A Preliminary Model of Problem Categorisation to Explore the Cognitive Abilities Required for Problem Solving in Engineering Education

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The provision of engineering education as a means of enabling students to develop contemporary transversal competencies such as problem solving, critical thinking, adaptive reasoning and communication, places a responsibility on curriculum designers to reposition these aptitudes within the hierarchy of desired skills. Problem solving is a fundamental attribute of each engineering discipline and plays a pivotal role in the work of an engineer. Problem solving is highlighted as a higher-order cognitive task that engages actions and thoughts, which prompts this investigation of it through a cognitive lens. With consideration of the range of abilities contributing to an individual's general cognitive ability, the likely cognitive abilities necessary for successful problem solving are explored and positioned within the context of engineering education and the broader engineering profession. The problems faced by engineers differ through a variety of means. Problems can vary from well- to ill-defined, and through the requirement of reflective or active means to solve them. It is proposed that the cognitive abilities necessary to problem solve vary depending on these factors. A model is presented which aims to support the identification of the cognitive abilities necessary for problem solving in consideration of the nature of and approach taken to solving a problem. Through consideration of these elements, the model aims to support engineering education and industrial training programs in addressing the skills gaps that have emerged through the advancements of technology and society.

Key Words: Engineering Education, Problem Solving, Cognitive Abilities.

1. INTRODUCTION

Problem solving is highlighted as a higher-order cognitive task (Hambrick & Oswald, 2005), however, there are a number of additional elements that may impact on an individual's problem solving performance. These influences include behaviours (Warden & Mackinnon, 2009), information processing (Cronin & Weingart, 2007), and personality (Hargadon & Bechky, 2006), which are also notable factors to be considered when exploring an individual's cognitive ability (Lubinski, 2004) and capacity to acquire skills (Kanfer & Ackerman, 1989). Considering problem solving as a solely cognitive task would be an oversight of these varying factors that contribute to an individual's performance. However, this is often necessary in individual studies to advance the pertinent remit of knowledge. Accordingly, though there are many elements that are important for problem solving. One of which, the cognitive abilities required for problem solving, is the focus of this paper.

In exploring problem solving, it is important to consider the cognitive processes that lead to the development of a solution, more specifically, the cognitive abilities that an individual requires to solve a problem. General cognitive ability (*g*), refers to the differences in individual capacity to learn or process information (Kanfer & Ackerman, 1989). Individuals with high levels of *g* can represent more information in working memory than those with lower levels of *g*, resulting in individuals with higher levels being able to learn from their experiences at an advanced pace (LePine, Colquitt & Erez, 2000). There are a wide range of broad and narrow abilities, which are discussed in more detail later in this paper, that contribute to general cognitive ability (Schneider & McGrew, 2012). Therefore, numerous cognitive abilities are required to solve a complex problem such as those that exist in engineering, and it is important to identify these to facilitate respective pedagogical advances.

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While exploring the cognitive abilities used in the development of a solution to a problem, the means through which information is presented and investigated must be considered. The approach taken to reach a solution to a problem will vary depending on the problem domain, type, processes needed to solve it, and the means through which a solution is conveyed (Jonassen, 1997). With such demands being placed on working memory in this situation cognitive load must also be considered. Cognitive load describes the amount of mental effort used during a task (Sweller, 1988). This occurs in the working memory due to its limitations (Kirschner, Sweller & Clark, 2016). As an individual has working memory limitations and does not have an infinite storage capacity, mental effort or strain is experienced (Paas, Renkl & Sweller, 2003).

Through experiencing excessive cognitive load, cognitive processing abilities may be impacted, therefore, hindering an individual's performance and the development of problem solutions (Pass, Renkl & Sweller, 2004; Sweller, 1988). In order for individual's to succeed in society and in their desired profession, such as engineering, it is important that the cognitive load experienced throughout their education is managed appropriately in order to support the acquisition of necessary abilities and skills (Schmidt et al., 2007; Sweller, 1988), such as the cognitive abilities necessary for problem solving.

Problem solving plays a pivotal role in many engineering education frameworks as a result of its position in engineering (Hanney, Savin-Baden, 2013; Hmelo-Silver, 2004; Kirschner, Paas & Kirschner, 2009). As the desired attributes and skills of engineers are constantly evolving (Hissey, 2000; SEFI, 2016), it is difficult for educational frameworks and industrial training (continuing professional development [CPD]), to keep pace with the development of the exact skills required for certain tasks. The evolving nature of engineering skills and the likelihood of these skills to become obsolete is a major issue in engineering (LePine, Colquitt & Erez, 2000). Through the development of transversal skills such as problem solving and adaptability, education and industrial training programmes may develop a capacity to address and manage this issue (SEFI, 2016). Through analysis of the cognitive abilities required for problem solving, it is intended that the model presented in this paper may be used as a means of addressing this skills gap and support education and industrial training in keeping pace with the rapid advancements of technology and innovation and the skills deficiencies exposed through this advancement.

2. LITERATURE REVIEW

2.1. Problem solving in engineering education

Problem solving has previously been outlined as one of the most important cognitive tasks in everyday and professional situations (Jonassen, 2000), particularly the engineering profession. Developing solutions to ill- and well-defined problems is a fundamental aspect of engineering (Jonassen, Strobel & Beng Lee, 2006) and a task that most engineers carry out daily, possibly multiple times daily. When problem solving, engineers are addressing a change that needs to be made, how the change may best be achieved, and the resources available to them (Koen, 2003). In consideration of this, it is clear that the problems faced between engineering disciplines may vary significantly. For instance, the changes that chemical engineers must address differ to those of a mechanical engineer (Koen, 2003), suggesting variances in the abilities they rely on to solve a problem. While the abilities to solve the problem may vary between engineering disciplines, problem solving is clearly a fundamental skill for engineers of all disciplines (Jonassen, Strobel & Beng Lee, 2006; Koen, 2003), emphasising the need to develop the proficient problem solving skills of engineering graduates.

Though differences have been highlighted between the educational frameworks implemented in engineering education, such as CDIO and PBL (Edström & Kolmos, 2012), one aspect that remains central to each of these frameworks is students' engagement in problem solving tasks (Crawley et al, 2011; Hanney & Savin-Baden, 2013; Savin-Baden, 2014) to support the development of problem solving abilities. There are many indicators of an effective problem solver such as the capacity to transfer reasoning from one problem to the next, and the ability to define the problem (Hmelo-Silver, 2004). In order for problem solving to be deemed effective, an individual must draw on different assumptions and skills depending on the type of problem they are solving (Schraw, Dunkle & Bendixen, 1995). As the context of problem solving in engineering and engineering education is so variable, *g* may play a significant role in the development of solutions to engineering problems (Faber & Benson, 2017).

Contemporary engineering education frameworks provide experiences for students to engage in a range of tasks to support the development of abilities necessary to reason solutions and solve problems (Crawley et al, 2011; Hanney & Savin-Baden, 2013). At the early stages of engineering education students may experience more difficulty when problem solving as they have not acquired the necessary schema to solve the problem (Jonassen, 1997; Stieff, 2007; Sweller, 1988), regardless of engineering discipline. For instance, if a solution requires a deep technical engineering knowledge, a student may experience significant difficulty as they have not yet acquired the necessary knowledge to solve it, which remains true regardless of the discipline of engineering. This emphasises the importance of scaffolding students in developing the underlying abilities and schema for successful problem solving in engineering education.

Through the literature, cognitive structures have been presented and discussed as possible predictors of problem solving ability (Jonassen, 1997; Sweller, 1988). When taking a holistic view to the development of problem solving ability in engineering education, an exploration of an individual's cognitive abilities is necessary as problem solving is a higher-order cognitive task (Hambrick & Oswald, 2005). Before problem solving can be effectively examined in this way, an analysis of cognitive abilities must take place to support an understanding of the relationship between these elements.

2.2. Cognitive abilities

As earlier outlined, *g* is the difference in individual's capacity to learn (Kanfer & Ackerman, 1989). General cognitive ability is represented as *g* through the work of Spearman (1904), and continues to be recognised through contemporary research (Conway, Kane & Engle, 2003; Deary et al, 2007). There are a number of studies which explore general cognitive abilities such as Cattell and Horn (1967) who developed the concepts of fluid and crystallised intelligence, while Carroll (1993) investigated the principia of human cognitive abilities. The most contemporary and comprehensive model of cognitive abilities brings together these two theories to present the Cattell-Horn-Carroll (CHC) model (Schneider & McGrew, 2012). Throughout the literature, it is often empirically presented that cognitive abilities are hierarchically organised, with *g* positioned at the top of this hierarchy (Lubinski, 2004). The CHC model proposes that this hierarchy could be presented through a three stratum model; stratum III - *g*, stratum II - broad abilities, and stratum I - narrow abilities, as illustrated in Figure 1, with each contributing to the structure of the next. Narrow abilities are a number of fine elements that contribute to the make-up of a broad ability. For example, quantitative knowledge (Gq) consists of mathematical knowledge (KM) and mathematical achievement (A3), while short-term memory (Gsm) consists of memory span (MS) and working memory capacity (MW) (Schneider & McGrew, 2012).

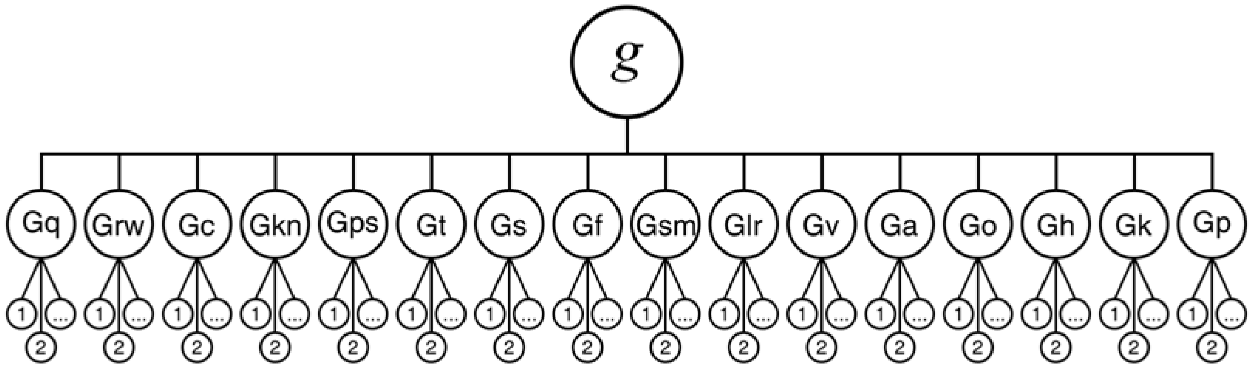

Figure 1. The Cattell-Horn-Carroll (CHC) model of intelligence (Schneider & McGrew, 2012).

Cognitive abilities are further categorised through acquired knowledge, cognitive speed, domain-free general capacities, and sensory- and motor-linked abilities (Schneider & McGrew, 2012). Stratum II, broad abilities, is the focus of this paper as through identifying the broad cognitive abilities engaged when problem solving, the narrow cognitive abilities are, simultaneously identified. Table 1, below, outlines the broad cognitive abilities presented through the CHC model (McGrew, 2009; Schneider & McGrew, 2012).

Table 1 Broad Cognitive Abilities as presented through CHC model.

Broad cognitive abilities	
Fluid reasoning (Gf)	Auditory processing (Ga)
Short-term memory (Gsm)	Psychomotor speed (Gps)
Long-term storage and retrieval (Glr)	Domain-specific knowledge (Gkn)
Processing speed (Gs)	Quantitative knowledge (Gq)
Reaction and decision speed (Gt)	Olfactory abilities (Go)
Comprehension knowledge (Gc)	Tactile abilities (Gh)
Reading and writing (Grw)	Kinesthetic abilities (Gk)
Visual processing (Gv)	Psychomotor abilities (Gp)

The necessity of each of these abilities to complete a task are dependent on the task requirements. For example, should an individual intend to solve a novel problem, fluid reasoning (Gf) may be more beneficial to utilise (as it is not dependent on any past knowledge and describes the ability to reason in noel situations), in comparison to domain-specific knowledge (Gkn) (as it is specified knowledge) as this knowledge may be unrelated to the problem itself. Likewise, if cognitive abilities are viewed in terms of their necessity for a particular profession, a chef would use their sense of smell (Go) and touch (Gh) frequently, whereas comparatively an engineer may rely more on their fluid intelligence (Gf) and domain-specific knowledge (Gkn). Therefore, the hierarchy of cognitive abilities for problem solving could vary significantly between professions and between disciplines, and within each of these professions e.g. between mechanical and software engineering and within disciplines (due to the variability of task contexts). Consequently, it becomes apparent that specific educational training is required to place a greater emphasis on certain cognitive abilities depending on the predominant skills of the profession in question.

Through analysis of these abilities (Carroll, 1993; Lubinski, 2004; McGrew, 2009; Schneider & McGrew, 2012), it can be seen that cognitive ability is a complex phenomenon. In addition to identifying important cognitive abilities which should be considered within education from the perspective of cognitive development, the relationship of these abilities to learning must also be considered. Depending on an individual's capacity relative to cognitive abilities, cognitive load may be experienced which may affect their capacity to learn (Sweller, 1988). In considering the complexity of cognitive abilities and information processing in the context of education, educationalists must reflect on cognitive load. This creates the need for teachers to acknowledge a balancing act. When the goal is learning (i.e. to invoke a change in students long-term memory through the acquisition of knowledge), cognitive load needs to be managed. The experience of cognitive load may be dependant in part on the level of capacity a student has in relative cognitive abilities. An intuitive response to this is that if cognitive abilities can be developed, there is an increased capacity for students to learn. However, the experience and effect of high levels of cognitive load may present the same impediment on the development of cognitive abilities. As such, in order to support student learning as much as possible from a cognitive perspective, the relationship between cognitive load and cognitive abilities needs to be explored. Such exploration can only be considered within the relativist context of education, and therefore there is a need to clearly frame the discipline which in this case is engineering or engineering education relative to the nature of learning tasks. The following is a preliminary attempt to create a framework that is useful for this purpose.

3. MODEL OF PROBLEM CATEGORISATION FOR ENGINEERING PROBLEM SOLVING

When learning in engineering is considered, one often thinks of the technical knowledge associated with the profession. However, the technical knowledge required for one field of engineering will be significantly different to that of another. For example, the technical knowledge required for mechanical engineering will differ greatly to the knowledge required for software engineering. While different knowledge bases are necessary, problem solving is a fundamental element common to all engineering fields, however, the types of problems they have to solve are significantly different. Jonassen (1997) outlined that problems are traditionally defined by the problem domain, type, processes needed to solve them, and the solution. Therefore, it is clear that the cognitive abilities necessary to solve different types of problems would consequently vary. This is an element that must be carefully considered in a model of the cognitive abilities required for engineering problem solving.

Each of the broad cognitive abilities outlined through the CHC model (Schneider & McGrew, 2012) are likely to be necessary for engineering problem solving. While one may debate the use of some of these abilities in engineering, such as olfactory abilities, they may be necessary depending on the context of the task or problem. For example, if a material is machined at an inappropriate speed, it may produce an odour which may alert the machine operator to an issue and allow for the problem to be rectified. While each of these cognitive abilities may be required in engineering problem solving at some point, it is not necessary for each of them to be used for every task, and they will likely be important to varying degrees within specific tasks.

The cognitive abilities necessary to solve a problem will largely depend on two factors: whether the problem is well- or ill-defined, or if it requires a reflective or active means of determining a solution (Jonassen, 2000, 1997; Simon, 1973). This is similar to the model of learning presented by Conole, et al (2004), whereby learning may vary through: experience to information, non-reflective to reflective, and individual to social. While learning experiences are presented as differing in these ways, the model presented in Figure 2 proposes the means through which problems vary in engineering in terms of structure. Considering the variances in problem structure presented through the model, we may begin to position the cognitive abilities necessary for problem solving. Through this model, problems can transition between each of the continuums depending on the context of the problem and the means necessary to solve it. Problems may be viewed in terms of:

- Abstract reflective problem solving
- Abstract active problem solving
- Concrete active problem solving
- Concrete reflective problem solving

Should problems be considered as existing in one of the four quadrants outlined above, the cognitive abilities necessary to solve them may be evaluated. Furthermore, if problem solving is viewed as a dynamic and evolutionary process, problems may begin as an abstract reflective problem and possibly fluctuate between any of the remaining three quadrants. For example, if an abstract problem is to be brought from conception into reality, it may begin as an abstract reflective problem and transition to a concrete active problem. Throughout solution development, the problem solver may transition between reflective to active on multiple occasions as they reason about the problem. Similarly, as they progress, some variables may transition to well-defined while others remain ill-defined. It is imperative that we acknowledge the dynamic nature through which problem solving occurs as it ultimately impacts the cognitive abilities necessary to solve the problem.

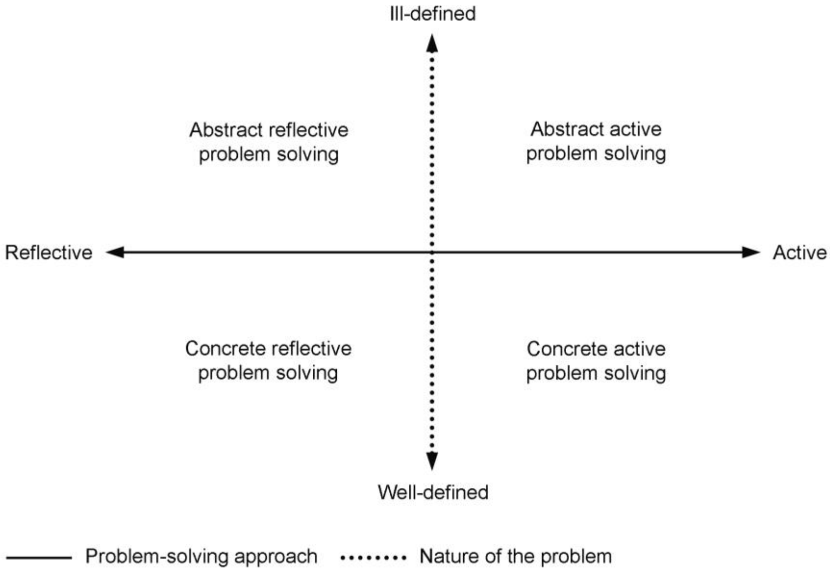

Figure 2. Proposed model for problem categorisation in engineering education.

Consider if an engineer was provided with an ill-defined problem brief and must develop and create a solution. The initial cognitive abilities to conceive a solution (abstract reflective problem), such as fluid reasoning (Gf) and comprehension knowledge (Gc), would vary significantly to those needed to bring the solution into reality (concrete active problem), such as kinaesthetic abilities (Gk) and psychomotor abilities (Gp).

Through viewing engineering problem solving in this way, we must also acknowledge that if an individual is presented with an ill-defined or open-ended problem, depending on their epistemic motivation, they may seize or freeze on a solution or approach (Kruglanski and Webster, 1996). Through doing this, the individual may turn the intended ill-defined problem to well-defined which may ultimately hinder the problem solving experience and cause variations in the perceived cognitive abilities necessary to solve the problem.

4. DISCUSSION

The significance of problem solving in engineering must be recognised and supported through engineering education due to its distinctive role in the engineering profession (Jonassen, Strobel & Beng Lee, 2006). The problems faced by engineers of all disciplines vary greatly from well- to ill-defined problems and reflective to active means of reaching a solution (Jonassen, 2000, 1997; Simon, 1973). The dynamic nature of problem solving and the unique relationship between problem solving and cognitive functions (Anderson, 1980; Hambrick & Oswald, 2005) emphasises the need for curricular designers, educators and researchers to ensure that the relationship between cognitive functions and problem solving is thoroughly examined.

The model (Figure 2) presented in this paper proposes that engineering problem solving occurs between two continuums: well-defined to ill-defined, and reflective to active. This is not to say that a problem will remain in the realm that it initially begins in, it may move due to the transient nature of engineering problem solving, which would result in the cognitive abilities used to solve the problem transitioning also. This is a factor that we must be cognisant of in engineering teaching and learning approaches.

Perhaps the most important aspect of engineering education is supporting students in developing the capacity to utilise abilities effectively for problem solving. Therefore, it is important that we focus on supporting students in developing the underlying abilities necessary for effective and adaptive engineering problem solving. In doing this, the skills gaps that have emerged due to the advancements of technology and innovation (LePine, Colquitt & Erez, 2000) may be addressed.

The model presented aims to support researchers, educators and curriculum designers in identifying the cognitive abilities necessary to solve problems with consideration of the context that they are presented. It is presented as a theoretical means of classifying the cognitive abilities necessary for problem solving in engineering and encapsulates the dynamic and transient nature of engineering problem solving. It is envisioned that upon analysis and investigation of the model, it may support the development of curricula for engineering education with consideration of the abilities necessary for adaptive problem solvers so that the skills gaps emerging in engineering may be addressed.

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