Challenging learning journeys in the classroom: Using mental model theory to inform how pupils think when they are generating solutions

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This paper presents a discussion about the interplay between Mental Model Theory and the generation of solutions to learning challenges in the primary classroom. It explores how pupils negotiate the problem solving spaces that can arise in the two learning areas of Mathematics and Design and Technology although the cross-curricula nature of learning in the primary classroom can conflate the two domains.

Learning challenges engage thinking. Teachers will think about, and subsequently design, challenging scenarios that will stimulate their pupils to generate a range of possible solutions. In turn, pupils will think about how they will meet the challenges. Mental Model Theory informs teachers' knowledge about thinking: it explains how mental models arise from the idiosyncratic methods of developing the dialogue and relationships necessary to guide thinking. Mental models are purposeful cognitive structures that have a process/product nature. They also have several functions that enable them to store data and enact strategies to generate outcomes. The theory explains how pupils engage in the thinking process to assimilate memory, new data and personalised strategies to find solutions to challenges. When faced with a novel challenge, pupils retrieve, restructure and/or create, and store useable mental models in accordance with their perceived relevance to generate an acceptable outcome.

This paper explores how a challenge, be it finding a solution to a mathematical conundrum or creating a response to a brief in Design and Technology, stimulates thinking processes. The discussion will consider how an understanding of the functions of mental models, through the use of the Mental Model Mode, can enhance constructive and inventive thinking in classrooms. It proposes implications for pedagogical practice and some key considerations for teachers as reflective practitioner – and designer of learning challenges.

Key words: mental models, problem solving, Design and Technology, Mathematics

1. Understanding mental model theory

The word “model” has lead to some vexation by researchers of cognitive theory because of peoples’ certainty that they understand what the word means when used in the designation *mental model*. Everyone knows what a model is! To remove any ambiguity about the word, “model” here serves two grammatical purposes: a *noun* where it is “a representation in three dimensions of … a proposed structure”, and as a *verb* “to form a thing in imitation of . . .[that is, to] devise a model of a phenomenon or system” (Moore, 1987, p. 900). Mental models, being “models” are bimodal (Edwards-Leis, 2010): as a *product* (Gentner & Stevens, 1983; Henderson & Tallman, 2006; Johnson-Laird, 1983; Newton, 1996) produced through cognition by individuals to create a representation or structure of a phenomenon or solution to a problem, and as a *process* (Carroll & Olson, 1988; Halford, 1993; Henderson & Tallman, 2006; Norman, 1983) where an action of retrieval, restructuring or creation occurs to form and reform these representations of the structure of a phenomenon or solution to a problem. Consequently, the term “mental modelling” can be used to explain the process that individuals undertake when they create, or retrieve, mental models in order to devise more useful or refined mental models to solve problems.

Confusion also exists in individuals’ beliefs that a “model”, in its purest form, may be a reproduction of the reality of a phenomenon in an environment. Mental models are not just reproductions: they have a dynamic existence that is separate to the reality they *model* once they have been produced by the individual (Edwards-Leis, 2010). When a mental model is seen as useful it is stored, by the individual, in long-term memory where it may be related or connected to many other mental models and cognitive structures such as schemes (Piaget, 1970), schema (Anderson, 1977), propositions (Kyllonen & Shute, 1989) and scripts (Preece, Rogers, Sharp, Benyon, Holland & Carey 1994). However, the mental model now exists within its own reality and no longer relies on the replication of its source phenomenon (Barker, 1999).

Novel problem situations are of interest to educators because they require learners to map knowledge and skills from known problems to new circumstances. Norman (1988) recognised that cognitive representations, such as schemata, could not explain what occurred when individuals encounter new or novel problems. Schema theory was seen to be inflexible due to schemata’s reliance on static propositional representations (Johnson-Laird & Byrne, 1991) and it did not account for the negotiation of irregular everyday encounters with the environment (Halford, 1993; Norman, 1988). Mental models use both propositional representations *and* schema to predict outcomes (Kyllonen & Shute, 1989) and in doing so, assist the functionality of short-term memory (Henderson & Tallman, 2006). Solving complex problems can be limited by working memory because it cannot hold all the components, such as which particular knowledge and which application of skills is necessary to solve the problem (Merrill & Gilbert, 2008).

Halford (1993) argued that mental models reflect the structure of phenomenon in the environment whether it is a situation, task, concept or a problem with which an individual is faced. He hypothesised that if we can correctly, or incorrectly, understand the phenomena then we generate a respective correct, or incorrect, mental model. In other words, individuals can store mental models, that is, representations of phenomena which they correctly or incorrectly comprehend but for which they see some value in retaining. Norman (1983) also highlighted this inaccurate and incorrect nature of mental models thereby suggesting an explanation for and individual’s retention of inaccurate information.

Senge (1992) suggested that mental models had a multifarious nature and explained that we “cannot carry all the complex details of our world in our mind” (p. 36). He argued that “. . . we do not have mental models . . . we are our mental models” as “they are inextricably woven into our personal life history and sense of who we are” (p. 37). The essence of mental model theory and its interest to teachers is its capacity to explain how pupils interact with the world. Gentner and Stevens (1983) and van der Veer and Peurta-Melguizo (2002) described this interaction by linking mapping with a mental model’s function as a performance control mechanism. This mechanism enables us to predict, interpret, and communicate. Craik (1943), the grandfather of mental model theory, described them as “representations in the mind of real or imaginary situations” (p. 12) and used the theory to explain how individuals explain, understand and solve anticipated events.

In summary, mental models are cognitive structures that are based on new understandings, prior knowledge, existing ideas and past experiences that we use to interpret and explain events in our world (Moseley, Desjean-Perrotta & Utley, 2010). Williamson (1999) proposed that mental models are malleable and require some accommodation by the user or learner and that this may not always be easy to do, particularly if they are anchored by deeply held beliefs (Norman; 1983). Social and cultural relationships (Vosniado, 2002) that anchor a mental model may be very strong due to their being based on experiences, personal perceptions, and superstitions that may attach to certain emotions and/or experiences. Therefore the educational, social, and cultural relationships that exist to create mental models can, subsequently, make the mental model difficult to manipulate and alter if it is inaccurate. However, human experience can also serve to make learning richer and, therefore, remembered.

2. Methodology to discern mental model functions

The study that was undertaken to investigate mental model functions was an empirical qualitative study, based in an Australian Primary school commencing in February 2005 and ending in October 2006. The methodology was centred within information processing theory and linked with the introspection mediating process tracing paradigm. This approach presented a significant conceptual framework (Kail & Bisanz, 1992; Lohman, 2000) to provide the model to “look inside the minds of learners to explore what happens when learning occurs” (McInerney & McInerney, 2006, p. 96) and when students are carrying out tasks that involve problem solving (Henderson & Tallman, 2006). This focus was essential because a determination of the in-action mental models used by students when they were solving problems would determine the functions of mental models that guide the process.

The context for the study was robotics, which is an optional component of the Queensland Technology Syllabus (QSA, 2003). It provides a rich, multi-disciplinary environment in which to engage middle years students in designing, building, programming, and activating robots to complete set tasks. This study illuminated the dynamic nature of mental models through a longitudinal approach that incorporated a variety of investigative instruments. The study involved a binary focus both on the journey markers where data was collected through Likert Scale questionnaires, semi-structured interviews, stimulated recall interviews, teach back episodes, journals and focus group interviews, and on the intriguing glimpses of the human experiences afforded along the way.

The research examined how one teacher and her students’ mental models can inform teaching, learning, and authentic assessment practices. There were twenty-four Year Six student participants and one teacher in the study. Four students were anonymously chosen to participate in the more in-depth aspects of the study including stimulated recall sessions and semi-structured interviews. All interview data were analysed using pattern coding (Miles & Huberman, 1994) in order to reduce data to workable units to enable both the determination of the mental models being studied and cross-participant analysis of common mental models. So while mental models are internal structures (Johnson-Laird, 1983; Norman, 1983) they can be exteriorised (Barker, van Schaik, Hudson, Meng Tan, 1998) when triggered by interaction with a domain system (Carroll & Olson, 1988; Norman, 1983) such as robotics. The resulting interactions, within the domain and with other participants, are physical (Jonassen, 1995) and those performances can be observed.

3. How the functions of mental models can assist problem-solving

Individuals construct idiosyncratic models (Norman, 1983) that may not be correct or useful to solve problems yet are retained because of their perception that they are functional. The uniqueness of a retained mental model retained arises from the way in which it reflects that individual's interactions with the environment (Halford, 1993). Mental models also contain reflections of problems, events, and stories that may be imaginary (Byrne, 1992). Such fanciful ruminations arise from our constant interaction with the world and reflect our individualistic ability to develop the relationships and dialogue necessary to guide understanding. The functions of mental models that enable problem environments to be explored have been established through longitudinal study (Edwards-Leis, 2010) and include how mental models help us:

- explain;
- predict;
- control action and thought;
- diagnose;
- communicate; and,
- remember.

The *explanatory* function enables understanding and selection of strategies because mental models "facilitate cognitive and physical interactions with the environment, with others, and with artefacts" (Henderson & Tallman, 2006, p. 25). Simply put, in order to understand their world by comprehending what causes, influence, controls or prevents phenomena, humans construct models of it (Johnson-Laird, 1983). But, not everything contained in a mental model is complete or accurate because, as Norman (1983) suggested, an individual's mental models are shaped by personal attributes such as their background experiences, expertise in different domains and, often, their unscientific or superstitious beliefs. Also, we forget thing, or store them poorly in long-term memory, and mental models that are not used regularly become stagnant (Norman, 1983), often needing re-evaluation and modification if they are to remain useful and functional as a means of explaining phenomena.

The *predictive* function enables problem solving in novel situations. This act is not always a straightforward, logical or tidy process due to mental models containing mental images, analogies, assertions, propositions, relations, abstractions, superstitious and beliefs (Norman, 1983), as well as the associated conceptual, declarative, and procedural knowledge (Johnson-Laird, 1983; Newton, 1996; Redish, 1994) for that situation. Mental models enable an individual to predict how a system will work or a problem will be solved (Johnson-Laird, 1983; Norman, 1983) and this function serves to differentiate mental models from other cognitive structures that do not account for novel situations that individuals encounter. If a mental model is accurate and complete then its predictive power should be greater and individuals can evaluate the plausibility of possible solutions. The search for solutions to classroom challenges usually requires pupils to concurrently run and link various mental models (Norman; 1983; Payne, 1991) as they predict possible outcomes.

The *control* function provides a platform from which to make decisions (Edwards-Leis, 2010) and control behaviour (Henderson & Tallman, 2006; Newton, 1996) because individuals consider options when faced with choice. Mental models are "what people really have in their heads and what guides their use of things" (Norman, 1983, p. 12). Individuals can be conscious of running mental models although they can also be run unconsciously or automatically (Henderson & Tallman, 2006). If a teacher is introducing a new idea that students are struggling to understand, they can retrieve and run mental models containing ideas, concepts, and/or strategies from past lessons that were successful. The teacher's retrieval of successful experiences (Henderson & Tallman, 2006) indicates that mental models can be controlled to adapt the environmental phenomena and subsequently enable successful mapping of the new knowledge to existing mental models.

The running of mental models enables even poor performances to be controlled because opposed to other cognitive structures such as schemata and scripts mental models have the capacity to deal with novel situations. The classroom experiences, documented by Henderson and Tallman's (2006) research, were found to be either "liberating or stultifying" (p. 25) for the teacher and pupil. The difference is due to control: either the individual controls their mental modelling by retrieving and/or adapting them when they are diagnosed to be ineffectual to facilitate an effective solution or the individual is controlled by an unadaptable mental model and cannot make progress to a solution.

The *diagnostic* function of mental models enables students to develop metacognitive awareness. The term "perturbation" (Ritchie, Tobin and Hook, 1997) was used to explain the contradictions felt by learners when new knowledge was needed to link with prior knowledge to create a remodified mental model. The customised mental model would incorporate the new experiences and concepts in order to overcome the perturbed state. Some guidance may be necessary for the learner to move through perturbation into a state of equilibrium (Piaget, 1970) and this need for guidance reflects Vygotsky's (1978) Zone of Proximal Development where it is important to take students "a little beyond" (p. 8) what they know or feel comfortable doing alone. The diagnostic function of mental models for pupils, therefore, relies on an understanding, or metacognitive awareness, that they may be working with a mental model that does not allow them to assimilate new concepts (Royer, Cisero & Carlo, 1993) without this guided assistance.

The *communication* function enables others to see and understand the externalisation of an individual's mental models. Mental models facilitate the communication processes of writing, reading, talking, and listening while thinking through problem-solving situations (Barker, van Schaik & Hudson, 1998). When students share or communicate their mental models to others in class it involves oral discourse (Craik, 1943) that requires discussion where the social negotiation of a transitory mental model that can jointly be held by the participants occurs. This sharing often necessitates a "collaborative critiquing of one's own and others' mental models" (Henderson & Tallman, 2006, p. 47). Mental models are communicated through a language and other individual and cultural nuances such as facial expression, body posture, and vocal shades which all need to be 'translated' so that communication is successful. Written discourse can be complex as well and involves some form of writing where text or symbolic script is used to express what is known (Barker, van Schaik & Hudson, 1998).

Mental models have a *memory function*. They are transient and permanent because of their existence in both working memory and long-term memory (Gentner & Stevens, 1983; Henderson & Tallman, 2006). However, it would seem that multiple mental models or parts of mental models could be run simultaneously (Norman, 1983; Payne, 1991). How an individual links the related parts of the mental models that are run depends on the network of related understandings (Henderson & Tallman, 2006) that they instantiate when the mental model is created and stored. Subsequently, how well an individual accesses or retrieves the required mental model, or part thereof, will depend on the efficacy of the storage process and the relevance of relationships perceived. Mental modelling can be influenced by many factors, including a student's meta-ability and their ability to effectively use their working memory (Newton, 1996; Power & Wykes, 1996).

4. The Mental Model Mode: a diagram of functionality

While mental models are internal representations they are externalised through some action. When pupils undertake problem solving in primary classrooms they are required to perform certain behaviours necessary to create or find a solution. While the learning areas, within which the students are operating, might differ the mental modelling required to complete the task should show similarities. The diagram (Figure 1) is the Mental Model Mode (MMM) that has been designed to explain the mental modelling that individuals undertake when they are addressing problem solving situations.

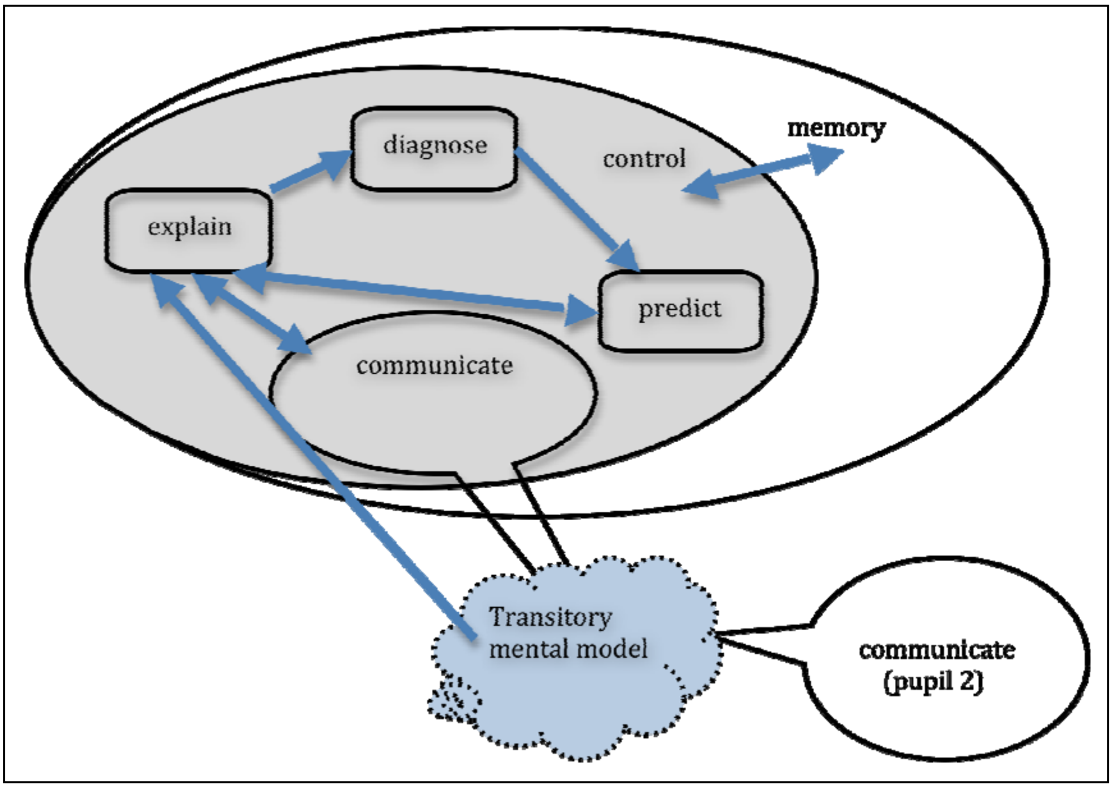

Figure 1. Mental Model Mode: diagram of functionality (Edwards-Leis, 2012)

The diagram accounts for the functions that mental models serve when an individual encounters a problem situation. The following discussion uses the domains of Design and Technology and Mathematics to illustrate the functions of mental modelling. It aims to establish the validity of the MMM to support teachers who are providing design or mathematical challenges for pupils in the primary.

One of the distinctions between problem solving in Design and Technology and Mathematics is the perception of complexity within the problem to be solved and the creativity afforded the pupil in seeking a solution. Design and Technology problems can be contextualised in most 'everyday' situations and while complex considerations need to be made the solutions available can be quite creative and unique. The solutions can be *new*. In mathematics, problems are most commonly used to introduce new mathematical knowledge (Jacobse & Harskamp, 2009) in order to contextualise the information and processes so that pupils can see how mathematics can be applied in 'everyday' situations. The solutions usually require some strategic processes, such as constructing a table to organise data or the comparison of features, and are most commonly *true*. This *new* versus *true* binary may not be mutually exclusive but offers and explanation for the delineation of the types of problems addressed in each of the learning areas.

Mental modelling using the MMM in Mathematics can involve a variety of processes to get to the same solution. Students encountering a problem to solve, such as how many pencil holders will be required for their Year Three classroom given *x* number of children, *y* number of tables, and *z* number of pencils, will need to retrieve the declarative knowledge about numerical values and operations from long-term memory necessary to explain what processes the problem involves. They will then diagnose their ability to solve the problem. This metacognitive process is essential because Johnson-Laird (2006) suggested that in most cases the inability to solve a problem is due to a lack of the knowledge required to do so. Once the pupil has established that they do have the necessary knowledge they make predictions or test solutions. If working with another pupil, they will share their transitory mental model predictions through oral, and perhaps written, communication (Figure 1). The pupil will decide whether, or not, to alter their chosen solution and adopt the transitory mental model or retain, and subsequently store, their own. They will need to be able to explain their solution and how it meets the criteria established in the problem and if it does – it is most likely *true.*

Design and Technology offers pupils opportunities to create novel solutions to everyday problems. Casakin (2011) discussed the access and retrieval process that students undertake when they design. This process, not dissimilar to that used by pupils to solve problems in Mathematics, engages the pupil in retrieving the conceptual, declarative and procedural knowledge required to transfer to a novel problem. The retrieval process depends on how a pupil explains the problem in light of their idiosyncratic ways of interacting with the world. If pupils, in the Year Three classroom above who established how many pencil holders were required, were subsequently given a brief to design and make them, then it is possible that a variety of ideals, values and intentions (Lawson, 2004) would inform the subsequent solutions. A teacher, who had exposed the students to a rich variety of materials, joining methods, and ethical design considerations, would anticipate disparate designs. The MMM (Figure 1) helps explain the processes that students undertake when designing where a constant cycle of explaining, diagnosing and predicting would occur as the pupil applied the design process to meet the requirement of the brief.

The MMM offers teachers a structure that explains the thinking processes that their pupils will use when meeting learning challenges. If pupils are encountering difficulties in negotiating a problem, then some part of the MMM may not operating effectively to advance learning. Newell and Simon (1972) explored the concept of problem space, which defined all possible sequences of the mental operations that pupils needed to address when solving a problem. An implication of this concept is that teachers need to consider this space and enact their own mental modelling, transacting the space to ensure that the all knowledge required for pupils to solve the problem is available.

Johnson-Laird (2006) suggests that “imagination helps us to reason and reasoning helps us to imagine” (p.351) and this has significance for teachers who are designing the challenges that will engage pupils in primary school classrooms. First, teachers should be creating the learning environments that expose pupils to rich problem states that enable them to mental model. Mental modelling, in Design and Technology or Mathematics should enable pupils to build upon the repertoire of skills, memories, strategies, and knowledge required to address novel problems. Problem states, regardless of learning areas, need to provoke robust mental modelling that engage both the *reasoning* that supports explaining, diagnosing and predicting functions necessary to problem solve and the *imagining* that promotes our idiosyncratic interactions with the world that create the relationships necessary to store mental models in our long term memory.

Providing significant opportunities to flex problem-solving strategies seems to be a key to success in learning to meet challenges. In addition to have the opportunity to problem solve, Joacobse and Harskamp (2009) recommend that pupils also be given some initiative for the approaches they will use thereby encouraging cognitive flexibility and adaptability. Mental model theory, through the MMM, enables the teacher to monitor the effectiveness of cognitive processes used by pupils when they are given such initiative. It can also help to explain why pupils repeat the same errors. Johnson-Laird (2006) reported that the most plausible explanation for a pupil’s preference for an erroneous predicted solution lies in her inability to consider all alternative solutions and these processes may continue unless the pupil is helped to relinquish them. The Mental Model Mode provides a way to explain constructive and inventive thinking in classrooms and enables a clearer understanding of what really happens when we meet challenges.

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