2_{P9}$	Physical actions	A set of processes involved in sketching ($V2_{P8}$) that pertain to sensory information, including: (i) making depictions; and (ii) looking at previous depictions.		
$V2_{P10}$	Perceptual actions	A set of processes involved in sketching ($V2_{P8}$) that pertain to perceptual (specifically, visual) information, including: (i) attending to visual features of sketch elements; (ii) attending to spatial relations among elements; and (iii) organising or comparing elements.		
$V2_{P11}$	Functional actions	A set of processes involved in sketching ($V2_{P8}$) that pertain to semantic (specifically, functional) information, including: (i) exploring interactions between artefacts and people/nature; and (ii) considering the psychological reactions of people.		
$V2_{P12}$	Conceptual actions	A set of processes involved in sketching ($V2_{P8}$) that pertain to semantic (specifically, conceptual) information, including: (i) preferential and aesthetic evaluation; (ii) setting up goals; and (iii) retrieving knowledge.		

(continued on next page)

Table 3. (continued)

$V2_{P13}$	Unexpected discovery of visuo-spatial features and relations in sketches	The process of perceiving a visuo-spatial feature/relation in a sketch that was not intentionally created and is therefore unexpected. Three types of unexpected discovery are proposed, namely discovery of: (i) the shape, size, or texture of a sketch element; (ii) a spatial or organisational relation among elements; and (iii) a space that exists in between elements (figure-ground reversal). Unexpected discoveries are classed as a type of perceptual action ($V2_{P10}$), and are argued to be correlated with the process of situated invention ($V2_{P14}$).	(Suwa *et al.* 2000; Suwa 2003; Yu *et al.* 2013)	AD
$V2_{P14}$	Situated invention of design requirements	The process of developing new design requirements based on what is perceived in sketches. Situated invention of requirements initially involves the definition of goals focusing on new issues identified during sketching (a type of conceptual action, $V2_{P12}$), with the issues eventually becoming general enough to constitute a new design requirement. Situated invention is argued to be correlated with the process of unexpected discovery ($V2_{P13}$).		
VIEWPOINT 3: DESIGN ACTIVITIES				
$V3_{P1}$	Problem analysis	The process of characterising and structuring the design problem by setting goals and defining constraints and requirements. Problem analysis may be carried out iteratively – that is, the problem may be redefined and restructured during the course of designing.	(McNeill *et al.* 1998; Jin & Chusilp 2006; Kruger & Cross 2006; Jin & Benami 2010; Lee *et al.* 2014)	AD; ED; PDE
$V3_{P2}$	Management of constraints and requirements	The processes of identifying, exploring, clarifying, and prioritising constraints and design requirements (involved in problem analysis, $V3_{P1}$).	(Kim *et al.* 2005, 2006; Lane & Seery 2011; Daly *et al.* 2012)	PDE

(continued on next page)

Table 3. (continued)

$V3_{P3}$	Concept generation	The process of generating ideas for solutions/partial solutions to design problems. The following processes are argued to be involved in concept generation: (i) memory retrieval ($V3_{P5}$); (ii) association of mental representations ($V3_{P6}$); (iii) transformation of mental representations ($V3_{P7}$); and (iv) analogical ($V3_{P8}$) and case-based reasoning ($V3_{P9}$). Synthesis ($V3_{P4}$) may also be positioned as part of concept generation. Concept generation may be termed idea generation by certain authors.	(Jin & Chusilp 2006; Kruger & Cross 2006; Jin & Benami 2010; Lane & Seery 2011)	ED; PDE
$V3_{P4}$	Synthesis	The process of combining and/or developing previously generated ideas to produce more mature concepts. Synthesis may be treated either as part of concept generation ($V3_{P3}$), or as a related but distinct process. The process may be termed concept composition by certain authors.	(McNeill *et al.* 1998; Jin & Chusilp 2006; Kruger & Cross 2006; Daly *et al.* 2012)	ED; PDE
$V3_{P5}$	Retrieval of representations from memory	The process of retrieving representations from long-term memory (e.g. semantic concepts and knowledge of past design episodes). Memory retrieval is argued to be a fundamental process involved in concept generation ($V3_{P3}$).	(Jin & Benami 2010; Lane & Seery 2011)	ED; PDE
$V3_{P6}$	Association of representations	The process of forming relationships between mental representations retrieved from long-term memory (e.g. semantic concepts and knowledge of past design episodes). Association is argued to be a fundamental process involved in concept generation ($V3_{P3}$), and is viewed as a largely subconscious, automatic process.	(Jin & Benami 2010)	ED
$V3_{P7}$	Transformation of representations	The process of altering mental representations retrieved from long-term memory (e.g. semantic concepts and knowledge of past design episodes) to produce new representations. Transformation is argued to be a fundamental process involved in concept generation ($V3_{P3}$).	(Jin & Benami 2010; Lane & Seery 2011; Leblebici-Basar & Altarriba 2013)	ED; PDE

(continued on next page)

Table 3. (continued)

$V3_{P8}/V1_{P9}$	Analogical reasoning	See $V1_{P9}$ for description. Analogical reasoning has been implicated in the generation ($V3_{P3}$) and synthesis ($V3_{P4}$) of concepts.	(Liikkanen & Perttula 2009; Jin & Benami 2010)	ED; PDE
$V3_{P9}/V1_{P10}$	Case-based reasoning	See $V1_{P10}$ for description. Like analogical reasoning ($V3_{P8}$), case-based reasoning has been implicated in the generation ($V3_{P3}$) and synthesis ($V3_{P4}$) of concepts.	(Chiu 2003; Kim *et al.* 2010; Daly *et al.* 2012; Kim & Ryu 2014; Yu & Gero 2015)	AD; PDE
$V3_{P10}$	Concept evaluation	The process of assessing concepts against design constraints, requirements, and other criteria to determine the extent to which the concepts fulfil the criteria. The following processes are argued to be involved in concept evaluation: (i) comparing ($V3_{P11}$); and (ii) judging ($V3_{P12}$). Concept evaluation is also closely related to decision making ($V3_{P13}$).	(McNeill *et al.* 1998; Jin & Chusilp 2006; Kruger & Cross 2006; Jin & Benami 2010; Lee *et al.* 2014)	AD; ED; PDE
$V3_{P11}$	Comparing	The process of comparing concepts against design criteria or other concepts (involved in concept evaluation, $V3_{P10}$).	(Kim & Ryu 2014)	PDE
$V3_{P12}$	Judging	The process of making judgements about concepts on the basis of value, aesthetics, affect, or objective criteria (involved in concept evaluation, $V3_{P10}$).	(Chiu 2003; Kruger & Cross 2006; Daly *et al.* 2012; Chandrasekera *et al.* 2013; Kim & Ryu 2014; Lee *et al.* 2014)	AD; PDE
$V3_{P13}$	Decision making	The process of determining what concept(s) should be taken forward for further development from a range of alternatives (involved in concept evaluation, $V3_{P10}$).	(Kim & Ryu 2014)	PDE

[1] Domain abbreviations: AD = architectural design; ED = engineering design; PDE = product design engineering.

a viewpoint (V) and process number (P) e.g. $V1_{P1}$ (column 1). Processes are listed and described as conveyed by investigating authors.

It should be highlighted that several processes presented in Table 3 involve multiple related processes, as conveyed in the process descriptions presented in column 3. We adopted the organisation and structure of Table 3 largely because it aligns with the manner in which processes are discussed by the authors investigating them. In turn, we found it to be the most conducive to clear explanation of the review findings. Nonetheless, we acknowledge that other authors may have different interpretations in this respect.

References[1]

Abraham, A. & **Bubic, A.** 2015 Semantic memory as the root of imagination. *Frontiers in Psychology* **6**, 1–5. doi:10.3389/fpsyg.2015.00325.

*__Akin, Ö.__ 1979 An exploration of the design process. *Design Methods and Theories: Journal of the DMG* **13** (3/4), 115–119.

*__Akin, O.__ & **Akin, C.** 1996 Frames of reference in architectural design: analysing the hyperacclamation (a-h-a-!). *Design Studies* **17** (4), 341–361.

*__Athavankar, U.__, **Bokil, P.** & **Guruprasad, K.** 2008 Reaching out in the mind's space. In *Design Computing and Cognition '08*, pp. 321–340. Springer.

*__Athavankar, U. A.__ 1997 Mental imagery as a design tool. *Cybernetics and Systems* **28** (1), 25–42. doi:10.1080/019697297126236.

Baddeley, A. 1983 Working memory. *Phil. Trans. R. Soc. Lond.* B **302** (1110), 311–324.

Baddeley, A. 2003 Working memory: looking back and looking forward. *Nature Reviews – Neuroscience* **4**, 829–839.

*__Ball, L. J.__, **Ormerod, T. C.** & **Morley, N. J.** 2004 Spontaneous analogising in engineering design: a comparative analysis of experts and novices. *Design Studies* **25** (5), 495–508. doi:10.1016/j.destud.2004.05.004.

Beaty, R. E., **Silvia, P. J.**, **Nusbaum, E. C.**, **Jauk, E.** & **Benedek, M.** 2014 The roles of associative and executive processes in creative cognition. *Memory & Cognition* **42** (7), 1186–1197. doi:10.3758/s13421-014-0428-8.

Benedek, M., **Jauk, E.**, **Fink, A.**, **Koschutnig, K.**, **Reishofer, G.**, **Ebner, F.** & **Neubauer, A. C.** 2013 To create or to recall? Neural mechanisms underlying the generation of creative new ideas. *NeuroImage* **88**, 125–133. doi:10.1016/j.neuroimage.2013.11.021.

*__Bilda, Z.__ & **Demirkan, H.** 2003 An insight on designers' sketching activities in traditional versus digital media. *Design Studies* **24** (1), 27–50. doi:10.1016/S0142-694X(02)00032-7.

*__Bilda, Z.__ & **Gero, J. S.** 2007 The impact of working memory limitations on the design process during conceptualization. *Design Studies* **28** (4), 343–367. doi:10.1016/j.destud.2007.02.005.

*__Bilda, Z.__, **Gero, J. S.** & **Purcell, T.** 2006 To sketch or not to sketch? That is the question. *Design Studies* **27** (5), 587–613. doi:10.1016/j.destud.2006.02.002.

Boyle, I. M., **Duffy, A. H. B.**, **Whitfield, R. I.** & **Liu, S.** 2009 Towards an understanding of the impact of resources on the design process. In *17th International Conference on Engineering Design (ICED '09)*. The Design Society.

Bruce, V., **Green, P. R.** & **Georgeson, M. A.** 2003 *Visual Perception: Physiology, Psychology and Ecology*. Psychology Press.

[1] The 47 articles included in the systematic review sample are marked with * below.

Buys, A. & **Mulder, H.** 2014 A study of creativity in technology and engineering. In *Proceedings of PICMET '14: Infrastructure and Service Integration*, pp. 879–891. IEEE.

*__Chan, C.-S.__ 1990 Cognitive processes in architectural problem solving. *Design Studies* **11** (2), 60–80. doi:10.1016/0142-694X(90)90021-4.

Chan, R. C. K., **Shum, D.**, **Toulopoulou, T.** & **Chen, E. Y. H.** 2008 Assessment of executive functions: review of instruments and identification of critical issues. *Archives of Clinical Neuropsychology: The Official Journal of the National Academy of Neuropsychologists* **23** (2), 201–216. doi:10.1016/j.acn.2007.08.010.

*__Chandrasekera, T.__, **Vo, N.** & **D'Souza, N.** 2013 The effect of subliminal suggestions on sudden moments of inspiration (SMI) in the design process. *Design Studies* **34** (2), 193–215. doi:10.1016/j.destud.2012.09.002.

*__Chen, X.__ & **Zhao, J.** 2006 Research on the model and application of knowledge-based industrial design. In *International Technology and Innovation Conference 2006, Vol 1*, pp. 258–263. Institution of Engineering and Technology.

*__Chiu, M. L.__ 2003 Design moves in situated design with case-based reasoning. *Design Studies* **24** (1), 1–25. doi:10.1016/S0142-694X(02)00007-8.

Cross, N. 2001 Design cognition: results from protocol and other empirical studies of design activity. In *Design Knowing and Learning: Cognition in Design Education* **(ed. C. M. Eastman, W. M. McCracken & W. C. Newstetter)**, pp. 79–103. Elsevier Science Ltd.

*__Daly, S. R.__, **Yilmaz, S.**, **Christian, J. L.**, **Seifert, C. M.** & **Gonzalez, R.** 2012 Design heuristics in engineering. *Journal of Engineering Education* **101** (4), 601–629.

Dietrich, A. 2004 The cognitive neuroscience of creativity. *Psychonomic Bulletin & Review* **11** (6), 1011–1026. doi:10.3758/BF03196731.

Dinar, M., **Shah, J. J.**, **Cagan, J.**, **Leifer, L.**, **Linsey, J.**, **Smith, S. M.** & **Hernandez, N. V.** 2015 Empirical studies of designer thinking: past, present, and future. *Journal of Mechanical Design* **137** (2), 1–13. doi:10.1115/1.4029025.

*__Dorst, K.__ & **Cross, N.** 2001 Creativity in the design process: co-evolution of problem-solution. *Design Studies* **22** (5), 425–437. doi:10.1016/S0142-694X(01)00009-6.

Dorst, K. & **Dijkhuis, J.** 1995 Comparing paradigms for describing design activity. *Design Studies* **16** (2), 261–274. doi:10.1016/0142-694X(94)00012-3.

*__Eckersley, M.__ 1988 The form of design processes: a protocol analysis study. *Design Studies* **9** (2), 86–94. doi:10.1016/0142-694X(88)90034-8.

Ericsson, A. K. & **Simon, H. A.** 1984 *Protocol Analysis - Verbal Reports as Data*. MIT.

Eysenck, M. W. & **Keane, M. T.** 2005 *Cognitive Psychology: A Student's Handbook*, 5th ed. Pyschology Press Ltd.

Federmeier, K. D., **McLennan, D. B.**, **Ochoa, E.** & **Kutas, M.** 2002 The impact of semantic memory organization and sentence context information on spoken language processing by younger and older adults: an ERP study. *Psychophysiology* **39** (2), 133–146. doi:10.1111/1469-8986.3920133.

Finke, R. A. 1996 Imagery, creativity, and emergent structure. *Consciousness and Cognition* **5** (3), 381–393. doi:10.1006/ccog.1996.0024.

Finke, R. A., **Ward, T. B.** & **Smith, S. M.** 1992 *Creative Cognition: Theory, Research, and Applications*. The MIT Press.

Fish, J. & **Scrivener, S.** 1990 Amplifying the mind's eye: sketching and visual cognition. *Leonardo* **23** (1), 117–126.

Ganis, G. 2013 Visual mental imagery. In *Multisensory Imagery* **(ed. S. Lacey & R. Lawson)**, pp. 9–28. Springer; doi:10.1007/978-1-4614-5879-1.

Gero, J. S. 1990 Design prototypes: a knowledge representation schema for design. *AI Magazine* **11** (4), 26–36. doi:10.1609/aimag.v11i4.854.

Gero, J. S. & **Kannengiesser, U.** 2004 The situated function-behaviour-structure framework. *Design Studies* **25** (4), 373–391. doi:10.1016/j.destud.2003.10.010.

Gero, J. S. & **Kannengiesser, U.** 2007 A function-behavior-structure ontology of processes. *AI EDAM* **21** (4), 379–391. doi:10.1017/S0890060407000340.

Gero, J. S., **Kannengiesser, U.** & **Pourmohamadi, M.** 2014 Commonalities across designing: empirical results. In *Design Computing and Cognition '12*, pp. 265–281. Springer; doi:10.1007/978-94-017-9112-0_15.

Gero, J. S. & **Tang, H.-H.** 2001 The differences between retrospective and concurrent protocols in revealing the process-oriented aspects of the design process. *Design Studies* **22** (3), 283–295. doi:10.1016/S0142-694X(00)00030-2.

Gobet, F., **Chassy, P.** & **Bilalic, M.** 2011 *Foundations of Cognitive Psychology*. McGraw-Hill Education.

Goel, A. K. 1997 Design, analogy, and creativity. *IEEE Expert* **12** (3), 62–70. doi:10.1109/64.590078.

*__Goel, V.__ 1995 Cognitive processes involved in design problem solving. In *Sketches of Thought* **(ed. V. Goel)**, pp. 95–126. MIT Press.

Goel, V. 2014 Creative brains: designing in the real world. *Frontiers in Human Neuroscience* **8**, 1–14. doi:10.3389/fnhum.2014.00241.

*__Goldschmidt, G.__ 1991 The dialectics of sketching. *Creativity Research Journal* **4** (2), 123–143. doi:10.1080/10400419109534381.

Hay, L., **McTeague, C.**, **Duffy, A. H. B.**, **Pidgeon, L. M.**, **Vuletic, T.** & **Grealy, M.** A systematic review of protocol studies on conceptual design cognition: Design as search and exploration. *Design Science* (under review).

*__Jin, Y.__ & **Benami, O.** 2010 Creative patterns and stimulation in conceptual design. *AI EDAM* **24** (2), 191–209. doi:10.1017/S0890060410000053.

*__Jin, Y.__ & **Chusilp, P.** 2006 Study of mental iteration in different design situations. *Design Studies* **27** (1), 25–55. doi:10.1016/j.destud.2005.06.003.

*__Kavakli, M.__ & **Gero, J. S.** 2001 Sketching as mental imagery processing. *Design Studies* **22** (4), 347–364. doi:10.1016/S0142-694X(01)00002-3.

*__Kavakli, M.__ & **Gero, J. S.** 2002 The structure of concurrent cognitive actions: a case study on novice and expert designers. *Design Studies* **23** (1), 25–40. doi:10.1016/S0142-694X(01)00021-7.

Khorshidi, M., **Shah, J. J.** & **Woodward, J.** 2014 Applied tests of design skills. Part III: Abstract reasoning. *Journal of Mechanical Design* **136**, 101101-1–101101-11. doi:10.1115/1.4027986.

*__Kim, J.__ & **Ryu, H.** 2014 A design thinking rationality framework: framing and solving design problems in early concept generation. *Human–Computer Interaction* **29** (5–6), 516–553. doi:10.1080/07370024.2014.896706.

*__Kim, J. E.__, **Bouchard, C.**, **Omhover, J. F.** & **Aoussat, a.** 2010 Towards a model of how designers mentally categorise design information. *CIRP Journal of Manufacturing Science and Technology* **3** (3), 218–226. doi:10.1016/j.cirpj.2010.11.004.

*__Kim, M. H.__, **Kim, Y. S.**, **Lee, H. S.** & **Park, J. a.** 2007 An underlying cognitive aspect of design creativity: limited commitment mode control strategy. *Design Studies* **28** (6), 585–604. doi:10.1016/j.destud.2007.04.006.

*__Kim, Y.__, **Jin, S.** & **Lee, H.** 2005 Dual protocol analysis based on design information and design process: a case study. In *Studying Designers '05*, pp. 71–85. Key Centre of Design Computing and Cognition.

*__Kim, Y. S.__, __Jin, S. T.__ & __Lee, S. W.__ 2006 Design activities and personal creativity characteristics: a case study of dual protocol analysis using design information and process. In *ASME 2006 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Philadelphia*, The American Society of Mechanical Engineers.

Kosslyn, S. M. 1995 Mental imagery. In *Visual Cognition: An Invitation to Cognitive Science, Vol. 2* **(ed. S. M. Kosslyn & D. N. Osherson)**, pp. 267–296. Cambridge.

*__Kruger, C.__ & __Cross, N.__ 2006 Solution driven versus problem driven design: strategies and outcomes. *Design Studies* **27** (5), 527–548. doi:10.1016/j.destud.2006.01.001.

*__Lane, D.__ & __Seery, N.__ 2011 Examining the development of sketch thinking and behaviour. In *Annual Conference for the American Society of Engineering Education, Vancouver, Canada*, The American Society for Engineering Education.

*__Leblebici-Basar, D.__ & __Altarriba, J.__ 2013 The role of imagery and emotion in the translation of concepts into product form. *The Design Journal* **16** (3), 295–314.

*__Lee, J.__, __Gu, N.__ & __Williams, A.__ 2014 Parametric design strategies for the generation of creative designs. *International Journal of Architectural Computing* **12** (3), 263–282.

Li, Y., **Wang, J.**, **Li, X.** & **Zhao, W.** 2007 Design creativity in product innovation. *International Journal of Advanced Manufacturing Technology* **33** (3–4), 213–222. doi:10.1007/s00170-006-0457-y.

*__Liikkanen, L. a.__ & __Perttula, M.__ 2009 Exploring problem decomposition in conceptual design among novice designers. *Design Studies* **30** (1), 38–59. doi:10.1016/j.destud.2008.07.003.

Lloyd, P., **Lawson, B.** & **Scott, P.** 1995 Can concurrent verbalization reveal design cognition? *Design Studies* **16** (2), 237–259. doi:10.1016/0142-694X(94)00011-2.

*__Lloyd, P.__ & __Scott, P.__ 1994 Discovering the design problem. *Design Studies* **15** (2), 125–140. doi:10.1016/0142-694X(94)90020-5.

Maher, M. L., **Balachandran, M. B.** & **Zhang, D. M.** 1995 *Case-Based Reasoning in Design*. Psychology Press Ltd.

*__Maher, M. L.__ & __Kim, M.__ 2006 The effects of tangible user interfaces on designers' cognitive actions. In *The International Workshop on Spatial Cognition 2006*, pp. 119–124. Springer-Verlag.

*__Maher, M.__ & __Tang, H.-H.__ 2003 Co-evolution as a computational and cognitive model of design. *Research in Engineering Design* **14** (1), 47–64. doi:10.1007/s00163-002-0016-y.

Martin, A. & **Chao, L. L.** 2001 Semantic memory and the brain: structure and processes. *Current Opinion in Neurobiology* **11** (2), 194–201. doi:10.1016/S0959-4388(00)00196-3.

McKoy, F. L., **Vargas-Hernandez, N.**, **Summers, J. D.** & **Shah, J. J.** 2001 Influence of design representation on effectiveness of idea generation. In *Proceedings of DETC'01: ASME 2001 Design Engineering Technical Conferences and Computers and Information in Engineering Conference, September 9–12, 2001, Pittsburgh, Pennsylvania*, pp. 1–10. The American Society of Mechanical Engineers.

*__McNeill, T.__, __Gero, J. S.__ & __Warren, J.__ 1998 Understanding conceptual electronic design using protocol analysis. *Research in Engineering Design* **10** (3), 129–140. doi:10.1007/BF01607155.

Mednick, S. 1962 The associative basis of the creative process. *Psychological Review* **69** (3), 220–232.

Milner, A. D. & **Goodale, M. A.** 2008 Two visual systems re-viewed. *Neuropsychologia* **46** (3), 774–785. doi:10.1016/j.neuropsychologia.2007.10.005.

Moher, D., **Liberati, A.**, **Tetzlaff, J.** & **Altman, D. G.** 2009 Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Medicine* **6** (7), 1–6. doi:10.1371/journal.pmed.1000097.

Mumford, M. D., **Medeiros, K. E.** & **Partlow, P. J.** 2012 Creative thinking: processes, strategies, and knowledge. *Journal of Creative Behavior* **46** (1), 30–47. doi:10.1002/jocb.003.

Newell, A. & **Simon, H. A.** 1972 *Human Problem Solving*. Prentice-Hall.

***Park, J.** & **Kim, Y.** 2007 Visual reasoning and design processes. In *International Conference on Engineering Design, ICED07*, pp. 1–12. The Design Society.

Poldrack, R. 2009 Cognitive Atlas: a collaboratively developed cognitive science ontology [online]. http://www.cognitiveatlas.org/about (accessed 05.09.17).

Poldrack, R. A., **Kittur, A.**, **Kalar, D.**, **Miller, E.**, **Seppa, C.**, **Gil, Y.**, **Parker, D. S.**, **Sabb, F. W.** & **Bilder, R. M.** 2011 The cognitive atlas: toward a knowledge foundation for cognitive neuroscience. *Frontiers in Neuroinformatics* **5**, 1–11. doi:10.3389/fninf.2011.00017.

Rabbitt, P. 2004 *Methodology of Frontal and Executive Function*. Psychology Press Ltd.

Runco, M. A. & **Chand, I.** 1995 Cognition and creativity. *Educational Psychology Review* **7** (3), 243–267. doi:10.1007/BF02213373.

Sarkar, P. & **Chakrabarti, A.** 2014 Ideas generated in conceptual design and their effects on creativity. *Research in Engineering Design* **25** (3), 185–201. doi:10.1007/s00163-014-0173-9.

Shah, J. J., **Millsap, R. E.**, **Woodward, J.** & **Smith, S. M.** 2012 Applied tests of design skills. Part 1. Divergent thinking. *Journal of Mechanical Design* **134**, 021005-1–021005-10. doi:10.1115/1.4005594.

Shah, J. J., **Millsap, R. E.**, **Woodward, J.** & **Smith, S. M.** 2013 Applied tests of design skills. Part II. Visual thinking. *Journal of Mechanical Design* **135**, 071004-1–071004-11. doi:10.1115/1.4005594.

Sim, S. K. & **Duffy, A. H. B.** 2003 Towards an ontology of generic engineering design activities. *Research in Engineering Design* **14** (4), 200–223. doi:10.1007/s00163-003-0037-1.

Sim, S. K. & **Duffy, A. H. B.** 2004 Evolving a model of learning in design. *Research in Engineering Design* **15** (1), 40–61. doi:10.1007/s00163-003-0044-2.

Squire, L. R. & **Zola, S. M.** 1998 Episodic memory, semantic memory, and amnesia. *Hippocampus* **8**, 205–211.

***Stauffer, L. A.** & **Ullman, D. G.** 1991 Fundamental processes of mechanical designers based on empirical data. *Journal of Engineering Design* **2** (2), 113–125. doi:10.1080/09544829108901675.

***Sun, G.**, **Yao, S.** & **Carretero, J. A.** 2013 Evaluating cognitive efficiency by measuring information contained in designers' cognitive processes. In *Proceedings of the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Portland, Oregon*, pp. 1–10.

***Suwa, M.** 2003 Constructive perception: coordinating perception and conception toward acts of problem-finding in a creative experience. *Japanese Psychological Research* **45** (4), 221–234. doi:10.1111/1468-5884.00227.

***Suwa, M.**, **Gero, J.** & **Purcell, T.** 2000 Unexpected discoveries and S-invention of design requirements: important vehicles for a design process. *Design Studies* **21** (6), 539–567.

***Suwa, M.**, **Purcell, T.** & **Gero, J.** 1998 Macroscopic analysis of design processes based on a scheme for coding designers' cognitive actions. *Design Studies* **19** (4), 455–483. doi:10.1016/S0142-694X(98)00016-7.

*__Suwa, M.__ & __Tversky, B.__ 1997 What do architects and students perceive in their design sketches? A protocol analysis. *Design Studies* **18** (4), 385–403. doi:10.1016/S0142-694X(97)00008-2.

Taborda, E., **Chandrasegaran, S. K.**, **Kisselburgh, L.**, **Reid, T.** & **Ramani, K.** 2012 Enhancing visual thinking in a toy design course using freehand sketching. In *Volume 7: 9th International Conference on Design Education; 24th International Conference on Design Theory and Methodology*, p. 267. ASME; doi:10.1115/DETC2012-71454.

Tulving, E. 1983 *Elements of Episodic Memory*. Clarendon Press.

Tversky, B. 2014 Some ways of thinking. In *Model-Based Reasoning in Science and Technology, Studies in Applied Philosophy, Epistemology and Rational Ethics* **(ed. L. Magnani)**, pp. 3–8. Springer; doi:10.1007/978-3-642-37428-9.

van Someren, M. W., **Barnard, Y. F.** & **Sandberg, J. A. C.** 1994 *The Think Aloud Method: A Practical Guide to Modelling Cognitive Processes*. Academic Press, London.

Viswanathan, V. K. & **Linsey, J. S.** 2012 Physical models and design thinking: a study of functionality, novelty and variety of ideas. *Journal of Mechanical Design* **134** (9), 091004. doi:10.1115/1.4007148.

*__Won, P. H.__ 2001 The comparison between visual thinking using computer and conventional media in the concept generation stages of design. *Automation in Construction* **10** (3), 319–325. doi:10.1016/S0926-5805(00)00048-0.

*__Yu, R.__, **Gero, J.** & **Gu, N.** 2015 Architects' cognitive behaviour in parametric design. *International Journal of Architectural Computing* **1** (13), 83–101.

*__Yu, R.__ & **Gero, J. S.** 2015 An empirical foundation for design patterns in parametric design. In *Proceedings of the 20th International Conference of the Association for Computer-Aided Architectural Design Research in Asia CAADRIA 2015* **(ed. Y. Ikeda, C. M. Herr, D. Holzer, S. Kaijima, M. J. Kim & A. Schnabel)**, pp. 1–9. The Association for Computer-Aided Architectural Design Research In Asia (CAADRIA).

*__Yu, R.__, **Gu, N.** & **Lee, J. H.** 2013 Comparing designers' behavior in responding to unexpected discoveries in parametric design environments and geometry modeling environments. *International Journal of Architectural Computing* **11** (4), 393–414.

*__Yu, R.__, **Gu, N.**, **Ostwald, M.** & **Gero, J. S.** 2014 Empirical support for problem–solution coevolution in a parametric design environment. *AI EDAM* **29** (1), 33–44. doi:10.1017/S0890060414000316.

Zhang, L. & **Lin, W.** 2013 *Selective Visual Attention: Computational Models and Applications*. John Wiley & Sons Singapore Pte Ltd.