Investigating Conceptualisation and the Approach Taken to Solving Convergent Problems: Implications for Instructional Task Design

A thesis submitted to the University of Limerick for the degree of

Doctor of Philosophy

by

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Declaration

I declare that this thesis has not already been accepted in substance for any degree and is not being submitted in candidature for any degree.

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Statement

I affirm that the substance of this thesis is entirely the result of my own investigation and that due reference and acknowledgement is made where necessary to the work of other researchers.

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Abstract

The constantly changing nature of contemporary society requires a skilled individual who is adept at solving complex and often ill-defined problems in a flexible manner. STEM education is a subject area that is appropriately placed to cater for the development of these aptitudes. The development of problem solving capacity in this area is generally supported through engagement with well-defined areas first in order to build robust structural knowledge before advancing to activities that are more complex.

Recent literature concerning the development of these problem-solving capabilities has cited potential areas for concern including limitations in solving complex problems (OECD 2014) and linear approaches to the engagement of problem solving. Within the research literature focusing on problem solving there is a dearth in the area of problem conceptualisation. This is a multifaceted area that is posited to have a strong effect on the approach to problem solving adopted and as a result the performance in completing a task. This research aimed to explore the relationship between problem conceptualisation, problem solving approach and ultimately performance.

The study was carried out with year three pre-service teachers in Initial Technology Teacher Education (ITTE) at the University of Limerick. A mixed methods research approach was adopted to capture evidence of the relationship between conception, approach and performance. This approach encompassed behavioural observation techniques such as visual and verbal protocol and performance efficiency measures from the field of cognitive load theory. As conceptualisation is posited to be a tacit process, an objective measure of cognitive activity was required. The cognitive basis of individuals’ conceptualisation strategies was captured using an electroencephalographic (EEG) recording device as participants solved convergent STEM problems.

This method provided a rich source of data relating to students conceptualisation process during the solving of convergent tasks. A significant relationship was found between the cognitive activity during the conceptual framing of a task and the cognitive activity over the entirety of the task. This suggests that the early stages of engaging with convergent STEM tasks determine the overall approach and ultimately the success of the outcome. Significant elements of cognitive rigidity in problem solving were uncovered and qualitative data indicates past school experience is an influential factor. The role of visuospatial cognitive processes during the conception of the tasks facilitated authentic flexible representations of problems, which in many cases lead to increased success.

The study concluded that there is a significant relationship between the conceptualisation of a convergent STEM task and performance. Past experience was found to be an influential factor and the need to cater for this in instructional design is recommended. It is theorised that visuospatial cognitive processes augment the conceptualisation stage of convergent STEM tasks by providing increased access to elements of long-term mental representations. This could aid in explaining the relationship between high levels of spatial ability and advanced attainment in other fields as identified by previous research and supports the general focus on developing these skills.
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1 INTRODUCTION
1.1 Overview

The development of advanced problem solving and critical thinking skills is a core necessity in contemporary educational provision. This is especially true given the rapidly changing nature of modern societies where significantly higher numbers of students are completing second level schooling and enrolling in third level courses. This pattern is expected to continue with third level student numbers projected to increase exponentially in the next decade (DES 2013). Therefore, it is expected that a large body of students will be adept at complex problem solving requiring adaptive and flexible behaviours. This is supported by organisations such as IBEC who are calling for graduates that have advanced problem solving skills and that will be able to make a meaningful contribution to the workforce (IBEC 2010).

However, in contrast to these aims, the recent international assessment on problem solving competence conducted by the "programme for international student assessment" (PISA) suggests that one in five students across "organisation for economic co-operation and development" (OECD) countries are only capable of solving "straightforward" problems (OECD 2014). This is an area for concern in regards to educational provision. Ireland ranks below average, when problem-solving ability is compared to other countries problem-solving ranking in mathematics, reading and science (OECD 2014). This report suggests significant issues in students' ability to problem solve.

This raises a number of key philosophical considerations for contemporary educational provision. In order to align with this current societal context, it is critical that education systems consider the nature of teaching and learning which is occurring in an aim to develop these highly valued problem-solving capacities.

The primary goal of second level education is to develop general competencies that align with the values espoused by organisations such as IBEC (2010). The core underpinning criteria for the development of complex problem solving abilities is a strong base of structural knowledge. Within an educational context, the
development of this structural knowledge is often achieved through carefully devised interventions centring on the use of convergent well-defined activities. One particular subject area where this approach is critically important is within science, technology, engineering and mathematics (STEM) education. An apparent commonality in learning approach within these disciplines is the use of problem solving activities for learning purposes (Williams et al. 2008).

This makes STEM an appropriate focus for this research. Engaging with divergent style problems where multiple solutions are possible is typical of the higher-level skills promoted by STEM. However, in order to facilitate these high-level capacities, students first need to develop a robust body of knowledge through the solving of well-defined convergent problems and tasks. The style of thinking indicative of problem solving within convergent tasks typical of STEM education is of core concern within this research given the issues highlighted by the OECD (2014).

Problem solving is a complex cognitive area and has been one of the major focuses of psychological research (Novick and Bassok 2005). Recent work by Kirsh (2009) suggests that in the majority of studies on problem solving to date there has been an overemphasis on the processes used to achieve solutions. Specifically, this refers to the application of certain processes and heuristics to achieve an outcome.

Within the pertinent literature, there exists an absence of research relating to the issue of problem conceptualisation. This is the first stage in problem solving that an individual will encounter when faced with a problem or task. Aligning with views on situated learning, this area holds the potential to inform the manner in which students engage in problem solving tasks. The use of inappropriate conceptualisation strategies could be compromising the quality of learning as a result of misaligned cognitive activity during engagement with convergent tasks which are typical of STEM education. The next section will present the research questions that were devised to explore this area.
1.2 Research Questions

The following principles guided the development of research questions for this study:

- Given the lack of empirical data surrounding the issue of problem conceptualisation or framing it is necessary to consider a possible relationship to problem solving approaches.
- Recent research in STEM education has suggested a ritualistic, linear approach to teaching problem solving skills. This could have implications for the development of adaptive and flexible behaviours.
- Problem conceptualisation is hypothesised to be a multifaceted process but little empirical evidence exists in this area.

The following are the research questions which guided this study:

1. Is there a relationship between the nature of the problem conceptualisation and the approach adopted by the individual?
2. What elements influence the manner in which individuals conceptualise convergent problems?
3. Is there a relationship between specific processes, the nature of the conceptual frame and ultimately performance?

1.3 Aims and Objectives of the Research

1.3.1 Aim

The overarching aim of this research was to explore the area of problem conceptualisation and the potential relationship this could have with reasoning approaches in convergent problem solving indicative of the styles employed in STEM education. Of particular interest were the cognitive activities utilised during the process and the association with performance.
1.3.2 Objectives

- To explore the relationship between problem conception and subsequent approaches for convergent STEM problems.
- To devise a strategy to capture the cognitive activity exhibited during conceptualisation and over an entire problem-solving episode.
- To investigate the degree of flexibility in students' approaches to solving convergent problems for students who have successfully completed second level in formal education.
- To investigate the nature of cognitive processing during problem conception and explore any patterns in relation to the capacity to solve STEM education tasks.
2 LITERATURE REVIEW
2.1 Introduction

This chapter will present an exploration of the literature, which forms the basis for the research method discussed later. This research study set out to answer a number of questions in relation to students’ approaches to engaging in convergent educational problems or tasks typically used to enhance underpinning structural knowledge. Evidence critiquing didactic styles of teaching and learning which are still being promoted in formal education (Claxton 2008) urges a reconsideration of educational interventions in general. Schank (2011) claims the need to re-examine our curricula in response to the desirable cognitive aptitudes of today is a critical necessity. A number of key authors have written about the philosophical shift needed in our education system (Robinson 2001) to focus on the fostering of aptitudes for the "conceptual age" (Pink 2006). There is an urgent need to reconceptualise our view of knowledge from that of a commodity to a fit for purpose entity. This will require the development of adaptive and flexible cognitive skills among all individuals and is one of the core aims of general education (NCCA 2010).

The use of convergent problem solving activities is a common approach within science, technology, engineering and mathematics (STEM) education (Williams 2011b). STEM education is an umbrella term that is used to describe the disciplines of science, technology, engineering and mathematics. Rather than treating them as four disparate areas, the rationale for housing them under the term 'STEM' is to emphasise the integration of each of the four areas (Pitt 2009). As Williams (2011b) contends, the integration of these disciplines is still a large concern within modern curricular initiatives and a common philosophy for all four elements of STEM may be unattainable. However, one of the primary pedagogical approaches of STEM education is the use of inquiry based approaches which centres on solving a wide variety of problems (Breiner et al. 2012). This makes STEM education a suitable focus for the purpose of this research, which is concerned with the development of the underlying structural knowledge needed for problem solving competency.
2.2 The Nature of Learning in STEM Education

Each of the sub disciplines of STEM education has unique characteristics to offer the learner in terms of cognitive development. For example, the mathematical and scientific disciplines cater very strongly for analytical modes of cognitive processing and developing "scientific method" (Gallistel and Gelman 2005, Murphy and McCormick 1997). Engineering offers further analytical and technical competencies but through a focus on applied problem solving and design (Breiner et al 2012). Technology offers a unique inquiry orientated approach to learning, which incorporates problem solving and learning through design at its core (Kimbell and Stables 2008).

Within STEM education, there are a large variety of reasoning processes, which are utilised in various activities. One of the chief characteristics of the nature of learning within the discipline is the focus on developing knowledge and skills through action (Banks 2009). The ability to model and develop ideas using a variety of knowledge and approaches lies at the core of this process (Baynes 2010). This concept of thinking through enquiry is characteristic of learning within STEM education and allows students to develop higher level educational competencies (Anderson et al. 2001). These types of skills are also concerned with the ability to problem solve in a variety of contexts (Lewis 2009, Mioduser 2009). This research is not directly concerned with the nature of problem solving activity at the higher-level spectrum of learning activities within STEM education. It is instead focused on the initial stages of learning which aim to build the underlying core competencies necessary to engage in such high-level creative activity.

2.2.1 Developing Core Competencies

The development of advanced problem solving skills is one of the overarching themes of STEM education (Williams 2011). In order to develop such skills, which will ultimately allow the individual to transfer knowledge across domains and solve problems, it is critical to firstly focus on the development of core knowledge (Sternberg 2003). As Torrance and Pryor (2001) discuss, learning must encompass
elements of scaffolding which allows the individual to develop effectively within a constructivist paradigm. It would be entirely inappropriate to expect a student, which is new to STEM education to engage with high-level open-ended design problems to begin with. Firstly, their ability to engage critically with problems that are designed to develop their core structural knowledge in the area must be facilitated.

In developing this fundamental knowledge, educators often use convergent style educational tasks which focus on the application of defined knowledge and skills (Torrance and Pryor 2001). Aligning with constructivist views of education, moving from closed to permeable tasks (Kimbell 1994) allows students to develop and then subsequently build on their core knowledge in the area.

One of the core competencies required for the development of complex problem solving skills is “structural knowledge” (Eysenck and Keane 2010). This refers to knowledge within a specific domain of both semantic content and also various strategies and approaches suitable to that context (Novick and Bassok 2005). The building of this structural knowledge would ideally begin with convergent well-defined type tasks and progress towards the more divergent ill-defined type. As discussed by Barak and Zadok (2009) it is unreasonable to expect that students will achieve high levels of competency in solving complex divergent problems before gaining specific experiences in convergent problem solving within pertinent areas. This is where the research will focus. Of concern within this study is the nature of thinking indicative of convergent problem solving activity, which is core to STEM educational practice. This requires an in-depth exploration of the process of problem solving.

2.3 Problem Solving Processes

Duncker (1945) defined problem solving as the phenomenon that occurs when people engage in goal-orientated behaviour. Problem solving involves the transformation from a current state to a goal state and requires the construction of a
problem representation and the generation of a solution strategy (Novick and Bassok 2005). The current state refers to the actual state of the problem before it is solved and the goal state refers to the desired outcome one wishes to reach (Eysenck and Keane 2010). It has been a deeply researched area within psychological domains and it is prudent to discuss some of the core concepts of the area for the purpose of this current research study.

The most common distinction between problem types is that of "well-defined" and "ill-defined" types (Sternberg 2003). A well-defined problem is one where all problem states, such as the initial state and goal state are easily identifiable (Eysenck and Keane 2010). This is the converse for ill-defined problems where the variables are not easily identifiable (Novick and Bassok 2005). Referring to an educational context this distinction is used to characterise convergent from divergent style problems. Convergent problems refer to a situation where one solution is possible and divergent problems refer to a case where many are possible (Torrance and Pryor 2000). Design problems are an example of divergent style tasks.

Another important distinction within the literature is that of "knowledge lean" and "knowledge rich" problems (Eysenck and Keane 2010). Knowledge lean refers to a type of problem where all the knowledge necessary for solving it is contained in the problem statement (Kirsh 2009). An example of these is puzzle style problems, which have been largely used, in classical research on problem solving (Novick and Bassok 2005). The second type, knowledge rich, refers to the requirement of prior knowledge within an area to solve a given problem (Eysenck and Keane 2010). The majority of educational tasks would conform to this description as they are attempting to develop skills in subject areas. Kirsh (2009) argues against the use of the term knowledge lean problems as in reality all problems that an individual encounters are in some way influenced by prior knowledge in different areas. This is an important point for educational problems, as it would align with constructivist views of educational provision (Banks 2009).
Research in the area of problem solving has generally focused on two main strands of investigation. These are either focused on the manner in which an individual represents a problem or the process used in searching for a solution (Novick and Bassok 2005). The achievement of high levels of competency within problem solving is not based on mastery of one of these as the problem solving process is an iterative one which involves elements of both representation and application of various heuristics or strategies (Bogard et al. 2013).

2.3.1 Representation

There are a number of core theories within the body of research on problem solving. The original line of research within the field has its origins in Gestalt psychology which looked at how individuals grouped elements of a problem to form an interpretation (Novick and Bassok 2005, Rock and Palmer 1990). The primary focus of this approach is the manner of problem representations that individuals undertook (Rock and Palmer 1990). Problem representation is one of the key focuses of investigations on problem solving. Problem representation refers to the model of a problem, which summarises its essential nature (Novick and Bassok 2005) and is constructed prior to pursuing a solution (Sternberg 2003). There are numerous forms a representation can take such as verbal or pictorial and they can occur internally and externally (Bogard et al 2013). An example of an internal representation would be a visual mental image whereas the external form of this could be a sketch. The problem solving process often takes place as an interaction between internal and external representations (Kirsh 2009).

Research has shown that the manner in which people represent problems is affected by the problem situation and individuals’ background knowledge (Novick and Bassok 2005). There is also a clear link between the nature of the problem representation and the success of the problem solving approach (Sternberg). Lesgold (1988 cited in Pretz et al. 2003) describes the differences between novice and expert problem solvers in terms of the representations they construct. Specifically, it was found that experts spend the largest amount of time in the problem solving cycle.
constructing their representation whereas novices spend the majority of time executing a process (Ibid).

One of the most prominent areas of research on the value of representation in the problem solving process comes from investigations into insight (Finke et al. 1992). Insight is generally described as the sensation of an "aha" moment following an impasse during problem solving (Novick and Bassok 2005). There has been a wide variety of debates on the issue of insight. Weisberg and Alba (1981) concluded that insight was based on retrieving correct processes from memory and so was no different on a cognitive level to standard problem solving. Metcalfe (1986) provided evidence against this theory, where sudden re-representation of the problem was found to be a key factor in insight problem solving. The involvement of representation has been shown to be a key process in the overcoming of an impasse that leads to insight. A study by Bowden et al. (2005) demonstrated a different neurological activation pattern during insight problem solving which indicates the involvement of representational processes. This is clear evidence showing how the representation of a problem can facilitate a successful approach (Bowden et al. 2005). Focusing specifically on convergent styles of problem solving, the representation after it has been constructed by the solver constitutes the “problem space” (Pretz et al. 2003). Once this space has been defined it can then be engaged with to search for a path to the solution (Eysenck and Keane 2010). This search process is one of the other major strands of research in the area of problem solving.

2.3.2 Problem Solving as Search

Another core line of research within the field looked at the problem solving process as a search through a problem space (Newell and Simon 1972). This involves looking for the optimal steps which could get the solver from the initial problem state to the goal state (Eysenck and Keane 2010). Newell and Simon (1972) attempted to take this line of research further and develop a "General Problem Solving" (GPS) theory. This referred to abstracting the problem solving process into a number of key steps, which could be applied to any problem. This has its
limitations however, in that it partially ignores the situated context in which problem solving takes place (Kirsh 2009). The core facet of Newell and Simon’s (1972) theory was conceiving problem solving as a search through a "problem space". This refers to the mental representation of the problem, which the solver constructs. Whether problem solving is treated with an emphasis on representation or on search there is significant relationship between the theories. Treating problem solving as search leads to the investigation of search strategies and processes which were implemented during solving. These search strategies are known as heuristics and will be presented in the next section (Novick and Bassok 2005).

2.3.2.1 Heuristics

Heuristics are roughly defined as "cognitive rules of thumb" which aid as guides during the process of problem solving (Abel 2003). They are differentiated from algorithmic strategies, which employ "optimal" approaches to problem solving by their emphasis on reliability and efficiency (Abel 2003, Todd and Gigerenzer 2000). This is also where the limitation of heuristics is illustrated, as they do not guarantee the achievement of an accurate solution (Raab and Gigerenzer 2005). Despite this limitation, heuristics are an integral part of the problem solving process and are naturally used in the majority of problem solving approaches and particularly "everyday" problem solving (Ollinger and Goel 2010).

There are an infinite number of heuristics which could be applied to the solving of a problem (Todd and Gigerenzer 2000). Abel (2003) presents a summary of the main types of heuristics as a problem solving process model. This is illustrated in Figure 1.
Representation heuristics refer to the methods of creating the problem representation and these can vary depending on the problem and the context (Abel 2003). Search heuristics refer to the process of exploring the problem space (representation) in order to find a path to a solution (Novick and Bassok 2005). A termination heuristic is used to select the approach, which will most effectively solve the problem, and the implementation heuristic evaluates whether it has succeeded (Abel 2003).

The core principle of heuristics in problem solving is effort-reduction in order to optimise cognitive efficiency. Shah and Oppenheimer (2008) outline five key points through which heuristics achieve this:

1. Examining fewer cues.
2. Reducing the difficulty associated with retrieving and storing cue values.
3. Simplifying and weighting principles for cues.
4. Integrating less information.
5. Examining fewer alternatives

It is important to stress that individuals will not necessarily adopt these strategies on a conscious level and that often it happens without the user being aware of the process (Shah and Oppenheimer 2008). The use of heuristics will vary depending on

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1 A cue refers to a characteristic of an entity which is used to weight it against
the types of problem but will also depend on the environmental context. Often the
dividual will use the artefacts that are available to him or her within the
environment they are engaging with the problem (Kirsh 2009). This leads to
considering the types of action that can occur during the process.

2.3.2.2 Epistemic and Pragmatic Actions

In reality, the nature of problem solving is much more interactive than that presented
by the classical views in the area. Consider simply placing a reminder on your
phone to pick up a prescription on the way home from work. This simple action has
alleviated some of the cognitive constraints (i.e. memory) and made the situation
much simpler. This is what Kirsh (2009) deems an "epistemic" action. The
converse is deemed a "pragmatic" action which is carried out to bring an individual
closer to a physical goal (Clark and Chalmers 1998). An example of this would be
erecting a higher fence to keep your dog from wandering free at home.

In a classic study based on the game of Tetris, Kirsh and Maglio (1994) found that
participants utilised a number of epistemic actions such as rotating configurations
numerous times to see its best fit. Despite these moves being superfluous, there is
obviously some cognitive payoff occurring during the process. Pragmatic actions
have been the focus of areas such as planning, which is viewed as a series of
transformations from initial to goal state (Novick and Bassok 2005). The types of
actions and heuristics an individual will use depend on the type of problem that they
will encounter.

2.3.3 Interplay between representation and approach

Despite the variety of strategies one can adopt in the face of a problem, there is a
complex interconnectedness between the representation and solution processes.
Representing the problem is normally one of the first steps in engaging with it
(Novick and Bassok 2005) and this allows the individual to create the problem space.
This representational process is very important in knowledge rich contexts as the
representation constructed is directly linked to schemas and mental models in long-
term memory (Jonassen 1997). Gick (1986) discussed this process stating that if the representation activates a well-established schema in long-term memory then the solution is more straightforward. Whereas if it does not, then a search for the solution must occur. This is summarised in Figure 2.

Figure 2: Schematic of Problem Solving Process (Gick 1986)

An area where representation has been shown to be strongly related to effective solution generation has been in mathematics (Novick and Bassok 2005). In a research study by (Wertheimer 1959), students were tasked with finding the area of various parallelograms. Students who represented the problem visually as a blend of triangles and rectangles were able to solve a wider variety of configurations. However, students who represented the problems as the standard mathematical formula for finding the area of a parallelogram found difficulty in solving these other geometric figures. This is a classic example where an approach based on a visual representation had a more profound positive effect on the solution generation than an algorithmic or logical approach.

Conversely, representations can also impede the problem solving process and lead to "fixation" (Finke et al. 1992). A classic example of this is the "nine-dot problem"
used by Weisberg and Alba (1981). Here the participant is asked to draw four straight lines, which shall connect all dots without lifting the pen from the paper.

Figure 3: Nine-Dot Problem (Weisberg and Alba 1981)

What is constantly found in using this task is an inappropriate assumption that the lines must remain inside the boundary of the figure (Finke et al. 1992). The representation has caused solvers to infer a constraint, which does not exist, and this is an example where a particular representation can impede the achievement of a solution.

Visual representations clearly have a key role and advantage in some areas of problem solving behaviour and the research into epistemic actions highlights this (Kirsh and Maglio 1994). Finke et al. (1992) discuss the advantages of using visual representations as they allow key features of problems to become easily identifiable which can then lead to the application of suitable approaches and heuristics. As presented earlier, studies have found that expert problem solvers spend the majority of time constructing their representation of the problem before pursuing an approach (Pretz et al. 2003). Another key differentiator between novice and expert problem solvers is the robust nature of experts' domain knowledge, which is contained within mental models and schemas (Finke et al. 1992). Bogard et al. (2013) discuss the link between representation and access to these mental models and schema in memory. It could be a combination of the two areas which leads to the development of problem
solving expertise, and therefore it is necessary to consider the role of knowledge in problem solving.

### 2.3.4 The Role of Knowledge in Problem Solving

It is widely accepted that knowledge, which is learned through various types of interactions with our environment, is ultimately stored in long-term memory (Stillings et al. 1995). The core of research in this area focuses on the nature in which this knowledge is stored. Eysenck and Keane (2010) state that some of the earliest work looking at knowledge in problem solving comes from research on chess players. Here a theory of "chunking" was developed where it was theorised that expert chess players could contain more information in "chunks" within their memory than novices (Eysenck and Keane 2010). This was a very simplistic view of knowledge representation within human memory particularly in relation to problem solving expertise.

Later research proposed the theory that declarative and procedural forms of knowledge were stored as propositional networks within mental schemas (Stillings et al. 1995). These will be discussed in more detail later in the chapter under long-term memory. Sweller et al. (1998) theorised that the development of mental schemas was the key factor in separating novices from experts in problem solving within a particular domain.

Focusing specifically on problem solving knowledge, recent work has posited that the key point of concern in problem solving expertise needs to be on the development of mental models (Bogard et al. 2013). Mental models consist of knowledge that is contextually focused and tied to certain situations (Jonassen and Strobel 2006). The core difference between a mental model and a schema is the multi-modal nature of the model (Bogard et al. 2013). Jonassen and Strobel (2006) state that an individual's mental model contains the following:

- **Structural knowledge** - the knowledge and structure of concepts in a particular knowledge domain.
• **Performance/Procedural knowledge** - knowledge relating to the implementation or use of a mental model within a particular environment.

• **Image of system** - mental images included within the model.

• **Metaphors** - relations to existing knowledge structures utilising associations with other objects or artefacts.

• **Executive knowledge** - knowledge of when to activate or use procedural models.

• **Beliefs** - underlying ontological and epistemological views.

This presents a more authentic view of the role of domain knowledge within the development of problem solving expertise (Bogard et al. 2013). The development of these mental models is one of the core aims within STEM education in order to develop students' competencies in solving complex divergent tasks. Jonassen and Strobel (2006) state that the best way to develop these mental models is to engage learners in the process of constructing and utilising them. This is also echoed by Sweller (2010) who discusses that the best way to develop these models in an adaptive and flexible manner is to engage the learner in problem solving. These mental models reside in the long-term memory system and in the process of solving a problem must be activated within working memory (Banich and Compton 2011). This places memory as one of the central components of the cognitive system in the process of problem solving. This will be explored in the next section.

### 2.4 The Function of Memory

Memory is a critical component of the human cognitive architecture and fundamental to cognitive processing. Memory is defined as a cognitive process which enables past experiences to be recalled (OECD 2007). Within the pertinent literature there exists a general distinction between types of memory system within the human neural architecture. It is generally claimed that educators do not understand enough about the cognitive architecture of memory (OECD 2002). It is
therefore important to explore this area and its function in developing problem solving competencies.

2.4.1 Architecture of Memory

There are multiple types of memory within the human cognitive architecture with the most basic theory being that of the "multi-store model" (Eysenck and Keane 2010). This incorporates the "sensory", "short-term" and "long-term" stores and deals with the processing and encoding of stimulus within our external environment (Sternberg 2003). In dealing with the development of problem solving expertise, it is more prudent to focus on the nature of long-term and working memory as these are more relevant to cognitive processing (Ericsson and Kintsch 1995).

Understanding their structural and functional properties is an important undertaking in order to explore the processes of thinking and reasoning indicative of problem solving in convergent STEM tasks. Effective learning interventions take cognisance of the workings of memory and attempt to build upon and develop existing knowledge structures (Petty 2009).

Long-term memory can be further broken into declarative (explicit) memory and non-declarative (implicit) memory (Squire et al. 1993, Ward 2010). Within declarative (explicit) memory, there exists episodic or semantic memory. These cater for memory of events within one's own life and conceptual based knowledge of the world respectively (Squire 2004). Non-declarative (implicit) memory caters for areas such as procedural memory and the perceptual representation system (Squire 2004). Figure 4 illustrates an overview of memory systems that was presented by Ward (2010).
The core characteristic of implicit memory is its sub-conscious nature. In activating elements of implicit memory, the subject may not even be aware that this is happening (Schacter et al. 1993). While acknowledging that the implicit component of memory is critical in learning, problem solving generally requires explicit processing (Novick and Bassok 2005). During the process of engaging with a problem the solver will need to call upon semantic and episodic memory, particularly within knowledge rich domains, as is the nature of STEM education. It is therefore appropriate to consider in more detail the storage of such memories.

### 2.4.1.1 Long-Term Memory Storage

One of the classical views of cognitive representations focuses on the theory that data is stored propositionally (Kosslyn and Pomerantz 1977). Internal representations can be thought of as a set of propositional truths, which can be true or false such as "Mary likes John" (Stillings et al. 1995). Propositions tend to reflect declarative information and are relational in nature. It is this relational characteristic of propositional representations that support their place in the storing of information within the cognitive architecture (Kosslyn and Pomerantz 1977). Propositions can be activated in long-term memory by input propositional data, which share some form of overlap with previously coded representations (Chi and Ohlsson 2005). Stillings et al. (1995) provide evidence for the existence of a “spreading” activation
routine when utilising propositional representations. Reaction times increase for propositions that are stored farther from each other within the memory system.

Propositional representations taken on their own are not sufficient to explain many of the intricate characteristics of cognitive processing. These propositions must be stored along with some form of conceptual scheme (Stillings et al. 1995). These schemes can be thought of as “nodes” in memory where propositions can be tied to as subcomponents (Stillings et al. 1995). The role of conceptual schemas is theorised to be a key factor in problem solving and the construction of these is one of the primary goals of learning (Sweller et al. 1998).

Conceptual systems are one of the core facets of human memory and represent an "individual's knowledge about the world" (Barsalou 2009). Theories often state that these concepts are stored in semantic networks, which can be activated during cognitive processing (Barsalou 2003). These conceptual schemas can exert a significant influence on the problem solving process, prioritising some problem information over others (Stillings et al. 1995). This could potentially lead to biases and errors if the activated schema were not appropriate to the task.

It is necessary to highlight the representational debate, which is one of the core debates in classical views of the cognitive architecture and specifically long-term memory (Pylyshyn 2003). This debate essentially focuses on whether there is a propensity to store conceptual representations propositionally or in a depictive format. Two of the primary opinions within these debates belong to Pylyshyn and Kosslyn respectively (Reisberg and Heuer 2005). The debate is centred on whether mental representations are depictive or propositional in nature. Pylyshyn argued the existence and importance of visual mental representations but originally claimed that these types of representation were coded and stored entirely propositionally (Pylyshyn 1981). This argument was in contrast to Kosslyn, who advocated the existence of depictive visual mental representations in long-term memory (Kosslyn 1981). After much empirical research, such as mental scanning paradigms and even
neuro-functioning studies, it is generally accepted that there is a strong interaction between the two styles of representation (Reisberg and Heuer 2005).

Focusing specifically on problem solving, conceptual schemas have a key role. The development of schemas for problem solving facilitate increases in expertise level and one of the highest levels an individual can reach is "schema automation" (Sweller et al. 1998). This refers to the ability to bypass working memory for some cognitive processes, which frees up capacity for more complex elements (Sweller et al. 1998). Overemphasis on this automation process can cause deficits in individuals' approach to problem solving and result in rigid behaviour and a balanced development must be considered.

During active processing, for example in engaging with a problem, schemas are activated depending on the problem characteristics (Eysenck and Keane 2010). This active processing is an essential part of the problem solving process and is catered for by working memory.

2.4.1.2 Working memory

Working memory comprises a set of central processes that allows conscious thought to occur (Morrison 2005). The concept of working memory is in essence an extension of the traditional theories of short-term memory (Ward 2010). Working memory has limited capacity with regards the storing of information and this capacity has been shown to be critical to a number of cognitively demanding areas such as reading comprehension, following directions and reasoning (Morrison 2005, Sweller et al. 2010). Working memory can be further divided into distinct components, which process and hold information from different modalities. The most utilised framework within the cognitive literature is that developed by Baddeley and Hitch (1974). This framework was subsequently revised by Baddeley (2000) and is presented in Figure 5.
The phonological loop is concerned with the holding, retrieval from long-term memory and manipulation of information from the verbal modality, whereas the visuospatial sketchpad deals with information from the visual-spatial modality (Baddeley 1996). The episodic buffer functions as a multimodal component of working memory and binds information from different modalities (Morrison 2005). The central executive (Baddeley 2000) is essentially the control mechanism in working memory and is important for tasks such as reasoning and language (Morrison 2005). Baddeley (1996) presents four key functions of the central executive in working memory. It:

1. Holds the capacity to coordinate performance on two different tasks simultaneously.
2. Has the ability to switch retrieval strategies such as those in the process of generating random numbers.
3. Controls the ability to focus attention on one stimulus and inhibit the processing of others.
4. Controls the holding and manipulation of information in long-term memory.
As Logie (2003) discusses, working memory plays a central role in the acquisition of new knowledge and retrieving stored knowledge and representations which is vital to many cognitive skills. This is especially relevant to problem solving as problems can involve representations consisting of multiple information modalities and one of the key factors in problem solving success is the ability to monitor progress (Sternberg 2003). This metacognitive process is governed by the central executive of working memory (Baddeley 1996) and is a central element in problem solving.

The role of visuospatial processes in the representational process of problem solving has been discussed as advantageous in developing robust interpretations of problem situations (Finke et al. 1992). It is prudent to examine the manner in which working memory caters for this style of processing in order to gain a better understanding of its role in the thinking and reasoning activities of convergent problem solving typical of STEM education. Firstly, it is necessary to consider the nature of spatial cognition in general before focusing specifically on its functioning within working memory.

### 2.4.2 Spatial Cognition

Spatial ability is defined by Sorby (1999) as “the innate ability to visualise that a person has before any formal training has occurred”. Hegarty and Waller (2005) define spatial ability as the manner in which people “mentally represent and manipulate spatial information to perform cognitive tasks”. These are just an example of the many varying definitions concerning spatial cognitive ability. Spatial ability is generally considered to comprise of a number of sub-elements. The most common method of determining these elements, in the spatial cognition literature, is through the use of factor analysis (Pittalis and Christou 2010). These elements are commonly deemed spatial factors.

A number of different spatial factors have been identified by various research studies in the past. Lohman (1979) proposed the existence of three different spatial factors, Spatial Visualisation, Spatial Relations and Spatial Orientation. Spatial visualisation
and spatial orientation have traditionally been identified as two of the major elements that comprise general spatial ability (McGee 1979, Pellegrino et al. 1984). Spatial visualisation is defined generally as a mental ability to rotate and manipulate two and three-dimensional visual objects (McGee 1979). Spatial orientation is generally thought to be an ability to imagine the visual appearance of objects from different perspectives or orientations (Hegarty and Waller 2005, Ekstrom et al. 1976). These two factors have been shown to be very highly correlated and difficult to separate in previous measurement studies (Hegarty and Waller 2004). The spatial relations factor originally explored by Lohman (1979) is described by tests of speeded performance in mentally rotating two-dimensional visual stimuli.

Gaughran (1990) developed a spatial factors framework, which included five separate sub factors of spatial ability, which he categorised as “sub-space” factors. These sub-factors are categorised according to degree of difficulty and are as follows:

1. (SF-1) Image Holding and comparing which involves the decomposition and observing of topographical spatial relations.
2. (SF-2) Planar Rotation of two or three-dimensional objects
3. (SF-3) Spatial Orientation which involves the observer moving to occupy different imaginary viewing positions
4. (SF-4) Kinetic Imagery which involves the imagining of an object changing position in space while moving in any axis
5. (SF-5) Dynamic Imagery which involves the ability to manipulate components/elements of an object

In Gaughran’s (1990) framework, SF-1 is a prerequisite to all the other categories and there is a significant relationship between the five sub-space factors (Gaughran 2002). This relationship is illustrated in Figure 6.
Carroll (1993) conducted a later study and determined six spatial factors, Spatial Visualisation, Spatial Relations, Closure Speed, Flexibility of Closure, Perceptual Speed and Visual Memory. Carroll's findings indicated the existence of closure speed (CS) and flexibility of closure (CF) which differs slightly from previous research in the area of spatial factors. CS involves the ability to access spatial representations from long term memory (Hegarty and Waller 2005) and additionally an ability to combine different elements of visual information into a meaningful whole (Carroll 1993). A typical measure of this ability is the "Snowy Pictures Test" developed by Ekstrom et al. (1976) where participants are asked to find the image amongst the visual noise (see Figure 7).
CF is associated with the ability to hold a stimulus in working memory and then compare it to a complex visual configuration (Hegarty and Waller 2005, Ekstrom et al. 1976). The "Hidden Figures Test" (Figure 8) taken from Ekstrom et al. (1976) is a typical test for this spatial factor.

![Figure 8: Hidden Figures Test for CF (Ekstrom et al. 1976)](image)

Perceptual speed (P) is defined by Ekstrom et al. (1976) as the "Speed in comparing figures or symbols, scanning to find figures or symbols, or carrying out other very simple tasks involving visual perception". A typical task to evaluate this factor is normally based on matching given visual stimuli (See Figure 9) however, these tasks tend to rely on predominantly visual as opposed to spatial processing (Hegarty and Waller 2005).
Visual memory was also identified by Carroll (1993) and involves the ability to remember the "configuration, location and orientation" of visual configurations (Ekstrom et al. 1976). The “Shape Memory Test” is a typical tool used to assess this factor where participants are asked to look at a visual configuration for approximately a minute and then asked to recall locations of objects once the stimulus is removed. Carroll's (1993) framework represents a general view on spatial factors, which is commonly adopted in areas such as psychometric testing. Gaughran's (1990) framework refers directly to a learning perspective concerned with the development of spatial abilities and this is where the primary difference lies.

2.4.3 Significance of Spatial Cognition

Spatial ability has been established as a type of intelligence which is separate to verbal intelligence and has been shown to be fundamentally important for a number of applications (Tversky 2005b). Spatial cognition is an innate ability in which development begins at birth, primarily with a style of “response learning” of new environments (Newcombe and Learmonth 2005). Piaget and Inhelder (1956 cited in Sorby 2009) proposed a classification of developmental spatial abilities and this comprised three categories, which are acquired with age, topological spatial concepts, projective spatial abilities and Euclidean spatial skills. Topological spatial concepts are qualitative in nature and are principally two-dimensional (Sorby 1999). An example of a topological relation would be a Venn diagram where overlapping circles are used to delineate relationships graphically. Projective spatial skills
involve the comprehension of relations from different viewpoints (Ben Youssef and Berry 2012). Euclidean spatial skills refer to an understanding of metric information including among others distance, angle and direction (Ben Youssef and Berry 2012). Spatial cognition is a fundamental aptitude, which individuals require on a daily basis to perform tasks such as finding a way around a familiar location or discovering one’s way in the world (Newcombe and Learmonth 2005). Hegarty et al. (2002) discuss the importance of spatial abilities in an environmental context and stress the importance of spatial thinking in many everyday tasks. High levels of spatial ability have also been shown to be associated with success in a variety of career paths (Steinhauer 2011). The importance of spatial abilities has been discussed as far back as Smith (1964) who estimated approximately 84 different careers which spatial ability plays a key role in including among others technical professions such as architecture as well as scientific disciplines such as chemistry. The role of spatial abilities is well established in the field of engineering and technology (McGee 1979, Steinhauer 2011) but also has been shown to be important in other areas such as mathematical and science studies (Pittalis and Christou 2010).

Spatial visualisation has been shown to be critically important in geographical disciplines such as creating and interpreting maps (Taylor 2005). Spatial cognition comprises an important set of skills in the medical profession particularly in surgical applications (Sorby et al. 2005). Through applied research in the area, Sorby (2009) has also shown that spatial skills are critically important within educational settings such as science education. She found that students with ‘weak’ spatial skills benefited greatly from spatial training. There is clear evidence within the literature available that spatial ability is a core cognitive aptitude that is vital in a great deal of tasks which humans engage with on a daily basis. Focusing specifically on problem solving, spatial ability underpins much of an individual’s competency in representing and interpreting problems (Tversky 2005b, Tversky 2005a) and is therefore an important skill in this regard. This process is catered for within the visuospatial component of working memory.
2.4.3.1 Visuospatial Working Memory

Although working memory holds and manipulates information from different modalities there are separable areas which deal with different forms of data. Visuospatial working memory is a separate component, which has been shown to be distinct from the verbal functions of working memory (Logie and Sala 2005).

Visual images are a key component of human memory mechanisms (Humphreys and Bruce 1989). One of the key principles of working memory is the ability to support the temporary retention of stimuli that were presented recently. If one considers the ability to close their eyes and form a brief mental image of the layout of the area immediate to us, the implication must be that we possess a mechanism in working memory for the retention of visual imagery (Logie 2003). Visuospatial working memory has been referred to as a gateway between perceptual input and long-term memory. However as Logie and Sala (2005) discuss, it is better to think of visuospatial working memory as a workspace which allows for the manipulation and synthesis of mental images.

As discussed previously, the visuospatial sketchpad is the component of working memory, which caters for this cognitive capacity (Baddeley 2000). Visual and spatial working memory can be treated as dissociable concepts where "visual" refers to the colour, vividness, size and texture of an object and where "spatial" refers to the dynamic characteristics of a scene or representation (Logie and Sala 2005). This distinction is also reported in the neuropsychological literature where research has shown that different brain areas are activated for visual and spatial tasks (Reisberg and Heuer 2005).

Other studies rely on information from cases of neurological disease or damage which show that deficiency in a ‘visual’ site of the brain results in difficulty performing visual memory tasks and not spatial memory tasks (Enns 2004). The inverse is also possible, which highlights that these subcomponents of visuospatial working memory are separable.
Logie and Pearson (1997) have conducted research in the division of the visuospatial sketchpad component of working memory and have described two subcomponents. They are the “visual cache” and the “inner scribe”, which provide a temporary store for information and a mechanism for the rehearsal of information in working memory respectively (Logie and Pearson 1997). This separation is similar to the model for the phonological loop of working memory, which was proposed by (Baddeley and Hitch 1974). However, the difference being that the phonological loop only handles information in a phonological code and the visuospatial sketchpad handles different codes, which gives rise to the visual and spatial distinction (Pickering 2001).

Despite the distinction between visual and spatial working memory being well documented it can be difficult to segregate the two during cognitive processing. Salway and Logie (1995) have argued that cognitively demanding tasks do require more than a single component of working memory. Vecchi and Cornoldi (1999) have declined to prove this distinction between spatial and visual components within their own research endeavours and have instead proposed an alternative, which is to consider visuospatial working memory tasks on a continuum from passive to active. This has been suggested to be a more useful explanation for visuospatial working memory distinctions particularly when engaging with tasks or problems (Pickering 2001). Passive processes refer to the retention of visuospatial information, which has not been modified after encoding whereas active refers to a form of transformation or manipulation that has been undertaken on stored visuospatial information (Vecchi and Cornoldi 1999). This theory on passive and active components of visuospatial working memory seems to be a plausible one given the dynamic nature of cognitive processing (Wang 2007) and gives a more functional perspective on these cognitive processes.

The role of memory in the problem solving process and subsequently learning is a critical one. Working memory deals with the current demands of a task or problem and is necessary in activating previously stored mental models for present action. Memory (long-term and working) caters for different modalities and the role of
visuospatial processing is important for problem representation processes (Finke et al. 1992, Tversky 2005). It is now necessary to consider some of the contemporary views on problem solving research in order to gain a more in depth understanding relating to the development of core competencies and structural knowledge for convergent problem solving reasoning in STEM education.

2.5 Problem Framing

2.5.1 Criticism of the classic view on problem solving

One of the core limitations with theories of schematic and propositional storage within long-term memory is the failure to account for modality driven representations. It is generally accepted that problem solving is not an abstracted process (Kirsh 2009) and occurs within particular contexts, which all have an effect on the process (Pretz et al. 2003). Therefore, it is inappropriate to treat the knowledge, which is used within the problem solving process as stored abstractly. As discussed earlier the theory of knowledge storage in the form of mental models (Bogard et al. 2013) offers a more situated view of the concept of storage. These are then used directly in the problem solving process (Van Gog et al. 2005) and encompass multi-modal elements (Jonassen and Strobel 2006). This aligns with the general acceptance of multiple modes of representational processing during a problem-solving task.

"These [problem solving] schemas are abstract in the sense that they include information that is common to multiple problems of a particular type but exclude information that is idiosyncratic to the individual problems over which the abstraction has occurred."

(Novick and Bassok 2005, p. 335)

The previous quote highlights the abstract nature in which problem solving schemas as part of the traditional view were treated. Recent research on the nature of knowledge representation asserts the importance of situated contextual factors on the
Barsalou (2009) presents a situated view on the development of conceptual schemas in long-term memory. Rather than treating the storage of conceptual schema as A-modal and schematic in nature, the author presents neuroscientific evidence for modality driven conceptual schema. Research (Barsalou et al. 2003) has indicated that underlying neural circuits evident during perceptual processing (vision, hearing etc.) are activated again in the absence of these stimuli, which points to the situated nature of conceptual schemas. This has specifically been found in visual mental imagery where cortical areas associated with perception have been shown to be active during visual mental imagery tasks (Kosslyn et al. 2006).

The alternative structure of conceptual schema proposed by Barsalou (1999, 2009) incorporates "simulators" and "simulations". A simulator is a conceptual schema, which contains the multimodal content of a category encompassing all its members (Barsalou 2009). An example of this would by a simulator for cars, which includes information on different makes, colours, styles and so forth. A simulation is a subset of content from a simulator (Kirsh 2009). Aligning with the previous example given, this may take the form of a particular car (e.g. Ford). The use of simulators and simulations is the basis of functional conceptual systems in humans and can be called upon and re-enacted as the context demands (Barsalou 1999).

Kirsh (2009) presents a large criticism of the classical approach to problem solving research citing a number of core points. One of the core limitations is the overemphasis of problem solving as a search process, which discounts much of the situated influences on the nature on the activity (Lave 1988). This point is also indirectly referred to by Pretz et al. (2003) who stress that much research on problem solving encompasses a focus on the latter stages of the activity as opposed to the earlier stages involving the construction of the problem space.
Among the specific limitations in classical problem solving research is the nature of problem framing which refers to the processes an individual implement in order to understand a problem before constructing the problem space (Kirsh 2009). This is considered a critical part of problem solving and ultimately can affect the success of approaches adopted in the latter stages of the activity (Kirsh 2009). This will be explored in more detail in the next section.

2.5.2 Problem Conceptualisation

Problem conceptualisation is the manner in which an individual frames the task or situation which they are currently engaged with (Adams 2001). Goméz et al. (2000) describe conceptualisation as “modelling by the problem solver”. This modelling process results in the formation of a “conceptual model” for that problem (Duit and Treagust 2012). However, it should be noted that there are a number of different conceptual models, which can be constructed for a particular problem (Adams 2001). This is not surprising given the diverse background knowledge and experience that students bring to the situation.

Literature on problem conceptualisation is limited and this is not surprising as it is an area, which is relatively under researched (Kirsh 2009). Gomez et al. (2000) hypothesise that the process of conceptualising involves two distinct phases: analysis and synthesis. Analysis is a regressive process where the problem is broken down and understood and involves elements of problem representation that is best described as a representation which solvers construct to summarise their understanding of the task (Duit and Treagust 2012, Novick and Bassok 2005). Presumably, this analysis process also allows activation of problem schema, which can be brought to bear on the approach. Synthesis is progressive in nature and allows all knowledge (representations) constructed in the analysis stage to be amalgamated and utilised to implement an approach (Goméz et al. 2000).

The manner in which an individual conceptualises or frames a problem is posited to either impede or facilitate the achievement of a solution (Adams 2001, Kirsh 2009).
Consider the nine-dot problem presented earlier in the chapter (Figure 3). Here it was discussed that the representation needs to be altered for individuals to realise that there is no boundary limitation in constructing the four lines. The more contemporary approach focusing on conceptualisation looks at the factors contributing to this mental set when framing the problem rather than just the nature of the representation (Kirsh 2009).

A representation, which was discussed earlier, refers to a mental or physical (sketch etc.) entity that summarises an individual’s understanding of a problem (Novick and Bassok 2005). A conceptualisation or conceptual frame is differentiated from this through incorporation of aspects such as past experience, environmental constraints and epistemological orientation among others (Barsalou 2009). It is possible that the outcome of a conceptual process results in a representation for a problem. This hypothesis is supported in the discussion by Bogard et al. (2013) who contend that an external representation is a window into an individual’s mental model of the problem. The formation of this situated model (representation of the task) is the result of the conceptualisation process. To clarify the potential relationship between conceptualisation and problem solving approach it is necessary to look at examples of conceptual frames. Aligning with the development of structural knowledge through convergent problem solving which is indicative of the style of activity in STEM, the examples will focus on analytical and visuospatial processes. Analytical processes are a core component of convergent style problems and visuospatial processes are an important element of representations.

### 2.5.2.1 Analytical/Mathematical Conceptualisation

Analytic processes in terms of cognition tend to be focused on the application of definite rules or steps to achieve a goal (Eysenck and Keane 2010). Mathematical cognition is a domain that is heavily reliant on analytical process (Gallistel and Gelman 2005). An example of a task, which relies on an analytical/mathematical conceptualisation, is word problems in algebraic reasoning. Consider the following problem that was presented by Adams (2001):
"Bob has three times as many pine cones as Dan. Between them, they have 28 pine cones. How many does each have?"

(Adams 2001, p.98)

There are a number of ways of conceptualising this problem which could ultimately work. For example one could take a sequential trial and error approach and verbally reason alternative possibilities (Adams 2001). However, if the problem were framed mathematically then the solution is likely much more straightforward due to a more efficient approach. One could frame the task visually and potentially represent the information as a sketch but this would be a less efficient strategy by comparison to mathematics. This is a clear example of where different conceptions can lead to the same solution but with varying degrees of effectiveness.

2.5.2.2 Visual Conceptualisation

A classic problem, which demonstrates a case where conceptualising a problem in a visual manner facilitates reasoning, is the "monk puzzle" which is discussed by Adams (2001).

"One morning, exactly at sunrise, a monk began to climb a tall mountain. A narrow path, no more than a foot or two wide, spiralled around the mountain to a glittering temple at the summit. The monk ascended at varying rates of speed, stopping many times along the way to rest and eat dried fruit he carried with him. He reached the temple shortly before sunset. After several days of fasting and meditation, he began his journey back along the same path, starting at sunrise and again walking at variable speeds along the way. His average speed descending was, of course, greater than his average climbing speed. Prove that there is a spot along the path that the monk will occupy on both trips at precisely the same time of day."

(Adams 2001, p. 4)

In this case it is unlikely that the problem can be solved with a mathematical or verbal style of conceptual frame. The optimum approach is to represent the problem visually plotting the two journeys (up and down the mountain) as two lines where a common intersection can be found indicating the time (Adams 2001).
As can be seen in the previous two examples, the conceptual frame adopted to a problem or task seems to have an effect on the manner in which the task will be approached. The core question, which needs to be addressed in contemporary accounts of problem solving, is the manner in which these frames are constructed. This is an issue which Kirsh (2009) claims has not yet been addressed with empirical research.

### 2.5.3 Significance for STEM education

So far, this section has focused on some of the more contemporary opinions on problem solving research. The focus of this research is on investigating the relationship between conceptualisation and approach of convergent problem solving tasks that require structural knowledge and reasoning skills, which are indicative of STEM education. It is therefore prudent to explore some of the core issues in developing these problem-solving skills cited within the pertinent literature. One of the most prominent concerns discussed by McCormick (2004) is the overemphasis on certain approaches to problem solving which eventually results in ritualistic behaviour. This often occurs in the face of external pressures such as terminal assessments (Entwistle 2000) and results in students following "algorithms" during the problem solving process (Murphy and McCormick 1997). This has significant implications for the nature of learning in STEM education as this approach could ultimately lead to rigid, inflexible approaches to reasoning.

The literature on problem solving research presents a large body of evidence relating to the processes of problem solving but little work has been conducted on the early stages (e.g. conceptual framing) (Pretz et al. 2003, Kirsh 2009). Considering the importance of appropriate conceptualisation processes is critical and could have benefits for the development of structural knowledge and problem solving capacities in convergent tasks which are emblematic of STEM education. Visuospatial cognition has been discussed as an important process during the representation of problems (Tversky 2005b). There is a large body of evidence, which has shown the benefits of achieving spatial skills in relation to further academic achievement.
Sorby (1999, 2009) has demonstrated that students who develop high levels of spatial ability go on to perform better in a variety of disciplines such as science and mathematics. Considering the importance of problem framing and the empirical evidence on the development of spatial abilities leads to a further hypothesis. It raises questions around the possibility that the higher levels of visuospatial competencies among students allows for the construction of more flexible and robust conceptual frames. This in turn facilitates higher levels of performance in convergent problem solving tasks used to develop structural knowledge.

Investigating the nature of these conceptualisation processes is a difficult undertaking. Midouser (2009) discusses the fact that a great deal of the processes utilised by a student within the problem solving process are tacit in nature and cannot be easily captured. Despite this it is necessary to focus on the process of the problem solving approach in order to gain a full understanding of the nature of the cognitive strategies which could impact on learning (Barak 2007, McCormick 2004). This capturing of the cognitive processes of problem solving will be the focus of the next section.

### 2.6 Capturing Cognitive Processing

Given the possible complexities outlined at the end of the previous section, it will be useful to consider some of the functional perspectives on cognition in order to gain insight into the process of problem framing. Previous research in the area of problem solving and cognitive investigations has been achieved through behavioural strategies. In order to further investigate the area of conceptualisation an alternative focus may be beneficial. One of the most promising perspectives for contemporary educational research is evolving from the field of cognitive neuroscience (OECD 2007). The workings of the brain are integral to a more comprehensive understanding of human cognitive competencies (OECD 2002).

A pervasive belief that has been dispelled in recent years is the limited capacity view of the human brain where it was assumed that we are born with a limited amount of
potential cognitive resources and these are fixed (Blakemore and Frith 2005). Contemporary research suggests that this is not the case as it has been shown that the adult brain is amazingly flexible and susceptible to change (McGilchrist 2009). This flexibility is known as “plasticity” within the neurological literature (Arrowsmith-Young 2012).

This “plasticity” refers to the brains ability to adapt and change continuously for different situations and circumstances (Blakemore and Frith 2005). Doidge (2007) discusses the negative impact which the outdated belief that the brain was fixed has had on educational philosophies and coined the term “neurological fatalism”. This refers to the belief that what you have (in extreme cases a learning disorder) at birth, in terms of brain potential is all you will ever have (Ibid). Arrowsmith-Young (2012) has provided evidence that functions and disorders in the human brain can be altered and improved with the correct educational interventions. First it is necessary to explore some of the known basic functions of the brain.

2.6.1 Neurocognitive Architecture

The brain is an extremely complex organ, which has a number of important sub-structures and elements. The research described in this particular study is housed in the context of cognitive functioning and it is therefore unnecessary to focus on many of the sub-structures.

The brain is broadly divided into two hemispheres. The left is generally associated with linguistic, logical and divergent functions and the right has been approximately associated with spatial abilities and divergent thinking (OECD 2007). This generalisation should be taken with caution as it is now known that many of the functions traditionally associated with left-brain aptitudes actually utilise elements of the right hemisphere as well and indeed vice versa for right-brain aptitudes (McGilchrist 2009). The false belief in left and right brain thinking has been coined a “neuromyth” (OECD 2007) and the development of "whole brain thinking" is the contemporary goal of education in general (Schank 2011).
It has been well established in the field of cognitive neuroscience that the cerebral cortex is primarily associated with many of our cognitive functions (Banich and Compton 2011, Ward 2010). Figure 10 illustrates the major subdivisions of the cerebral cortex.

![Major subdivisions of the cerebral cortex.](image)

**Figure 10: Major Subdivisions of the Cerebral Cortex (OECD 2007)**

Each one of the respective lobes of the cerebral cortex can be broadly associated with certain cognitive functions (OECD 2007). Some of these will be discussed briefly in the next section.

### 2.6.1.1 Functional Organisation

The functions associated with different brain areas is a complex area of research and is still quite contentious among the cognitive neuroscience research community (Blakemore and Frith 2005). An extensive analysis is beyond the remit of this study and so a general overview relating to competencies specifically associated with each of the roughly defined areas of the cerebral cortex (Figure 10) will be presented.
2.6.1.1 Frontal Lobes

As discussed previously, memory systems comprise the key foundations for cognitive processing. The frontal lobes have been found to be a key component of working memory mechanisms (McGilchrist 2009). For verbal working memory tasks, activation in the left frontal lobe was found to be significant and in visuospatial tasks a bi-lateral activation of the frontal lobes was found (Gruber 2009). Some visual tasks will predominantly engage the right side of the frontal cortex (McGilchrist 2009). In general, working memory demands activation of both sides of the frontal lobes and are critical in recalling data from memory (Cabeza and Nyberg 2000).

2.6.1.2 Temporal Areas

The temporal areas cater for four main functions within cognition: "memory, visual item recognition, auditory processing and emotion" (Banich and Compton 2011). These regions are particularly important for processing of memory related functions of both semantic and episodic natures (Ward 2010). As Cabeza and Nyberg (2000) discuss, there is evidence to suggest a strong link between the hippocampus, which is a core component in memory, and the temporal areas. This suggests that they not only have an important role in recalling from memory but are also critical in forming new memories.

2.6.1.3 Parietal Areas

The parietal areas play a very important role in a great variety of cognitive processes as they are capable of integrating information from different regions and modalities (Stillings et al. 1995). Principally, they are involved in the majority of visuospatial processes where they facilitate the manipulation and synthesis of different visual and spatial information (Rescher and Rapplesberger 1999). The right parietal region has been implicated in this particular process by a number of researchers (Roberts and Bell 2003). The left parietal area has also been found to play a significant role in a
number of spatial competencies coupled with the involvement of frontal areas particularly in the right hemisphere (Gill et al. 1998).

These areas also play a key role in working memory and have been shown to be activated during recall tasks of both semantic and episodic content (Cabeza and Nyberg 2000). The activation of the left parietal region is a key indicator of linguistic or semantic processing in working memory (Banich and Compton 2011).

2.6.1.1.4 Occipital Areas

Visual perception processes have been found to activate regions of the occipital lobe, which is also host to what is known as the visual cortex (Arrowsmith-Young 2012). Generally, stimuli are perceived by the retina and transferred to the occipital areas via two distinct pathways. These are the ventral or the “what” pathway which controls the abstract characteristics of visual processing (i.e. the identification of objects) and the dorsal or “where” pathway which controls the spatial characteristics (i.e. where objects are located) (Enns 2004). These areas have also been associated with visual memory or visualisation processes where there is no actual perceptual processing occurring. Kosslyn et al. (1995) discuss the key role that the occipital regions play in building visual mental images. In addition Farah (1984), found significant activation of the posterior left hemisphere in visualisation processes.

In general, visuospatial processes typically involve significant activation of the occipital and parietal regions as well as the frontal areas. A common “neuromyth” is the sole involvement of the right hemisphere in visual and spatial tasks (OECD 2007). However, as McGilchrist (2009) explains, all cognitive activities require the involvement of both hemispheres and therefore involvement of the left cannot be ignored. The manner in which activity occurs in the cerebral cortex is of core interest at this point as it reflects the cognitive basis of the problem solving process. As Mioduser (2009) suggests investigating these cognitive processes should form the focus of contemporary approaches to problem solving research. It is necessary at this point to consider more closely the mechanics of function within the cerebral cortex.
2.6.1.2 Neurons

Neurons are the critical cells in the human brain, which control many of our functions. They have the unique property of being capable of communicating with other neurons over great distances in the cortex (Stillings et al. 1995). A typical neuron is shown in Figure 11. Neurons generally have three main components, a dendritic tree, a cell body and an axon (Banich and Compton 2011).

![Figure 11: Structure of the Neuron](image)

As mentioned, the primary function of the neuron is to transfer information to other neurons by means of electrochemical signals (Ward 2010). The cell membrane of the neuron allows ions to flow in or out, which drives the electrical charge of the neuron in either the positive or negative direction (Banich and Compton 2011). Once a certain threshold of electrical charge has been breached by this flow of ions, the neuron reverses its charge rapidly causing the phenomenon commonly called “firing” (Banich and Compton 2011). This entire process is also called the “action potential” (Haken 2008).

Neurons communicate with other neurons through the formation of synapses which transfer activity from one neuron (the presynaptic neuron) to another (the postsynaptic neuron) by means of a chemical “neurotransmitter” mechanism (Haken 2008, Ward 2010). These synapses are the critical connections made as the neurophysiological response to learning (Onians et al. 2012) and are thus crucial in understanding educational endeavours from a cognitive neuroscientific perspective. Further research has focused on the communication of specific organisations of
neurons, which are tied to certain cognitive functions and can be indicative of certain forms of cognition (OECD 2007).

As can be seen in this brief overview, there are a number of studies, which have proven the involvement of distinct areas of the cerebral cortex in specific cognitive functions. This field is emerging with an ever increasing body of research and literature and there is evidence to suggest the biological representation of certain cognitive processes in the brain. This avenue of cognitive research is very promising as a functional perspective on styles of cognitive activity occurring within problem solving activity as part of STEM educational designs.

The conceptualisation process, which is an element of the primary aim of this research, is tacit and often hard to articulate (Barsalou 2009). The cognitive processes that are illustrated during problem solving are directly related to mental models or simulators in long-term memory (Bogard et al. 2013). Therefore, capturing evidence of the type of cognition utilised during a problem would give insight into the nature of the conceptual frame adopted. It is important to consider how this can be achieved in an objective manner for the purposes of research. The next section will look specifically at how these cognitive processes can be captured using various approaches.

2.6.2 Measurement Strategies

This section will present a brief review of various physiological research tools in cognitive neuroscience. Studies in cognitive neuroscience are generally divided into two distinct categories. The first is the study of neurologically impaired individuals. These are people who have sustained damage through illness, injury or deformity to specific areas of the brain (Ward 2010). Studies of this nature isolate the core of the impairment and ascertain whether there is an effect on performance in particular scenarios or tasks. The alternative approach is to utilise specifically designed tools to measure physiological activity and this can be applied to both impaired and
healthy participants (Ward 2010). The fact that these tools can be applied to healthy individuals presents significant potential for their applicability to cognitive research.

2.6.2.1 Functional Brain Imaging Methods

This category of imaging methods utilises the changes in blood flow and metabolic rate to determine areas of activation within the brain. The most commonly used strategy to achieve this is functional magnetic resonance imaging (fMRI) which assesses changes in the oxygenation of blood in the brain (Banich and Compton 2011). The use of fMRI has a number of advantages including non-invasiveness and the ability to measure deep brain structures such as activity in the hippocampus (Ward 2010). There are however limitations in the capturing of functional data as what is measured is a hemodynamic response which is much slower (normally occurs approximately 2 seconds after the event) (Freeman and Quiroga 2013). This presents issues for studies looking at particular stages of performance in applied tasks, as the data is an average over an entire episode (Banich and Compton 2011).

Another method in the family of functional methods is positron emission tomography (PET). PET allows researchers to investigate the presence and activity of a specific substance in the neuro-anatomical system (Banich and Compton 2011). Normally, this is achieved by the introduction of a radioactive substance into the body by means of an injection (Ward 2010). PET is very advantageous in the study of metabolic disorders in the brain or the impact of various substances on neural activity (Banich and Compton 2011). Eysenck and Keane (2010) cite its advantage as having accurate spatial resolution but a significant disadvantage being the poor temporal resolution. PET is capable of capturing accurate readings of activated areas of the brain but this can only be captured across large time spans.

2.6.2.2 Electromagnetic Recording Strategies

The previously discussed methods rely on analyses of the metabolic rates of activity within the brain. The methods presented in this section capture electrical activity produced by neurons or neuronal networks. The most simplified of these methods is
the “single-cell recording”, where a sensor is placed on the surface of the brain (Banich and Compton 2011). This is normally conducted in animal research and makes it an unsuitable candidate for educational research due to the highly invasive nature.

One of the most popular electromagnetic recording methods is the electroencephalogram (EEG). This technique utilises a series of sensors placed on the scalp which record activity from the cerebral cortex in the form of electrical currents (Ward 2010). This technique is less invasive than single cell recordings and modern EEG equipment comes in a variety of portable forms such as headsets, which makes them a strong candidate for educational research contexts (Esfahani and Sundararajan 2012). One of the strengths of EEG research is the high temporal resolution, which can be achieved during recording. Behavioural events can be tied to underlying neural activity with great accuracy, often within milliseconds of the occurrence (Banich and Compton 2011). This process is often referred to as “event related potentials” (Freeman and Quiroga 2013)

One of the disadvantages associated with this method is its poor spatial resolution in comparison to techniques such as fMRI (Eysenck and Keane 2010). This makes it difficult to locate exact neuronal areas which are used during an event. This inaccuracy in the spatial domain can be improved with appropriate processing techniques and much of the modern studies utilising EEG have shown, with accuracy, activation of various neural regions (Fink et al. 2009, Anderson et al. 2011).

Another established electromagnetic approach is that of “magnetoencephalography” which uses concentrated magnetic fields to assess brain activity. This approach has high temporal and spatial resolution but is extremely expensive and requires large amounts of equipment plus cooling agents to operate (Eysenck and Keane 2010).
What is clear from the previous sections is that there are varieties of mechanisms with which cognitive function measured as cortical activity can be captured. In looking specifically at problem solving cognition, it is critically important that the instruments (problems) which will ultimately be used will allow for the accurate collection of rich data. The use of inappropriate tasks has been discussed as one of the core limitations in much problem solving research (Novick and Bassok 2005). The next section will consider this in more detail.

2.6.3 Considerations for Research Instrument Design

One of the core focuses within contemporary problem solving research is on the capturing of the process as opposed to the product of the activity (Midouser 2009, McCormick 2004). As the previous sections have discussed, the most objective way of achieving this is through the application of a measurement strategy from the field of cognitive neuroscience (Blakemore and Frith 2005, Fink et al. 2009). This in theory will allow for rich evidence of cognitive function to be obtained but only if the strategy is aligned with appropriate problem solving instruments.

As Kirsh (2009) discusses, there are certain limitations in previous studies on problem solving regarding the instruments utilised. The focus of the majority of these studies was on "knowledge lean" instruments as was typical of the abstracted nature of classic problem solving research (Kirsh 2009). Focusing on problem solving within STEM education necessitates the use of "knowledge rich" problems (Eysenck and Keane 2010) as there is specific domain knowledge necessary for engaging with these types of tasks. This adds complexity, as arguably there are more potential factors within the problem solving process during domain specific tasks such as previous experience, level of knowledge etc. (Kirsh 2009). Along with this are the potential cognitive factors which can be extraneous to the instrument and which could invalidate the data the same as it could impede learning (Sweller et al. 2011). This will be discussed under the heading of cognitive load theory next.
2.6.3.1 Cognitive Load Theory

Cognitive load theory (CLT) is a consideration, which is often overlooked in the design of instructional materials. Sweller et al. (1998) outline the three main types of cognitive load as follows:

- **Intrinsic**: This is imposed by the nature of the information (simple/complex, concrete/abstract) contained within the task or material
- **Extraneous**: This is imposed by the design of the instructional or learning material and occurs where information irrelevant or unnecessary to the situation is present
- **Germane**: This is a third category of cognitive load, which is directly related to intrinsic cognitive load. It occurs when attention and resources are focused on the intrinsic nature of the learning material utilized and is considered relevant to learning

The type of load that is most relevant in the context of this review is extraneous load as it is the one that is controlled directly by the design of the problem-solving instrument (Sweller et al. 2011). It is crucial to consider extraneous load in the process of designing an instructional task in order to maximise the amount of germane cognitive load, which can then result in maximum learning (Sweller et al. 1998). Extraneous cognitive load becomes an issue when the working memory resources, which have to deal with all types of cognitive load, are exceeded (Sweller et al. 1998). This could potentially present artifacts in the objective cognitive data captured by means of a neuroscientific measurement approach.

It is difficult to completely eliminate all sources of extraneous load in the design of a learning task due to the idiosyncratic nature of the student population. Areas such as learning styles, cognitive style and epistemological orientation affect the manner in which an individual commits resources to a task (Paas et al. 2003). In designing a learning task or activity, it is important to minimise the amount of extraneous load so that more mental resources can be allocated to intrinsic and germane load. This is also important from a research perspective, as the existence of extraneous cognitive load has been shown to affect the problem solving approach and provide inaccurate
data relating to cognitive processes in conceptualising the problem. It is important to note that extraneous load does not always inhibit task performance if the working memory resources are not exceeded when intrinsic and extraneous cognitive load are combined (Sweller et al. 1998). Extraneous cognitive load is the primary type that can be controlled in the instructional design stage and has an inverse function with germane load. To clarify, as extraneous load is reduced germane load is increased which promotes higher levels of learning (Sweller et al. 2011).

The intrinsic nature of the instructional design is determined by the number of elements contained within the material and their associated interactivity (Sweller et al. 2011). As discussed by Sweller et al. (1998), elements which can be learned in isolation (such as the letters of the alphabet) do not demand a vast amount of mental resources. It is when the elements start interacting that the allocation of resources becomes critical (for example when learning words). As expertise in an area develops, mental schemas are constructed which can combine elements so that they now are treated as one element in future situations (Sweller et al. 1998). This once again highlights the importance of developing structural knowledge of problem solving. Therefore, reduction of extraneous cognitive load in the design of problem solving tasks is a core consideration in order to maximise the amount of working memory resources (germane load) which can be allocated to developing these schemas (Paas et al. 2003).

Cognitive load can be measured in a variety of ways. Some of the most common are the use of a subjective rating of mental effort (Paas et al. 2003) and physiological indicators such as heart rate, eye tracking and EEG (Anderson et al. 2011).

2.6.3.2 Causes of Extraneous Load

There are a number of areas within the design of an instructional task, which can contribute, to an extraneous load. One of the most common issues is the presentation of irrelevant or unnecessary information within the task or activity (Guttormsen and Zimmerman 2007). In such a situation, the learner has to allocate resources to processing the redundant information, which monopolises working
memory resources and negatively impacts on problem solving efficiency. The core implication here in relation to task design for educational purposes is the loss of working memory resources that could have been devoted to the intrinsic nature of the task (Hoffman and Schraw 2010). The intrinsic nature of the task relates to the core of the problem that needs to be solved (Kirsh 2009) and therefore it is necessary to ensure that ability to engage with this is not compromised.

Another area which is closely related to this is the "split-attention" effect which is concerned with the modality in which information, within the task, is presented (Sweller et al. 1998). It is widely accepted that working memory primarily supports two different modalities. As indicated by Baddeley (2003), these comprise of the "phonological loop" and the "visuospatial sketchpad". Both deal with primarily verbal and visual data respectively. According to the split attention effect, if one of these channels becomes overloaded, as a result of task presentation, then extraneous cognitive load can be increased (Guttormsen and Zimmerman 2007). A simple example would be presenting over complex written text and a visual representation, which both have to be processed by the visuospatial component of working memory.

Again, it is important to note that extraneous cognitive load will not become an issue as long as there are sufficient working memory resources, which can be allocated to the task (Sweller et al. 1998). There are a variety of characteristics within a task which combined with the introspective characteristics of the learner can cause a detrimental extraneous cognitive load. It must be acknowledged that not all extraneous cognitive load can be entirely removed however the general optimal approach is to reduce the effects as much as possible while enhancing the capacity to learn from the instructional design (Hoffman and Schraw 2009).

2.6.3.3 Determining Cognitive Load Effects

Outlined in the previous section is some of the pertinent literature on the nature of cognitive load, its various types and the complex relationship to instructional task design. It is clear that reducing extraneous cognitive load is of paramount importance when considering or designing instruments for learning or research purposes. This will aid in maximising the working memory resources which can be
focused on the intrinsic nature of the task (increase in germane cognitive load) leading to the development of robust mental schema in the case of learning or accurate cognitive data in the case of research.

This section will consider how cognitive load effects might be captured during an individual's engagement with a problem-solving instrument. Pass and van Merrinboer (1993) considered this an important aspect of instructional design as ultimately it would inform the educator or designer of the "cognitive cost" of learning. Two instructional designs can produce the same outcome but have achieved these using very different levels of cognitive resources (Sweller et al. 2011).

A notable approach that should be considered is that of problem solving efficiency. Hoffman and Schraw (2010) discuss the importance of studying problem solving efficiency so that a deeper understanding can be gained of the time and effort required to develop knowledge and skills. Using such a measure would also indicate the efficacy with which an individual engaged with a problem-solving instrument (Hoffman and Schraw 2009). This becomes particularly relevant within educational settings as there are often numerous constraints placed on the learning process such as class periods and external examination deadlines. Efficiency within a learning context is broadly defined as “the ability to reach established learning or instructional goals with a minimal expenditure of time, effort, or cognitive resources” (Hoffman and Schraw 2010)

By determining an optimal efficiency within a pedagogical intervention, the effect of extraneous cognitive load will be reduced and germane load will be increased. There is a wide variety of methods utilised to calculate efficiency scores and each has its own set of merits depending on the context of the study in question. The most widely referenced models in the literature on CLT are the:
- **Deviation Model:** this is a formulaic approach for determining the magnitude and direction of the difference between z scores for performance and effort (Hoffman and Schraw 2010, Paas and van Merrienboer 1993)

- **Likelihood Model:** this is computed as the ratio of performance in a task to the mental effort exerted during the task (Hoffman and Schraw 2009, Kalyuga and Sweller 2005)

- **Conditional Likelihood Model:** this approach computes a score between performance and another variable such as effort while controlling for an additional variable such as reading ability or study time (Hoffman and Schraw 2010)

The deviation model is more suited to the analysis of groups of students as it computes standardised scores using group variables. The other two approaches are more suited to analysing individuals as they work on a principle of calculating a "rate of change between variables" (performance and effort/time) (Hoffman and Schraw 2010). It should be noted that effort within these studies is often collected by means of a subjective rated scale and this has been validated in numerous previous research investigations (Kalyuga and Sweller 2005, Sweller et al. 2011).

The use of principles from CLT can aid in selecting a valid problem solving instrument for research purposes on problem solving in STEM education. In theory, this along with the approaches from cognitive neuroscience discussed earlier would allow an objective and accurate measure of cognitive processing associated with the nature of the problem. Another important consideration however, is the metacognitive characteristics of problem solving which are known to be a critical element of the process (Pretz et al. 2003). This coupled with the tacit nature of an individual's conceptual framing process (Barsalou 2009) necessitates a consideration of approaches to capturing these. The next section will review literature focused on the evidencing of behavioural and perceptive states.

### 2.6.4 Capturing Behavioural and Perceptive Evidence

The necessity to observe the behavioural and perceptive characteristics of an individual's approach to solving convergent problems indicative of the type used to
develop structural knowledge in STEM education highlights the need to consider qualitative approaches to research (Bryman 2007).

2.6.4.1 Visual and Verbal Protocols

One of the most commonly used approaches in educational research is the strategy of observation combined with “think-aloud” protocols (Montague et al. 2011). The resulting method is often called “visual-verbal protocol” and has been used in a number of studies in the areas of mathematics education (Montague et al. 2011) and within technology education research (Lane et al. 2010).

The visual data gathered during this process is a rich source for analysis relating to participant behaviour. Not only can the direct process of the activity under investigation be observed but additional behavioural data, such as erratic movements and pauses, can be captured. This type of data can allow valuable insight to be gathered relating to factors which are connected to the activity under scrutiny (Middleton 2008).

“Think-aloud” data provides a rich source of data containing evidence of underlying thinking and reasoning processes which the research participants engage during the activity in question (Ostad and Sorensen 2007). During a prescribed task, which is designed to complement a pre-designed research question, a participant is requested to think aloud and state any thoughts relevant to the task as they progress (Montague et al. 2011). An obvious concern, particularly within cognitive research, with implementing this style of method is the potential interference with the activity under investigation. This interference can be minimised using a careful implementation procedure and aligning the tasks used within the activity in an “authentic” manner (Middleton 2008). Considering the principles of CLT should aid in this. The use of this approach is advocated by Young (2009) who believes the benefits of employing this method within human behavioural research far outweighs the limitations.

The visual data will clearly provide evidence of the participants’ behavioural actions during problem solving (Middleton 2008). The think aloud process, in addition to
capturing evidence of reasoning, will allow elements of metacognitive processes to be observed (Montague et al. 2011, Ostad and Sorensen 2007).

2.6.4.2 Interviewing

Interviewing is a commonly used technique in qualitative research and is extremely powerful in extracting interoceptive states from participants relating to an event or activity (Coolican 2009). As discussed by Bryman (2008), interviews are the most widely used tool in qualitative social science research and there are essentially two main types: structured and semi-structured approaches. Structured interviews can often be inappropriate in research studies that are concerned with exploring participants’ personal beliefs or views (Yang and Tsai 2010). This places semi-structured interviewing methods as a valid approach in this type of research as it is structured in a basic manner which increases validity and reliability (Coolican 2009). It is also open enough to allow participants elaborate and discuss different opinions and viewpoints as they emerge during the discourse (Cohen et al. 2007).

There are potential areas of concern in utilising an interview approach. An area which is posited to effect introspective accounts as a research method is "cultural training" (Bernard et al. 1984). This occurs when a participant presents a conditioned response, as a result of cultural influence on memory encoding processes, for specific events (Lyle 2003). The risk is that the data captured now reflects a level of cognitive abstraction away from the events, which actually occurred during the task under investigation. This presents a concern for investigating something as tacit as conceptualisation processes during problem solving.

2.6.4.2.1 Stimulated Recall

In addressing issues of “cultural training” (Bernard et al. 1984) and reducing the possibility of participants introducing biases to their introspective reporting, the stimulated recall approach is beneficial (Lyle 2003). Stimulated recall generally occurs after the event in question and involves retrospective interviewing techniques,
which incorporate various stimuli to aid recall and reflection (Gass 2001, Lyle 2003). The stimulus can take many forms including a picture, participant produced work or videos. It is an advantageous technique in addressing cultural biases as it presents the participant with a more objective account of their behaviour for comment.

Another important justification for incorporating a retrospective stimulated recall analysis of the participant’s problem solving episode within a methodological approach is the reduction of possible interferences from the visual and verbal protocol method. As discussed by Lyle (2003), there are a number of possible concerns with utilising think aloud protocols. Included among others is the effect of bias on verbalisation of cognitive processes or difficulty in verbalising tacit knowledge. In addition, there are a number of auxiliary factors, which could be occurring during the task such as motivational issues and time constraints. It is possible that these could prevent accurate reporting during the implementation of the visual and verbal protocol method.

The most obvious limitation with retrospective accounts of behaviour is the potential issue of memory decay. There are a number of studies citing the need for the stimulated recall procedure to be carried out as immediately as possible post-task (Gass 2001, Lyle 2003). This is in attempt to reduce the memory decay effect. However as discussed by Bernard et al. (1984) utilising a “recent” time frame (e.g. 24 hours) can only account for six percent of informant accuracy. As suggested by Cohen et al. (2007), the issue of respondent validation is critical in this style of research and revisiting the process after a period of time while using evidence from the first session can add rich insight into the data. Research by Maquet (2001) has also stated the potential benefits of allowing a night's sleep to occur after the event given the key role this plays in consolidating one's memories of an event or situation.

The use of a post task follow up session in conjunction with the immediate post task interview falls under the framework of “bounded recall” (Bernard et al. 1984). A baseline interview session is used in comparison with a later retrospective account, in this case the stimulated recall. This approach safeguards against the phenomenon
of “telescoping” where participants recall events as more prominent or relevant than they actually are and has been shown to increase overall accuracy by ten percent (Bernard et al. 1984). The use of stimulus during interview techniques can aid the participants' metacognitive reflection of events (Bryman 2008) which is an important characteristic of problem solving processes.

2.7 Summary

The literature review explored a number of interrelated areas as follows:

- The chapter began by looking at the nature of learning within STEM education. There was a key emphasis placed on the ability to think critically and problem solve.

- One of the core aims within STEM education is to develop students’ reasoning abilities to the stage where they can solve “ill-defined” problems with multiple solutions effectively. In order to achieve this, students first need to develop a sound body of structural knowledge, which they can use to help transfer to different problem situations. A key strategy in developing such knowledge is the use of problem solving strategies in “well-defined” applications (Jonassen and Strobel 2006).

- According to the classical approach, problem solving is a process of representing an initial problem state in order to implement a search (set of heuristics) through a problem space to achieve a goal state (solution). Two of the core strands of research have focused on representation and search. One of the core differences between novice and expert problem solvers is access to schemas in long-term memory (Sweller et al. 1998).

- Experts have more robust problem solving schemas than novices and also are able to access more of a scheme. Within much of the literature, the manner of storage in long-term memory is considered to be schematic with propositional node representations (complete units of thought) subsumed within them. Mental models were proposed by Bogard et al. (2013) to be the
manifestation of these stored representations of knowledge specific to problem solving.

- Memory is therefore a key process which problem solving is reliant on and the architecture of function of memory was explored.

- Visuospatial cognition is a key component of memory, which facilitates performance in a great many tasks from everyday navigation to advanced visualisation. It is particularly important in the representation of convergent problems, which are typically used to develop structural knowledge in areas such as STEM.

- Criticisms of the classical approach to problem solving were discussed. These centred around the predominant focus on latter stages of the problem solving cycle in an abstracted manner. A more situated approach to research advocated by Kirsh (2009) was discussed and this lead onto the delineation of conceptual framing (conceptualisation) as a core process in problem solving.

- The process of framing is particularly important within areas like STEM education as problem solving forms one of the core learning approaches. Previous research by Sorby (1999, 2009) has demonstrated a link between the development of high levels of spatial ability and performance in STEM disciplines such as mathematics and science. This could possibly be as a result of spatial ability contributing to flexible problem conceptualisation strategies.

- As the process of conceptualisation is a tacit area this created a need to observe the cognitive process in an objective manner. This necessitated a closer look at neuroscience perspectives for capturing evidence of cognitive processing relating to problem solving. A number of different approaches were considered.

- In order to capture valid data of cognitive processing during the activity, the instrument selected will need to align with the method of capture. The principles of cognitive load theory were explored to address this and it was shown that materials can be adapted to reduce extraneous load (Sweller et al.
2011) and thus allow allocation of cognitive resources to the intrinsic nature of the instrument.

- Also highlighted in the review was the need to look at the subjective interpretations of participants and access some of the metacognitive narrative, which is known to be a critical part of problem solving (Midouser 2009).
3 METHOD
3.1 Overview

Through analysis of pertinent literature in the area of problem solving a lack of empirical evidence was identified in the research with regards to "problem framing" (Kirsh 2009). The focus of the method will be on exploring the nature of how individuals conceptualise educational problems, which are typically utilised within STEM type disciplines, and what cognitive factors are impinging on the process.

The current investigation was concentrated on exploring the relationship between participants’ conceptualisation of tasks, the approaches adopted to solving the tasks and the associated efficacy of performance. As investigations of such relationships are limited within the current literature, this posed a number of complexities in devising a suitable method. The method presented in this chapter has a number of objectives:

1. To devise and apply a data collection strategy capable of capturing rich evidence of an individual’s conception of convergent STEM tasks
2. To investigate the existence of a relationship between conceptualisation of problems and subsequent approaches on a cognitive basis.
3. To explore and identify some of the contributing factors to an individual's conceptualisation process and examine their association with task performance.

Given the subjectivity of an individual's conceptualisation of a task, care must be taken to assure an authentic data source, which can uncover some of the underlying variables. The objectives outlined above formed the focus for the design of a suitable method, which will be outlined subsequently. The chapter is broken into four key sections for clarity and they are as follows:

1. Theoretical Approach
2. Participants
3. Research Tasks
4. Implementation
3.2 Theoretical Approach

The study is focused on the applied nature of problem solving utilising a lens of problem conceptualisation. The primary concern of the method will be on eliciting evidence of the cognitive basis of an individual's conceptualisation process, the association to subsequent approach and task performance. Given the hypothesised complexity of the relationships between the variables of conceptualisation, approach and efficacy of performance, consideration of a suitable approach was a complex undertaking. Aligning with Barsalou’s (2009) theory of situated conceptualisation the nature of the relationships must be studied within the context of individual experience. Conceptions can vary dramatically among individuals and situations so therefore a “pragmatic mixed methods” approach was identified as a suitable strategy (Feilzer 2010).

3.2.1 Pragmatic Approach

The interpretation of the situation (in this case an applied problem) from the perspective of the individual lay at the core of the research project. This presented a number of complexities in devising a method for investigating this process. The study was concerned with capturing problem solving behaviour during a set of applied tasks. The process was captured and analysed utilising the approach illustrated in Figure 12.

![Figure 12: Research Approach](image_url)
The hypothesis under investigation in this study centred on the key variables of conceptualisation, approach and efficacy of performance. Approaches to capturing these variables were an important consideration at this stage due to the lack of empirical research in the area.

The research presented in this study aligns with the field of situated cognition and learning. These fields consider knowledge and experience as individualistic entities, which are constructed uniquely and are affected by elements such as culture, environment and past experience (Robbins and Aydede 2009). This meant that the idiosyncratic nature of the learner was of core consideration in the design of a suitable method.

The "pragmatic" research approach allows a fit for purpose synthesis of research methods that are utilised to provide a "superior product" (Johnson and Onwuegbuzie 2004). This was seen as a promising approach as it avoids any absolute epistemological or ontological stance concerning social science research (Feilzer 2010). It was also useful when considering the lack of empirical work in the area.

"Pragmatism, when regarded as an alternative paradigm, sidesteps the contentious issues of truth and reality, accepts, philosophically, that there are singular and multiple realities that are open to empirical enquiry and orients itself toward solving practical problems in the 'real world'"  
(Feilzer 2010, p.8)

It must be remembered that this research represents the first exploration into this area and the ultimate goal is to gain a deeper understanding of the underlying phenomena. Therefore, it would have been inappropriate to adopt any other theoretical approach due to the lack of prior empirical data.

3.2.2 Capturing the Evidence

One of the core considerations in the adoption of any research approach are the issues of validity and reliability. Therefore, consideration of the methods to be employed is paramount (Coolican 2009, Cohen et al. 2007).
In previous research into cognitive processes involved in applied problem solving and reasoning tasks, a number of methods have been implemented. These include, among others, visual and verbal protocol analysis (Lane et al. 2010, Middleton 2008) stimulated recall techniques (Lyle 2003), semi-structured interview techniques (Cohen et al. 2007) and physiological measures (Anderson et al. 2011, Fink et al. 2009). This necessitated a mixed methods approach in order to explicate the underlying relationships between conceptions and performance (Cohen et al. 2007). Along with providing multiple sources of data, the mixed methods strategy facilitated triangulation of methods, which increased the validity and reliability of the data collected during the study (Bryman 2008). Each of the relevant methods for this study will be elaborated on chronologically in subsequent sections.

![Figure 13: Mixed Methods Research Approach](image)

### 3.2.2.1 Quantitative Analysis of Cognitive Processes

As the primary aim of the study is to investigate the relationship between conceptualisation, approach and performance a method of capturing data relating to cognitive processing was a key consideration. Qualitative approaches such as direct
observation can provide evidence on underlying cognitive processes (Cohen et al. 2007) but this relies on making inferences from observed behavioural events. As conceptualisation is posited be a personal and tacit phenomenon (Barsalou 2009), an objective measure would provide valuable data relating to this process. Gaining insight to the underlying cognitive processes of participants as they engaged in applied problem solving was essential in investigating the multifaceted relationship between conceptualisation, approach and task performance.

The field of cognitive neuroscience has been presented as an area with possible potential for educational research (Arrowsmith-Young 2012). Within this field there are a number of possible approaches to cognitive research which were considered as part of the literature review in the previous chapter.

3.2.2.1.1 Research Tool

One of the core aims within the area of cognitive neuroscience is developing understanding of the relationship between brain and mind (Doidge 2007). This refers to the empirical relationship between cortical function and particular modes of cognitive activity. This physiological approach presents objective quantitative data relating to cognitive processing which can be attributed to certain observed behaviours during situations such as problem solving (Eysenck and Keane 2010). In the context of this study, it was hypothesised that such an approach would complement the qualitative methods already presented and increases the validity of the approach.

Having considered the assortment of research techniques for measuring physiological function within the literature review, it was necessary to decide on a particular strategy. While the functional imaging methods provide accurate spatial resolution of activated brain regions during an event, the poor temporal resolution made them unsuitable for the current investigation. Under scrutiny in this research were particular processes within the context of problem solving. Therefore, having
the ability to isolate specific events was a significant requirement. As functional methods naturally provide an averaged level of activity, they are unsuitable.

The electromagnetic approaches were therefore a more promising option. Magnetoencephalography and single cell recording were deemed unsuitable for the educational research context due to the equipment requirements and invasiveness cited earlier. Electroencephalography (EEG) was selected as a suitable method owing to its non-invasive nature and high temporal resolution. Although this method has relatively poor spatial resolution in comparison to other strategies, these issues can be overcome using appropriate analysis strategies (Delorme and Makeig 2004). These will be elaborated on later in the chapter under the heading of implementation.

Utilising this approach allowed an objective measure of cognitive activity to be obtained which provided indicators of the nature of the conceptualisation individuals built in response to a prescribed problem. This method provided evidence of the cognitive element of conceptualisation. However, it was also necessary to gain evidence of the approach adopted and this required consideration of qualitative strategies to compliment the use of the EEG.

3.2.2.2 Visual & Verbal Protocol

As the goal of the research study was to examine the nature of problem conceptualisation and its relation to approach and efficacy of performance, a method of observation was necessary. As discussed in the review of the literature, visual and verbal protocol analysis has the potential to capture behavioural and underlying evidence of this process.

This data provides a rich source containing evidence of underlying thinking and reasoning processes which the research participants engage in during the activity in question. This strategy also provided a visual account of the participants’ performance in real time but it was also necessary to consider how that performance could be evaluated for effectiveness.
3.2.2.3 Capturing Evidence of Performance

Capturing evidence of the efficacy of participants' performance involved consideration of two key factors. These were the assessment of participant performance in each of the applied tasks and measures of cognitive load. The combination of performance and cognitive load can be utilised to obtain a measure of task efficiency, which provides valuable insight in task design and instructional conditions (Hoffman and Schraw 2010) as was explored in the literature review.

The assessment of task performance is a less complex consideration and this will be outlined further in the implementation of the method. By comparison, cognitive load is a complex area and there are a number of considerations, which must be reflected on. As discussed by Sweller et al. (1998) and Sweller et al. (2011), cognitive load can be used to inform instructional design and there are varieties of measures which provide critical information on this. For the purposes of this study, it was posited that obtaining a measure of cognitive load could be combined with evidence of conceptualisations to provide data on the relationship to task performance.

3.2.2.3.1 Measuring Cognitive Load

Cognitive load theory (CLT) is concerned with the maximisation of cognitive resources, which can be allocated to a learning intervention. It acknowledges the limited capacity of the human cognitive architecture and aims to aid in informing educational practices through the reduction of extraneous sources and the maximisation of germane sources of cognitive load (Antonenko and Niederhauser 2010, Sweller et al. 1998). One of the core facets of any research method employed in examining the effects of cognitive load, is the manner in which evidence of load is gathered.

Cognitive load can be measured in a variety of ways. Given the tacit and personal nature of conceptualisation processes (Barsalou 2009), the use of subjective scale was deemed appropriate. A subjective rating also aligns with the pragmatic approach this study adopts as the prime focus is on the conceptual framing of
educational tasks. The use of subjective measures is in line with previous literature on cognitive load theory, which has validated the use of a subjective rating scale (Sweller et al. 1998, Sweller et al. 2011). This measure can then be combined with variables such as performance scores to calculate efficiency values which can provide indicators of the effectiveness of problem solving approaches (Hoffman and Schraw 2010).

This approach has considered the capturing of cognitive data by means of EEG, visual recording of participants while solving the problems and the evaluation of that performance. An important factor, which has not yet been addressed as part of this approach, is the processes and approaches from the point of view of the participant. This is an important aspect of the investigation due to the tacit nature of conceptualisation. It is also important to consider the metacognitive reflections of students given that this is a critical component of problem solving ability (Pretz et al. 2003). The next section will consider how these perceptive data will be captured.

3.2.2.4 Interviews

In order to clarify the conceptualisation processes and subsequent approaches of the participants during the problem solving process post-task interviews were implemented. The interview is a powerful tool in educational research and has the ability to uncover levels of knowledge and understanding not easily observable by simple questionnaires (Cohen et al. 2007). As conceptualisation is a subjective intellectual process, a qualitative approach to interviewing was adopted. For the purposes of this study, two stages of interview were implemented for each participant in the study:

- An immediate post-task interview
- A follow up stimulated reflection

The rationale for the choice of two interview sessions is multi-faceted and will be outlined in the next two sections.
3.2.2.4.1 Post-Task Interview

The use of a post-task interview was necessary to uncover specific aspects of a participant’s conception of the applied tasks. Bryman (2008) discusses the use of unstructured or semi-structured approaches, which allow for a flexible investigation of underlying phenomena compared to that of structured or quantitative approaches. Utilisation of a semi-structured format also aligned with the phenomenological principle of entering the “lifeworld” as it provided opportunity for participants to voice their experiential understandings of the situation under scrutiny (Finlay 2012).

In addition, given the importance of introspective characteristics in conceptualisation, as advocated by Barsalou’s (2009) theory of situated conceptualisation, the semi-structured approach was deemed most suitable. Utilising a semi-structured approach also allowed for a higher level of reliability (Cohen et al. 2007) across interviewees while still delving deeper into underlying mental processes as represented by the interviewee.

Given that the core focuses of this interview method was on introspective accounts of behaviour, a number of potential concerns existed. An example is the incorporations of potential biases within participants’ responses. An area which is posited to effect introspective accounts as a research method is “cultural training (Bernard et al. 1984) or conditioning. This occurs when a participant presents a "sanitised" response, as a result of cultural influence on memory encoding processes to specific events (Lyle 2003). The risk is that the data captured now reflects a level of cognitive abstraction away from the events, which actually occurred during the task under investigation.

With the subjectivity of a participant’s conceptualisation of a task as an inherent independent variable, this potential issue required consideration. The decision to utilise a second post-task interview strategy was informed by this.
3.2.2.4.2 Follow up Stimulated Recall

It was decided to adopt a second post-task interview strategy in an effort to reduce the effects of the possible concerns discussed previously. This follow up strategy involved a retrospective reporting of the problem-solving episode. The use of a stimulated recall framework was adopted as it was deemed most appropriate to the research questions. There were a number of core reasons for this choice.

As discussed in the review of the literature, stimulated recall safe guards against possible biases in students' reflection on actual events. It does this by presenting participants with a more objective account of their actual behaviour during the event in question. In addition, it also allows students a suitable time-frame to reflect on the event and research has shown that allowing a night's sleep after the event and before the stimulated recall allows for the consolidation of memories (Maquet 2001). However, care must be taken to conduct this follow up strategy as soon as possible after the event.

3.2.3 Summary of Research Methods

This section has presented the philosophical underpinning of the research approach and its associated methods. The research methods were vigilantly chosen with the underpinning principles of "triangulation" and "completeness" in mind (Bryman 2008). The mixed methods approach was chosen with the principle of triangulation as a critical requirement. This triangulated framework of research methods as presented in Figure 14.
3.3 Research Participants

The research study was concerned with the problem solving approaches of students during convergent tasks that are typical of STEM education. These will be discussed in the next section. This focus required a suitable sample of participants from the field and it was decided to concentrate on pre-service technology teacher education students. The rationale for this choice is as follows:

- The study is concerned with problem solving behaviour during convergent tasks that are indicative of the type used in STEM education. Technology education students are therefore familiar with the area and should be capable of solving these styles of tasks, which are knowledge-rich in composition.
- The nature of learning within technology education is reliant on the use of problem solving as a significant pedagogical approach (Williams et al. 2008). Therefore, technology education students should adept at various forms of problem solving required for this study.
The fact that these students are pre-service teachers means that they have developed sufficient communicative skills in the area of technology education. Therefore, they should be able to effectively articulate their approaches to solving the prescribed tasks.

In addition, the nature of learning in initial teacher education involves significant amounts of self-reflection. This is an important aspect of the study as metacognitive reflection is a key component of problem solving. These students should therefore be able communicate, in an accurate manner, their reflective thoughts to the researcher.

The participants in the study were all third year undergraduate students of initial technology teacher education (ITTE) at the University of Limerick. Participants were recruited by email informing them of the details of the study and requesting participation on a voluntary basis. A total of twelve participants agreed to take part in the study. It should be noted that all participants were male as no female volunteered to participate. The descriptive statistics for all participants are shown in Table 1.

<table>
<thead>
<tr>
<th>Descriptive Statistics</th>
<th>N</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
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<td>12</td>
<td>19</td>
<td>28</td>
<td>22.5</td>
<td>3.089</td>
</tr>
</tbody>
</table>

### 3.4 Research Tasks

This section will present the details of the problem solving tasks that were utilised during the study. Careful selection of the tasks was a requirement to ensure validity for the study.

The focus of the study was to examine the behaviour of participants, both physical and cognitive, while solving a set of prescribed tasks. One of the core concerns in selecting the tasks was the context in which they were set. The focus of the study
was on convergent problem solving approaches within the context of STEM education, therefore the tasks needed to be representative of the subject area. The tasks would need to be technical in nature and engage problem-solving processes that are common in the STEM subjects. These include among others analytical and visuospatial reasoning (Ben Youssef and Berry 2012, Clark 2012).

Another core consideration was the style of the task and particularly the use of convergent or divergent style tasks. This decision was informed by the work of Kitchner (1983), who developed a three-tier model of cognitive processing for problem solving. In this model, well-defined (convergent) problems can be solved without making epistemic assumptions whereas ill-defined (divergent) problems cannot. As epistemological orientation is likely to affect the manner in which an individual conceptually frames a problem (Barsalou 2009), it was decided to control this variable as much as possible by utilising convergent tasks.

The other concern was of validity in the design of the tasks. It was necessary to select a range of tasks which were predominantly designed with different cognitive skills in mind. This would allow any issues of adaptability and flexibility of cognitive behaviour, which was one of the core objectives outlined in the introductory chapter, to be addressed. In order to achieve this and retain a high level of validity in the task it was decided to utilise existing tasks that have already been validated. This lead to investigating international assessment initiatives that utilise convergent style tasks.

### 3.4.1 Selecting the Tasks

One such initiative is the “Organisation for Economic Co-operation and Development” (OECD) who conducts the “Programme for International Student Assessment” (PISA). The aim of the PISA assessment programme is to ascertain a ranking of countries performance level in "real-life" problem solving situations (OECD 2012). The core aim that this initiative sets out to achieve is to determine the suitability of education systems in preparing students for the real world. Access
to PISA tasks was restricted at the time of this study, possibly due to an on-going PISA assessment. The only tasks that were available were the online samples which can be found on the OECD website. The concern here was the access participants in the current study may have to these tasks, which could undermine the findings.

Another initiative which was designed on PISA principles and where the tasks are not readily available to the public was the "Improving Numerical Literacy Skills" (INULIS) framework (O' Donoghue and Van Der Kooij 2007). The tasks were designed following the PISA framework.

The INULIS database is primarily concerned with quantitative reasoning skills and was modelled in line with the PISA framework on mathematics assessment. This assessment not only concerns mathematical type reasoning but also elements of visuospatial reasoning as well (OECD 2004). Examples of these are shown in Figure 15.
Figure 15: Example of "Space and Shape" Tasks from PISA Assessment Model (OECD 2004)
As one of the objectives of the research study was to investigate the adaptability and flexibility of students' conceptualisation processes, a variety of tasks were needed. These tasks had to be related to content that is typical of the field of STEM education. It was therefore decided to use three categories of task, which were as follows:

- Mathematical
- Visuospatial
- Dual Approach

All tasks were taken from the INULIS databases are described in detail in Table 2.

<table>
<thead>
<tr>
<th>Task</th>
<th>Category</th>
<th>Task Styles</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Mathematical</td>
<td>Application of Theorem</td>
</tr>
<tr>
<td>B</td>
<td>Simple Arithmetic</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Application of Formula</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Algebraic</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Identification and Application of Theorem</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Dual Approach</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>Simple Arithmetic/Image Holding and Comparing</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>Simple Arithmetic/Image Holding and Comparing</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>Application of Formula/Image Holding and Comparing</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>Probability/Image Holding and Comparing</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>Visuospatial</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Dynamic Imagery</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>Planar Rotation</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>Dynamic Imagery</td>
<td></td>
</tr>
<tr>
<td>O</td>
<td>Kinetic Imagery</td>
<td></td>
</tr>
</tbody>
</table>

In total 15 tasks were selected which encompassed three categories. The task is denoted by a letter with an associated description of the nature of the task. The three categories contained tasks, which were selected based on specific principles.

The *mathematical* category encompasses a diverse range of tasks in relation to complexity. The tasks that are included in this category range from simple to more
complex and encompass a number of different focuses in application. This was a more inclusive approach for participants as the successful completion of the tasks was now not dependent on specific knowledge in one area of mathematics.

The visuospatial category included tasks that were selected along the same premise of range in complexity. These tasks were originally designed under the category of "space and shape" (OECD 2004) and so required a visuospatial approach. In selecting the tasks cognisance was taken of Gaughran’s (1990) framework of spatial factors, which describes spatial abilities, within a learning context with varying degrees of complexity. The tasks included in the visuospatial category were selected based on their alignment with this framework and range in complexity from simple (image holding and comparing) to complex (dynamic imagery) (Gaughran 1990). Mapping every factor defined by Gaughran (1990) onto the tasks for this study was not possible as this was not the underpinning design principle originally used for these tasks. Task O (Table 2) proved difficult to map. As defined in Gaughran’s (1990) spatial factors framework, “kinetic imagery” the fourth spatial factor refers to the ability to imagine an object changing position in space. “Spatial orientation” involves the observer moving to occupy a new viewing position. Either of these approaches could yield a solution but it was deemed more likely to be a kinetic process given the nature of the participants in the study.

The dual approach category encompassed tasks that could be solved in two distinct manners, which were either mathematical or visuospatial. The focus of this category was on the flexibility of approach a participant adopts so therefore it was critical that the tasks were of the same complexity to control, as much as possible, the influence of cognitive load on the process. All the tasks required either a fundamental mathematical approach or the application of “image holding and comparing” Gaughran (1990).

It is important to stress that the categorical groupings are theoretical. They have been placed in a group according to the most effective approach to solving them. The tasks could be solved differently than the category states but these would be less
effective despite achieving the same outcome (Hoffman and Schraw 2010). These tasks were originally designed based on the PISA mathematics framework (OECD 2003). Within the design of these tasks the core philosophy was on competence in mathematical reasoning so therefore the majority of problems could be solved in varying ways and were not just reliant on applying a routine formula (O’ Donoghue and Van Der Kooij 2007). As with the majority of problems in general, there are approaches which are more effective for a given situation (Sweller et al. 2011).

An example of a task from each category is shown in Figure 16. All tasks that were utilised in the study are presented in Appendix 1.
Figure 16: Sample of Tasks from All Categories

**Task A**
A TV measures 26 inches across the diagonal of the screen, which is 20 inches wide. What is the height of the screen? (Answer to the nearest half inch)

ANS: 16.5 Inches

**Task H**
Drinks cans are made by stamping out circular discs from a sheet of metal.

The rectangular sheet from which the circles of 10cm radius are stamped out measures 1m by 2m. How many can tops can be made from this sheet?

ANS: 50

**Task N**
Which of the following pentominoes will make an open topped box?

ANS: All
3.4.2 Delivery of Tasks

Of concern in delivering the 15 tasks to the participants of the study was the possible effect of order bias on the nature of the problem solving activity. In order to counteract any possible effects of bias in this sense a randomisation of the presentation tasks had to be considered. This lead the researcher to implement a Latin square randomisation in the delivery of the tasks. The Latin square contains a number of rows of letters where each letter is represented once in each row. The algorithm randomises the distribution of letters, which lends itself to controlling order bias effects as shown by Vecchi and Cornoldi (1999). The 15 x 15 Latin square utilised within the study is illustrated in Figure 17.

The square was produced using an online generator, which allows a square of $n \times n$ to be specified\(^2\). Rows 13-15 are precluded, as they were not needed during the study due to the sample of 12 participants.

\(^2\) See http://hamsterandwheel.com/grids/index2d.php for more information.
The next consideration was the timing of the tasks. The INULIS guidelines suggest an hour to complete 20 test items (O’Donoghue and Van Der Kooij 2007). This would result in about 3 minutes per task. For the purposes of the current study, it was decided to use a time limit of 5 minutes per task. The decision to allow an increased length of time was taken to minimise any possible influence of the research conditions (EEG headset, video recording etc.). It would also allow students sufficient time to explore different approaches or strategies if required as the focus of the study was on problem solving behaviour as opposed to competency measurement which the tasks were originally designed. It was also necessary to allow sufficient time at the end of the tasks for students to rate the mental effort they exerted during problem solving. This is discussed further later in this section.

Due to the randomisation of the tasks and the restricted time limit for each task, it was decided to utilise an electronic presentation of the tasks. This was conducted in a PowerPoint presentation where the questions were given a slide with timed transitions of five minutes. After the five minutes was exceeded, the slide simply advanced to the next task. A PowerPoint presentation was created for each participant using the Latin square randomised distribution of tasks. For the purposes of the study these individual files contained numbered tasks as opposed to the lettered denotation presented earlier. Accompanying the PowerPoint presentation was a blank workbook numbered 1-15 with a space for rough work and for the final solution. This can be seen in the participant solutions presented in Volume 2.3 Appendix 1.

Located at the bottom right of each blank worksheet was a nine-point symmetrical likert scale for rating the mental effort expended on each task. This was adopted from previous studies capturing evidence of cognitive load (Hoffman and Schraw 2009, Hoffman and Schraw 2010, Paas et al. 2003). The scale printed on each worksheet is illustrated in Figure 18

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3 Volume 2 is located on CD attached at the back of the thesis
This section has presented the philosophy and design of the problem solving tasks, which comprised the central stimulus of the research study. The next section will detail the exact implementation of the research study.

### 3.5 Implementation

The implementation of the pragmatic mixed methods approach was conducted in a laboratory setting (Figure 19) which students were familiar with from previous learning experiences. This setting was the same for all participants to reduce the potential influence of environmental affects during the gathering of data. During the implementation of the research study a research assistant (R.A) was recruited to assist with the data collection and interview conduction. This R.A was a postgraduate research student who was specifically trained by the researcher in the implementation of the method.
3.5.1 Recording Setup

In order to collect the EEG data a commercial EEG headset developed by Emotiv technologies, was utilised (See Figure 20). The headset consists of 14 sensors, which are placed at different locations on the scalp according to the international 10-20 system for electrode placement (Ward 2010). This system is illustrated in Figure 21 and displays the variety of cortical regions associated with different electrodes.

Figure 20: Commercial EEG Recording Headset by Emotiv

Figure 21: The System of Electrode Placement According to International 10-20 System
The odd number electrodes indicate sites on the left hemisphere of the brain and even numbers indicate sites on the right hemisphere. Electrodes CMS and DRL (Figure 21) are the references used for measurement. These are the ground signals and all electrical measurements in the process are in the form of potentials measured in comparison to the reference activity, which is assumed to be theoretically neutral or zero (Rowan and Tolunsky 2003). The data from the Emotiv headset is recorded at a frequency of 128Hz so there are 128 samples taken from each of the 14 recording sites every second. The voltage measured is in microvolts and is a mixed signal of neural and other activities, which are commonly deemed artifacts (Da Silva 2010).

The participants placed the headset on themselves and the researcher aided them with adjustments so that a good contact was found between it and the participant’s scalp. Once this was completed, the materials and process were explained.

In order to obtain an accurate EEG measurement the use of baseline interval recordings was selected. This process was adapted from a previous study by Esfahani and Sundararajan (2012) who used EEG activity to classify reasoning and comprehension of different geometric forms for use in a brain-computer interface programme. This process is a common approach used in EEG research (Pfurtscheller and Silva 1999), where a baseline fixation segment is used for comparison with the period of activity of interest. The baseline fixation recording in this study asked participants to sit still and view a neutral stimulus on the PowerPoint presentation for a period of time. The stimulus was a simple black coloured cross symbol approximately 100mm x 100mm similar in nature to the stimulus employed by Fink et al. (2009). This process is represented in Figure 22.
The separation of the signal into distinct segments of activity is useful for analysis purposes after the task. Normally this involves subtracting values in the fixation period from the activity period, which leaves an accurate measure of activity related to the task. This is the basis of the "task related power" (TRP) method described by Pfurtscheller (1992). Aligning with previous research from Fink et al. (2009), the first fixation period at the beginning of the session was 60 seconds in length and all subsequent fixation periods between tasks were 20 seconds in length. The rationale for allowing a longer period at the beginning is to allow the participant to become familiar with the process and to dampen the effect the visual nature of the environment may have on collection of data. This would ensure a more accurate calibration of each participant's cognitive data. The EEG data was collected using Emotiv software, which ran on the researcher's laptop using a wireless connection to the headset. Shown in Figure 23 is the recording setup of the problem solving session.
The webcam was positioned at a height of 270mm to ensure optimum visibility of the workbook and video capture software was running in the background behind the tasks, which were presented in the PowerPoint presentation. The materials, which were provided for students, consisted of a calculator, pencils and a setsquare. They were explicitly told that there was no necessity to use any of them except for the pencils and that they could approach the tasks anyway they desired.

3.5.2 Post-Task Interviews

As presented earlier in the chapter, two post-task interview sessions were utilised. One was conducted immediately following the problem solving session. This took the format of a semi-structured interview and was conducted to ascertain information of the participants' approaches and conceptions of the tasks. The interview schedule is located in Appendix 2.

The second follow up interview was conducted the following day. This was the shortest conceivable time following the period of activity in which the stimulated recall interview could take place. The visual data from the problem solving session needed to be reviewed and performance needed to be assessed prior to the
conducting of this follow up session. Performance scores were assigned to students’ solutions and three tasks were selected for the focus of the stimulated recall procedure. A task encompassing high, low and average levels of performance were selected.

An interview schedule, which followed a semi-structured format, was constructed for the interview session. During the session, participants observed the video of their performance in the various tasks and provided commentary on their approaches. This session was treated as more open where issues could be discussed as they were raised by the participant. The interview schedule for the stimulated recall can be viewed in Appendix 2. Both interview sessions were held in the same laboratory to minimise environmental influences (See Figure 24).

Figure 24: Research Assistant Conducting Follow-up Interview using Stimulated Recall

Both sets of interview data were transcribed and analysed using "open coding" (Cohen et al. 2007) and then "selective coding" (Bryman 2008) where categories and themes were allowed to emerge from the data.
3.5.3 Summary Stages of Data Collection

In summary, it is important to highlight the main stages of data collection once again. The participants positioned the headgear first and then this was adjusted by the researcher until a good contact signal with the software was established. The problem solving session then started and the behavioural activity was recorded using a webcam. The beginning of each problem was preluded by a fixation period to calibrate the participants' cognitive data. Once the problem was completed, students rated the mental effort they exerted and progressed to the next activity. Following all 15 tasks, participants were asked to participate in a brief interview about their performance and approaches. This was then followed up 24 hours later with an interview using a stimulated recall approach. These key stages of implementation are illustrated in Figure 25.

![Figure 25: Key Stages of Research Implementation](image)

3.5.4 EEG Data Analysis

This section will detail the analysis of EEG data used within the study. This is the first time this method has been utilised within technology education research in this context and warrants explanation.
3.5.5 Data Processing

Once the data has been gathered, it is stored in an Emotiv file format with a large DC offset. The large DC offset ensures the accurate wireless transmission of data from the headset to the software (Anderson et al. 2011). Pre-processing is therefore necessary to remove this DC offset and enable the viewing of the raw activity readings in microvolts. This is achieved using an established EEG analysis toolbox, which is built on the Matlab programming environment. "EEGlab" (Delorme and Makeig 2004) is a widely used analysis package, which is based on a graphical interface and does not require advanced knowledge of technical programming techniques which many other strategies employ.

Data from the recorded session is imported into Matlab and then opened in the "EEGlab" toolbox. A high and low pass filter are applied at a frequency of 0.16Hz and 50Hz respectively to remove the DC offset and high frequency artefacts such as motor movement which are unrelated to underlying cognitive activity recorded during the process (Esfahani and Sundararajan 2012). The result of this can then be viewed as a raw signal (See Figure 26).

![Figure 26: Raw Signal Plotted as Waveform](image-url)
Data is then visually inspected for continuous, high amplitude activity, which can be indicative of further artifacts or signal noise contaminating the cognitive signal (Da Silva 2010). An example of high amplitude signal noise is shown in Figure 27.

![Figure 27: Example of High Amplitude Signal "Noise"](image)

One of the core problems associated with the EEG is source localisation of neural activity. Despite the processing of data and removal of artefacts there are still possible contaminants present within the data as sources are difficult to separate from the entirety of the recorded data. This concept is known as "volume conduction" where activity from multiple sources are recorded at single electrode sites (Onton and Makeig 2006). The recorded activity is therefore a mix of underlying neural activity, indicative of possible cognitive activity, and contaminative sources such as eye blinks (Esfahani and Sundararajan 2012).

Delorme and Makeig (2004) devised an analysis function within the EEGlab interface based on independent component analysis (ICA) which has been shown to accurately separate the sources (Esfahani and Sundararajan 2012). As the emotiv headset has 14 sensors, it is assumed that there exists 14 independent source components (Esfahani and Sundararajan 2012). The resulting plots obtained after running ICA display the neural and contaminated sources. A typical eye blink component scalp plot is shown in Figure 28.
Once these artifacts are identified in the data it is a matter of removing them from further analysis.

### 3.5.6 Frequency Power Analysis

Once these sources have been plotted the components related to contaminated sources can be removed and the data remaining represents, as near as possible, the cognitive activity recorded as electrical signals (Delorme and Makeig 2004). Due to environmental interference and some minor muscular or pulse related activity it can never be absolutely decontaminated. When the data has been cleared of artifactual sources the signal is transformed from the raw microvolt recordings to frequency bands which have been shown to be related to different cognitive processes such as convergent/divergent thinking (Razoumnikova 2000), creative cognition (Molle et al. 1999) and memory (Osaka 1984).

This is achieved using a "fast fourier transform" (FFT) which decomposes the complex signal, gathered in the raw EEG, into its spectral elements (Freeman and Quiroga 2013). The frequency bands most utilised within EEG research are the theta (4-8Hz), alpha (8-13Hz) and beta (13-30Hz) frequencies (Fink et al. 2009, Klimesch 1997, Razoumnikova 2000). Matlab has an inbuilt FFT function, which allows the
output of graphical topographic scalp maps. These highlight the active locations for specified frequency bands. An example of these can be viewed in Figure 29.

Figure 29: Frequency Scalp Plot Illustrating Power Distribution

Values can tend towards the positive or negative but either way indicates power changes in that area. The closer the colour is to green, the less significant the activity in that area. This strategy will only provide a graphical output and although rich in terms of data on cognitive activity, it lacks the numerical data for statistical analysis.

In order to obtain this, a manual FFT calculation was undertaken. This was conducted using the analysis toolbox in excel and resulted in numerical values for power in each of the specified frequency bands. This will be presented in more detail in the findings.

3.6 Summary

The method, which has been presented in this chapter, resulted in the collection of distinct types of data as follows:
• Objective quantitative data of cognitive processing collected using the EEG headset and subjected to strict data processing techniques as defined in the literature.
• Visual data gathered during the recording of the problem solving episodes and the hard copy solutions produced by participants to the prescribed tasks
• Performance data gathered from students' hard copy solutions to the prescribed tasks and data generated from the application of principles of cognitive load theory
• Qualitative data from the interview sessions (post-task and follow up) which provided insight into the approaches adopted by participants and some of the underlying rationale for such approaches.

All of this data provided a rich source for investigation of the cognitive activity underlying the conceptual framing and subsequent approach to solving prescribed convergent tasks. This will be presented in the next chapter.
4 FINDINGS
4.1 Introduction and Layout of Chapter

This chapter will present the key findings arising from the research study. As a result of the quantity of data, which was generated during the implementation of the method, the chapter will be broken into key areas. The primary goal of the research study was to explore the possible relationship between task conceptualisation processes and performance. It was first necessary to gain an understanding of performance trends among the participants on particular tasks before investigating the cognitive evidence. Once overall performance was understood, it became necessary to investigate the particular cognitive functions that could have had a related impact on this.

The chapter has been broken into key elements and will be presented in the following order:

- Overview of Performance
- Conceptualisation and Approach
- Cognitive Behaviour and Efficacy
- Specific Cognitive Patterns
- Summary of Key Findings
4.2 Overview of Performance

All participants (N=12) were required to complete 15 tasks in total and were given a maximum of 5 minutes to complete each task. The overall performance scores were determined using the participants' hard copy solutions and the visual/verbal data gathered during the study. The solutions were assessed using a sliding scale of professional judgement, which is detailed in table 1.

<table>
<thead>
<tr>
<th>Marks Awarded</th>
<th>Sliding Assessment Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-10</td>
<td>Effective approach and correct solution</td>
</tr>
<tr>
<td>5-8</td>
<td>Reasonable approach (likely to lead to a solution)</td>
</tr>
<tr>
<td>4-5</td>
<td>Ineffective approach (unlikely to yield solution)</td>
</tr>
<tr>
<td>1-3</td>
<td>Incorrect approach (marks for attempt)</td>
</tr>
</tbody>
</table>

All participant solutions were assessed using this rubric and the full set of scores can be viewed in appendix 1. These scores were then further revised into the categories of 'successful' and 'unsuccessful'. Any solution achieving 5 or less was deemed unsuccessful and any solution with a score greater than 5 was deemed successful. This procedure aligned with the primary focus of the research study, which was concerned with efficacy of approach as opposed to solely achieving a correct solution. This binary analysis of performance is presented in Table 4.

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4 Solutions were scored based on the likelihood of achieving a correct solution with the approach evidenced both in the hard copy solution and in the visual/verbal data.
Table 4: Detailed Breakdown of Binary Performance by Participant and Task

<table>
<thead>
<tr>
<th>Task</th>
<th>Part 01</th>
<th>Part 02</th>
<th>Part 03</th>
<th>Part 04</th>
<th>Part 05</th>
<th>Part 06</th>
<th>Part 07</th>
<th>Part 08</th>
<th>Part 09</th>
<th>Part 10</th>
<th>Part 11</th>
<th>Part 12</th>
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<th>Failed</th>
<th>%Pass</th>
<th>%Fail</th>
</tr>
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<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>9</td>
<td>3</td>
<td>75</td>
<td>25</td>
</tr>
</tbody>
</table>

Passed | 7       | 8       | 9       | 13      | 11      | 9       | 9       | 11      | 8       | 7       | 9       | 8       | 7      | 9      | 8     |
Failed | 8       | 7       | 6       | 2       | 4       | 6       | 6       | 4       | 7       | 8       | 6       | 7       |        |       |       |
%Pass   | 46.67   | 53.33   | 60      | 86.67   | 73.33   | 60      | 60      | 73.33   | 53.33   | 46.67   | 60      | 53.33   |        |       |       |
%Fail   | 53.33   | 46.67   | 40      | 13.33   | 26.67   | 40      | 40      | 26.67   | 46.67   | 53.33   | 40      | 46.67   |        |       |       |

Note. 1 = ‘successful’, 0 = ‘unsuccessful’
Figure 30: Participant Performance

Figure 30 outlines the performance based on the percentage of successful and unsuccessful approaches for each participant in the study. As can be seen, the overall performance was poor when the age and educational level of the participants in the study are taken into account. Participant 4 achieved the highest success rate at 87%, whereas participants 01 and 10 achieved the lowest rates at 47%. A more detailed analysis of participant performance is presented in Table 4. Presenting the data in this manner allowed a clearer picture of participant performance during the study to be obtained.

Participants 3, 6, 7 and 11 displayed similar performance where all students achieved 9 successful responses and 6 unsuccessful responses. This represented the most common ratio of success to failure. Participants in this study achieved success and failure on different tasks apart from two in particular which will be discussed in the next section.

It is important to explore these performance results in relation to students' general ability as evidenced by their performance within the degree programme. This will aid in further contextualising the performance of participants. These students gained
entry to the degree programme with a minimum requirement of 430 CAO points\(^5\), which is equivalent to a B grade average. Within their undergraduate studies, these students have performed successfully, progressing to the third year of their studies and achieving a cumulative quality credit average (QCA) of 2.72. This is equivalent to an average grading performance of between a C1 and B3. Students must record at least a QCA of 2 per semester in order to progress to the next stage of their studies.

The QCA values of the participants (n=12) within this study had a small standard deviation of 0.312 and were normally distributed as indicated by a Shapiro-Wilk test significance value of \(p=0.962\). These students are therefore of average ability and on average their performance mirrors that of year three students. It is important to note that these students willingly volunteered to participate in the study during their spare time so lack of motivation should not be a variable of concern within the data. To assess whether there was any relationship between participants’ level of QCA and performance on the tasks utilised within the study a Spearman correlation was conducted. There was no significant relationship found between level of QCA and performance \((r = .063, n = 12, p = .846)\) on the tasks within this study.

### 4.2.1 Performance Statistics for Tasks

The previous section presented the overall performance of all twelve participants. This section will look specifically at the performance of participants on particular tasks. Figure 31 illustrates the performance when task is considered as the independent variable. The full set of tasks utilised within the study can be seen in Appendix 1. For the purposes of clarity, the tasks were segregated into their categories (mathematical, visual and non-specific) and reordered from most successful to least successful within each category. Included under each of the task labels (x-axis) are brief descriptors of the nature of the task. These descriptors are discussed in more depth in the method (Table 2).

\(^5\) These were the minimum CAO points for entry in 2011 which was the year these participants entered the course
The simple arithmetic/image holding and comparing task (G) was completed successfully by all participants whereas the probability/image holding and comparing task (J) was not completed successfully by any of the twelve participants.
Figure 31: Performance by Task
Depicted in Figure 31 is the breakdown of time taken to complete each task represented as a box plot to illustrate the spread of values obtained. Performance is also represented in the graph for comparative purposes.

The *image holding and comparing and planar rotation* tasks L and M recorded the shortest task times on average (74.3s and 74.4s respectively) and were completed equally well with each achieving a success rate of 83%. The *algebraic* task (D) illustrated the highest average time at 242.4 seconds with just one of the twelve participants illustrating a successful approach. The standard deviation recorded for this task was also relatively high at 82.8, which indicates that there was a large spread of time values recorded for the task by the participants. The *probability/image holding and comparing* task (J) and *formulaic/image holding and comparing* task (I) were ranked in second and third for the longest times respectively.

An interesting finding is noticeable when considering the task times in relation to the performance scores. Participant 01 displayed a failure rate of 53% but displayed one of the shortest task times with a mean time of 95.8 seconds. This is similar to participant 09 who also displayed a poor performance (47% fail rate) along with the shortest mean task time of 82.4 seconds. This evidence indicates the participants were unaware of the effectiveness of their performance or that they may have given up on the approach.
Figure 32: Time Recorded on Task
4.2.2 Cognitive Load

One of the core areas of interest within the study was to investigate the efficacy of problem solving approaches based on the initial conceptualisation of a task. A critical area for consideration within this objective was cognitive load theory. The rationale for including cognitive load as a variable of performance is centred on the concept of efficacy of performance. There are multiple means of conceptualising different prescribed tasks, which are hypothesised to lead to different approaches of varying effectiveness. Aligning with the literature on problem solving efficiency (Hoffman et al. 2008), a more effective approach to a task would reduce the overall amount of cognitive load and lead to higher performance for a participant. It was therefore necessary to gain a measure of cognitive load for use in the study.

4.2.2.1 Effort Statistics

As discussed in the method chapter, subjective measures of cognitive load were collected for each task and participant using a 9-point symmetrical likert scale, rating the amount of mental effort required to complete a problem. This approach has been adopted in previous studies which have used cognitive load as a variable. A complete set of mental effort scores for participants and tasks can be seen in Appendix 3. The probability/image holding and comparing task (J) displayed the highest mental effort scores with a median of 7 being recorded. The largest range scores of 7 were found for the algebraic and kinetic imagery tasks D and O. This indicates that the 12 participants committed different mental resources to the completion of this task.

The simple arithmetic task (B) illustrated the lowest median effort score of 2 indicating that overall participants needed to allocate less mental resources to complete the task. Depicted in figure 4 are the mental effort scores for each task. A box plot format is used to illustrate the spread of rating values between tasks. Performance is also represented on the graph so possible relationships can be viewed.
Figure 33: Mental Effort Scores
The majority of tasks display a predominance of mental effort scores with values less than 5. This indicates likelihood that most participants perceived the tasks as low in terms of complexity. The probability/image holding and comparing task (J) recorded the highest mental effort scores and as can be viewed in Figure 33, displays a large clustering of values in the 5 to 7 range. The simple arithmetic (task B) and image holding and comparing and planar rotation tasks L and M display a clustering of values below a rating of 3 indicating that the majority of students believed these tasks were the least complex.

Observing the effort scores provided by each participant (Appendix 3), participants 2 and 3 had the highest median ratings of effort. This would indicate that these participants had to exert a higher level of mental effort to complete these tasks by comparison to the majority who took part in the study. Participants 5, 8, 9 and 10 exerted the lowest mental effort according to their median ratings of 2. Again this would indicate that these students had to exert significantly less effort overall to complete the prescribed tasks.

4.2.2.2 Effort and Performance

When considering the relationship between conception and capacity to perform in an educational task, it is important to take into account the relationship between effort and performance. Hoffman and Schraw (2010) suggest a useful technique to achieve this by computing efficiency scores for each participant. Efficiency is an important concept to consider within educational task design, as ultimately any task which is used, will be undertaken under certain constraints such as time (e.g. class period). It is therefore important to consider the efficiency of someone's approach to a problem as an indicator of his or her efficacy during an activity.

There exists a variety of methods for computing an efficiency score depending on the particular model adopted for the study. As discussed in the method chapter, “the likelihood model” proposed by Hoffman and Schraw (2010) was selected for the purposes of this study. This focuses on computing a value taking the ratio of
performance to another variable such as effort or time. The formula for computing the value is shown in Equation 1.\(^6\)

\[
E = \frac{P}{R}
\]

(1)

The result of applying this leads to a value being obtained for efficiency. The smaller the value, the less efficient a participant was during the problem. The maximum efficiency value which could be obtained in this study was 10 (10/1) whereas the lowest was 0.1 (1/9). The full set of efficiency scores can be seen in Table 5.

\(^6\) Where E = efficiency, P = performance and R = effort
### Table 5: Efficiency Scores

<table>
<thead>
<tr>
<th></th>
<th>Part 01</th>
<th>Part 02</th>
<th>Part 03</th>
<th>Part 04</th>
<th>Part 05</th>
<th>Part 06</th>
<th>Part 07</th>
<th>Part 08</th>
<th>Part 09</th>
<th>Part 10</th>
<th>Part 11</th>
<th>Part 12</th>
<th>$\bar{x}$</th>
<th>$\sigma$</th>
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<td>2.5</td>
<td>5</td>
<td>4.40</td>
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<td>5</td>
<td>0.5</td>
<td>2.5</td>
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<td>0.4</td>
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<td>-</td>
<td>0.14</td>
<td>0.67</td>
<td>0.33</td>
<td>0.38</td>
<td>0.43</td>
<td>0.5</td>
<td>0.33</td>
<td>0.5</td>
<td>0.5</td>
<td>0.25</td>
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<td>5</td>
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<td>3.13</td>
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<td>5</td>
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<td>1.24</td>
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<td>3</td>
<td>0.5</td>
<td>1.8</td>
<td>2.14</td>
<td>1.49</td>
</tr>
</tbody>
</table>

**Note.** All blank cells indicate failure to provide an effort score
Taking a task focus, the *probability/image holding and comparing* (task J), *algebraic* (task D) and *application of formula/image holding and comparing* (task I) illustrate the poorest efficiency scores respectively. This indicates that, in general, participants displayed a very poor efficacy of performance during these tasks. Again, to clarify the ratio of performance to effort was low. Participants had to exert higher amounts of mental resources and achieved poor performance results on these tasks. A plausible conclusion at this stage would be to consider the tasks outside the ability levels of the participants. However, these tasks were designed in line with PISA guidelines, which cater for ability levels of middle secondary level (15 year old) students so task difficulty should not have been a concern.

The most efficient approach to solving the tasks utilised within the study was evidenced by participant 08 with a value of 4.22. Participant 02 displayed a poor efficiency recording a score of 1.18, which illustrates a higher allocation of effort, compared with less gain in performance. The majority of efficiency scores range from between 1 and 2, so generally it can be inferred that the efficiency of problem solving approach was poor.

To explore further the relationship between performance and mental effort allocation a Chi-square test was conducted on all performance and mental effort scores. Performance was treated as a categorical variable where a successful score was indicated by a value of one and an unsuccessful indicated by a value of zero. A strongly significant association was found between performance and mental effort, $\chi^2 (8, n=178) = 29.043, p < .0001$. There was a large effect size indicated by Cramer’s $V = .404$. This indicates that, in general, where participants performed well they had to exert little mental effort to do so.

Time spent on task increased with poorer performance and the associated mental effort was rated higher. However, there were instances where low mental effort and less time spent on task were illustrated along with unsuccessful performance. This necessitated an analysis of participants' perception of performance.
4.2.3 Perception of Performance

Given the statistical significance of ratings of mental effort associated with performance, it was important to consider participant perception of the tasks. An analysis of the qualitative interview transcripts revealed a large amount of data supporting a conception of minimal complexity in relation to the tasks. Examples of these styles of comments are shown below. These comments are taken from the full set of post-task interview transcripts and follow-up interview transcripts located in Volume 2 Appendix 3. Participant 02 who displayed an average performance stated:

"... the tasks weren’t overly difficult I suppose but clarity in some of them would have been a little bit easier".

(Participant 02)

Participant 03 who achieved slightly better also indicated a perceived low-level complexity among the tasks:

"..... as far as problems go like straight away you could answer them straight away but there is a little bit of figuring out in them. But I wouldn’t say they were impossible”.

(Participant 03)

Participant 04 displayed the best level of performance stated:

"They were average they ....the majority of them were easy”.

(Participant 04)

There were some comments indicating diversity in terms of task complexity. Participant 05 performed above average:

"Grand easy enough besides that second last one or third last one I can even remember the task right now"

(Participant 05)

 Participant 11 who achieved an average level of performance reiterated this perception of varied complexity among the tasks:

"A few of them were puzzling enough. Now I thought I did okay but there probably a few of them going to be wrong”.

(Participant 11)
Participant 08 presented evidence in the interview, which indicates an expectation that the tasks should be more complex than they were. This participant achieved a reasonable level of performance.

"..... they were just very straightforward and I was kind of thinking there has to be more to this. Do you know?"

(Participant 08)

Participant 10, who performed poorly overall, initially stated that the tasks were generally low in terms of complexity but when given the chance to reflect he altered his opinion slightly.

"..... I had them ranked fairly low but maybe they were a bit more difficult than I thought"

(Participant 10)

As already indicated in the statistical analysis, low measures of mental effort were strongly correlated with high measures of performance. An important consideration in examining this relationship is the nature of the cognitive process on which the mental effort was exerted. The following participant comments, which are taken from the post-task interview transcriptions (Volume 2 Appendix 3), indicate that the low amounts of mental effort have been exerted on recalling from memory.

"The mathematical ones were just going through the formula Pythagoras theorem and stuff like that"

(Participant 05)

"There was two of them Pythagoras theorem so it was only a matter of filling in your values and calculating it..."

(Participant 06)

"I found some of those quite easier some of those using Pythagoras Theorem once I knew how to use that it was okay."

(Participant 12)

This indicates that where the mental effort recorded was low, that effort was placed on recalling previously learned mathematical procedures. Small levels of effort are associated with high performance. Therefore, when the participant was successfully recalling formulaic procedures the effort was deemed to be low. Conversely, there is
evidence within the qualitative data to suggest that high effort was exerted where a procedure could not be recalled.

"Yeah the shelf one required more, the last one say how many open top boxes, when I read it first I assumed it was either A, B or C and then I realised all three could be open topped..."

(Participant 09)

"Well the ones that I actually completed were grand minimal effort. It was just the one that there were three in it that kind of threw me off."

(Participant 07)

There is a variety of approaches occurring when considering the evidence in the previous comments. What is more interesting is when the perception and performance are taken together. There are a number of students who perceived the tasks to be quite low in terms of complexity but performed quite poorly. This is also evident where the mental effort and time spent on task are recorded as low but performance is poor. It is clear that there is some uncertainty among the participants about their own performances.

The evidence presented so far points to a mismatch between students' perception of performance and the mental effort allocated to the tasks. This necessitates the use of an objective measure of cognitive function to explore the true nature of the underlying approaches to the tasks.
4.3 Conceptualisation and Approach

4.3.1 Initial Data Exploration

The focus of the study is to explore the nature of conceptualisation and its relationship with performance. As already presented, there appears to be disparity between the perceptions of students' performance and the actual behaviour occurring during the problem solving episodes. This requires the use of an objective tool to further explore the underlying cognitive activity.

In terms of analysing an individual's conceptualisation of a given situation or task, there are a number of variables which may be considered. These include among others; epistemological orientation, learning styles and past experience (Barsalou, 2009). Taking a problem based learning perspective; a person's internal representation of a task/problem would provide significant insight into the nature of the conception. This internal representation was the focus of the cognitive investigation employed within this study.

As discussed in the method, cognitive activity was captured using an EEG headset and subjected to spectral analysis to decompose the data into frequencies. These frequencies are known to be associated with particular cognitive functions and are obtained using a Fast Fourier Transform.

The Fast Fourier Transform, which is used to decompose the signal into frequencies, is limited to calculating values based on a defined number of samples. In Excel the maximum number of data samples that can be catered for is 4096 presumably due to processing demands on the software or hardware. As the sampling rate of the headset is 128Hz or 128 samples per second, this value of 4096 equates to 32 seconds of data. However, this placed too large a processing demand on the hardware used within this study so it was decided to take samples of 2048 (16 seconds).
These limitations in data analysis caused concern, as there is no definitive evidence to suggest a time limit on an individual's construction of an initial internal representation. It was decided to take two samples of 16 seconds from the beginning of each task and then average the values. An average value of power for each frequency band (Alpha, Theta and Beta) was obtained for the first 32 seconds of every task. This provided a reasonable timeframe for analysis and in extreme cases (where the participant exceeded the time limit of five minutes) would provide at least 10% of the cognitive activity of the entire task period. This timeframe selection is in line with previous studies using FFT (Sun et al. 2013). Initially a conception-approach sketch for each participant across the 15 tasks was completed. An example of one of these is demonstrated in Figure 34.
Figure 34: Conception-Approach Sketch
This conception-approach sketch (Figure 34) encompasses a number of different elements. The topographic scalp maps are produced within the EEGLab environment within matlab and provided an overview of cortical activation sites for each defined frequency band across the entirety of the task. These are averaged values and display the location of the most active neuronal assemblies. The table titled *Subjective CL Efficiency* provided a measure of efficiency, which was discussed earlier in the chapter when considering performance. The second table provides the event related synchronisation as a percentage for the first 32 seconds of the task period. The negative values indicate a synchronisation or increase in cognitive activity from the fixation to task periods. Positive values indicate a de-synchronisation (decrease) from fixation to task periods. This approach is discussed by Pfurtscheller (1992) who explored alpha de-synchronisation as a key indicator of cognitive activity.

The graphs on the left of the sketch indicate the task related power (TRP) for each grouping of electrodes encompassing frontal, centrotemporal and parietooccipital areas. TRP was explored by Pfurtscheller and Silva (1999) and is computed using Equation 2.

\[
TRP (logPowi) = \log(Powi activation) - \log(Powi reference)
\]  

Applying this formula results in synchronisation and de-synchronisation values being obtained for each electrode and for each frequency band. These are then graphed for visual representation (See Figure 34). This gives a detailed account of activation patterns at each electrode for each individual task across the twelve participants. A complete set of these conception-approach sketches can be found in Volume 2 Appendix 6. To confirm that these sketches were capturing activity of a cognitive nature, a series of Wilcoxon Signed Ranks tests were conducted on the power values captured during the fixation and task periods. The tests were predominantly significant and indicated that different cognitive activity was being displayed during the tasks. These statistical results can be seen in Volume 2 Appendix 6. These provided a starting point for further data exploration.
4.3.2 Interpretation of EEG Cognitive Data

This section will present in detail the process of interpreting the data that was introduced in the previous section. In particular, it will explain the process of interpreting the synchronisation/de-synchronisation data and topographic scalp maps.

4.3.2.1 Synchronisation/De-synchronisation Interpretation

The synchronisation/de-synchronisation data was gathered in line with the TRP method first discussed by Pfurtscheller (1999). This involves subtracting the activity recorded during a neutral time period from activity recorded during a specific task or event. A neutral stimulus is normally used to focus the participants’ attention and dampen the potential effects of the task environment on the data collection process (Fink et al. 2009). This process was discussed previously in the method. It is important to note that the neutral activity for each participant is different in terms of cognitive patterns and amplitude. Utilising this neutral activity period for analysis purposes allows accurate calibration of the EEG device on an individual participant basis.

After the neutral period of data is subtracted from the activity of interest the resultant is the task related synchronisation (increase) or de-synchronisation (decrease). This can be completed per sensor which total 14 or as was the case in this study for groups of sensors. The rationale for creating groups of sensors is to reduce the effects of "volume conduction" on the data (Rowan and Tolunsky 2003). Volume conduction is a phenomenon where multiple sensors may register the cognitive data, which is being emitted from a single source within the cortex. This has implications for data analysis as it may lead to inaccurate inferences being made regarding the location of the cognitive activity. Within this study, 6 groupings were used which encompassed the frontal, centrotemporal and parietooccipital regions across both hemispheres (left and right). This is displayed in Figure 35.
It is useful for interpretation purposes to consider briefly the various cognitive functions associated with each area.

- **Frontal Left**: Typically associated with working memory functions particularly those addressing analytical or phonological processes
- **Frontal Right**: Also indicative of working memory processes and particularly active during visuospatial processes
- **Centrotemporal Left**: Associated with long-term memory processes, particularly episodic processes when theta is synchronous in this area and semantic processes when alpha is de-synchronised in this area
- **Centrotemporal Right**: Generally associated with long-term memory for specific visual objects
- **Parietooccipital Left**: Associated with long-term recall when theta is synchronous in nature in this region and visuospatial cognition (mental rotations) when alpha is de-synchronised in this area
- **Parietooccipital Right**: Indicative of visuospatial cognition particularly the generation and manipulation of visual mental imagery
During the FFT calculations, values are obtained for the power of the theta and alpha frequencies at each sensor. To obtain the grouped values an average was calculated for all the sensors contained within each of the 6 groupings. For display purposes, these values were then converted to percentage synchronisation/de-synchronisation and presented in bar chart format as is shown in Figure 36.

![Figure 36: Synchronisation/De-synchronisation Graph for Theta and Alpha Frequencies](image)

It is important to note that these graphs (Figure 36) only refer to data gathered during the first 32 seconds of the task. The colours of the bars refer to a particular zone in the cortex as illustrated in Figure 35. This indicates activity occurring in that area. The next stage in interpreting these graphs is to ascertain whether the data is synchronous or de-synchronous in nature.

Synchronisation (positive increase) in the theta frequency is a known indicator of cognitive activation (Klimesch 1999). This is the opposite within the alpha frequency where de-synchronisation is known to be associated with cognitive activation. Both frequency bands typically indicate different types of cognitive process depending on the location of the activity on the scalp. For example, theta generally indicates activation of memory related process such as episodic recall in the left centrotemporal area and working memory activation when it is located in the
frontal areas (Klimesch 1999). Alpha generally refers to semantic recall in the left centrotemporal areas and visuospatial cognition in the parietooccipital areas (Cabeza and Nyberg 2000). Another pattern to note is the relationship of synchronisation and de-synchronisation between the theta and alpha frequencies. Generally, as cognitive load in an area increases, theta synchronises whereas alpha de-synchronises. Therefore, as is clear in Figure 36, the right parietooccipital region is indicating significant activity as it is synchronised in the theta frequency and de-synchronised in the alpha frequency.

In addition to presenting the synchronisation-de-synchronisation data, an additional graph was provided to clarify the amount of different types of cognitive activity occurring during a task. These graphs encompassed indicators of visuospatial cognition, working memory, episodic and semantic long-term memory processes. These graphs were created for representative purposes and were calculated using the synchronisation/de-synchronisation data values relevant to specific cognitive processes as defined in the literature. These are as follows:

- **Visuospatial Cognition:** Related to de-synchronisation within the alpha frequency located in the parietooccipital regions (Cabeza and Nyberg 2000, Rescher and Rapplesberger 1999). Therefore, the values in alpha for these regions were added and the negative value was removed for presentation.

- **Working Memory:** Indicated by theta synchronisation in the frontal areas (Klimesch 1999) so the values in theta were added for these regions.

- **Episodic Memory:** Indicated by theta synchronisation located in left centrotemporal sites (Cabeza and Nymberg 2000, Klimesch 1999). The theta value for this area was taken to represent this function.

- **Semantic Memory:** Related to alpha de-synchronisation within left centrotemporal locations (Klimesch 1999) therefore, the alpha value in this site was taken to represent this function. Once again, the negative value associated with de-synchronisation was removed for presentation purposes.

Here, positive values indicate implementation of that cognitive process whereas a value of zero illustrate that this processes was not evident in the data. Illustrated in
Figure 37, is the format in which this data was presented. The synchronisation/de-synchronisation data is illustrated in the left of the figure and the indicators of cognitive processes are located underneath. On the right of the figure is a topographic illustration indicating the active sites associated with these cognitive processes. As is shown in Figure 37, semantic memory is indicated, as it is de-synchronous in nature and confined to the left centrotemporal sites as shown in the topographic illustration.

Figure 37: Sample of Conceptualisation Data Indicating Type of Cognition and Location

4.3.2.2 Interpretation of Topographic Scalp Maps

This section will deal specifically with the interpretation of the topographic scalp maps. These are produced during the data analysis stage within the Matlab software environment. The synchronisation/de-synchronisation graphs were calculated in reference to a neutral activity period. This was not the case for the topographic scalp maps as these were utilised to observe changes in cognitive patterns with regards location of activity during the task period. Therefore, the data that is referred to in
the topographic maps may highlight areas, which are not task relevant if they are interpreted without the synchronisation/de-synchronisation data (Figure 37). A sample topographic plot for the alpha frequency for the same participant (08) throughout a task is illustrated in Figure 38.

![Figure 38: Topographic Scalp Map Displaying the Alpha Frequency for Participant 08 during Task A](image)

The alpha frequency encompasses values from 8-13Hz and a range of these values is plotted above. The rationale for this is to capture a wider range of frequencies within alpha that can demonstrate whether changes are occurring, at any frequency level, in patterns during the task. The colours displayed in the above figure indicate cortical activity occurring in specific areas of the brain. The brighter the colour becomes the higher the level of activity that is occurring in those areas. The blue colour references a negative type of activity and a red colour indicates a positive type of activity (See Figure 39). In either case, this indicates a location for the activity at a defined frequency. The green colour indicates a lack of activity in those specific areas of the cortex. Figure 38 presents distinct stages of the task beginning with the first 32 seconds, which is referred to as the conception period. This is the same
period of data analysed in the synchronisation/de-synchronisation graphs presented earlier.

Figure 39: Spectrum of Frequency Activity in Topographic Maps

Semantic memory was indicated for participant 08 in Figure 37 and this is located in the left centrotemporal area within the alpha frequency. Looking at the topographic activity throughout the task now (Figure 38), it can be seen that this left centrotemporal area is active in alpha throughout the entire task. This indicates that this process was utilised throughout the task and that the participant did not alter their cognitive strategy. It is important that the synchronisation/de-synchronisation data is interpreted first to determine the conceptual activity and then the topographic maps are interpreted to observe any changes in cognitive pattern during the task.

The next section will now explore some of the evidence that was uncovered during the analysis stages of the research study.

4.3.3 Relationship between conception and approach

Before further exploring the nature of the conceptualisations constructed by participants during the study, it is necessary to examine the relationship between the initial representation and the overall approach. This proved a difficult analysis as there is no evidence to suggest a time period for a person's construction of an internal representation during a problem-solving episode.

In order to observe cognitive patterns from an EEG signal the frequency and primary location of the activity on the scalp are the two indicators of primary significance. Both of these variables can be seen when plotted as a topographic map as illustrated previously in Figure 38. The primary question involved in this element of analysis is whether the initial cognitive pattern in representing the task varied from the overall cognitive pattern over the entirety of the task. It was decided to use topographic
scalp maps plotted using increments of time from each problem-solving episode for each participant.

The problem solving episodes were analysed in incremental steps. First, the conceptualisation period of 32 seconds was calculated as a percentage of the total task time. Then this was plotted as a topographic scalp map. Then three further increments normally at 50, 75 and 100 percent were taken to provide an overview of cognitive patterns that occurred during the entirety of the problem-solving episode. The reason for taking cumulative time samples is due to a necessity to view the nature of cognitive patterns over the duration of a task.

The rationale for selecting such period lengths is based on two factors. Firstly, the time spent on each task varies between participants with some spending markedly less time on tasks than others. This coupled with a maximum time on task of 5 minutes means that there is not a large period of EEG data in total. Secondly, reducing the data windows, which comprise the FFT analysis, increases momentary accuracy and is the basis of event related potentials research (Freeman and Quiroga 2013). This research typically investigates the neurological activity triggered by the onset of a stimulus such as an image (Banich and Compton 2011). As this study is interested in patterns of cognition in relation to a task, minor windows were inappropriate. It was thought the smaller time windows would be more susceptible to stimulus effects and potential artifacts and possibly compromise the reliability of the data. What was of core interest in this particular study was the pattern of cognitive activity across a task period and this would require a more substantial sample period.

On further consideration of the pertinent literature on spectral analysis for cognitive research, it was decided to exclude the beta frequency from further analysis. This band is not well defined in terms of associated cognitive functions within the pertinent literature (Klimesch 1999). The Beta band can also contain artifacts which

\[7\] At times the conceptualisation period of 32 seconds exceeded 50% of the data for the entirety of the task.
are difficult to remove due to the high frequency composition which have been shown to be associated with functions such as physical movement and eye blinks (Da Silva 2010).

Theta and Alpha frequencies were selected as the primary focus for cognitive analysis. Theta and alpha have been shown to be highly correlated with specific cognitive functions, especially working memory and visualisation (Klimesch 1999, Razoumnikova 2000). They have also been shown to be highly sensitive to specific task demands (Antonenko et al. 2010) and therefore specific cognitive actions taking during a problem solving episode would be illustrated in theta patterns. In order to increase reliability a range of theta and alpha values from 4-8Hz and 9-13Hz were calculated and output as topographic maps. Any changes in location of activity from the initial conceptualisation period of 32 seconds would be illustrated across the topographic maps for later segments. This indicated whether the overall cognitive activity differed from that gathered during the initial task representation phase.

Topographic maps for both the theta and alpha frequencies across all tasks and for every participant were generated. Samples of these are shown in the following figures.
Figure 40: Theta Activity across Application of Theorem Task (A) for Participant 01
Figure 41: Alpha Activity across Application of Theorem Task (A) for Participant 01
Figure 42: Theta Activity across Identification & Application of Theorem Task (E) for Participant 02
Figure 43: Alpha Activity across Identification & Application of Theorem Task (E) for Participant 02
Figure 44: Theta Activity across Simple Arithmetic/Image Holding and Comparing Task (G) for Participant 05
Figure 45: Alpha Activity across Simple Arithmetic/Image Holding and Comparing Task (G) for Participant 05
Figure 46: Theta Activity across Dynamic Imagery Task (N) for Participant 08
Figure 47: Alpha Activity across Dynamic Imagery Task (N) for Participant 08
A sample of these topographic comparisons can be found in Appendix 4 and are taken from an entire task within the dual approach category. The full data set is located in Volume 2 Appendix 2. As can be seen in the previous figures, there is very little variation in cognitive patterns when the initial conceptualisation period is compared to the latter periods of the problem-solving episode. This indicates that the predominant cognitive activity, which occurs throughout the entirety of the task period, varies very little from the initial pattern of cognition during conceptualisation. This suggests that there is a significant relationship between the nature of the conception that is constructed and the overall approach to the tasks.

This relationship is also supported in the qualitative comments gathered during the interview stages of the research study.

"How you interpret the problem, may be your interpretation of the problem influences what approach you take."
(Participant 02)

"I was kind of forming the approach in my head... it was immediate reaction to jump to algebra once I read the question it was I suppose from other questions I might have done before the approach I would have taken."
(Participant 02)

The above comments taken from the same participant in both interview sessions indicate a belief in the relationship between conceptualisation and approach. Interestingly past experience is presented as a possible influencing factor during the conceptualisation period.

R: "How did you conceive the task?"

Participant: "I thought it was going to be simple because I was going slow there thinking that it was going to be okay, but then as I done my first two steps going eastwards and then southwards, I seen all the different possibilities that I could use to actually get to B."

R: "So if you were to describe your actual approach to solving the question?"

Participant: "...just kind of highlighting the line in my head, I can remember."
(Participant 07)
As can be seen in the above participant’s comments there is a direct relationship between the initial conception indicated by "seeing different possibilities" and the description of the approach. A visual conception would appear to have initiated a visual approach to this task for this participant.

"I think you build up a picture of what you have; the information given ... the first thing you have is a development A, B and C... Then the next bit of information was which one would be the development of an open topped box"  
(Participant 03)

The commentary of participant 03 indicates a process through the problem solving episode. This begins with a conception of the task ("I think you build up a picture of what you have...") and proceeds through a number of subsequent and related iterations.

The evidence presented here indicates the conceptualisation of a task has a direct bearing on the approach that an individual will adopt when faced with a problem. This is indicated by the lack of variance between cognitive patterns throughout different stages of the task period.

So it can be seen in the evidence presented that there is a relationship between the cognitive activity which occurs during the conceptualisation period and activity throughout the entire task. This appears in the majority of participant topographic plots for all tasks and is occurring regardless of the performance outcome. This indicates a trend of cognitive rigidity in the approach adopted to solving convergent problems. The data reveals that once participants conceptualise a task, they then pursue a solution with the same style of cognitive actions and do not alter their strategy. The data presented in the topographic analysis (Appendix 4 and Volume 2 Appendix 2) support this theory. As can be seen in Appendix 4, the cognitive patterns between participants are idiosyncratic but when the time periods for a participant are considered there is little variance.
4.4 Cognitive Behaviour and Efficacy

4.4.1 Introductory Remarks

Following the investigation of variance in cognitive patterns in participants' problem solving episodes it was necessary to take a specific look at the nature of the cognitive activity. The first stage in this element of the analysis was to determine whether any trends or patterns in cognitive activity were evident during the conceptualisation stage.

In order to achieve this all task synchronisation/de-synchronisation data for the conceptualisation period (32 seconds) was graphed as illustrated in Figure 48. The data encompasses six sensor groupings moving from frontal to posterior regions and across both hemispheres. This was explained earlier when interpreting the cognitive data was discussed. A full set of these exploratory graphs can be located in Volume 2 Appendix 5.

![Cross Participant Comparison Task A (Theta)](image)

**Figure 48: Application of Theorem Task (A) Participant Comparison for Theta Frequency**

The culmination of this initial process did not demonstrate any clear patterns of activity within the EEG data across tasks or participants for the conceptualisation stage of the tasks. Therefore, the evidence so far suggests that participants
demonstrated different cognitive patterns during the conceptualisation of tasks. However, participants generally demonstrated the same pattern of cognition throughout the tasks after the construction of the conceptualisation as was indicated in the lack of variance in cognitive activity in the topographic maps.

This section will look specifically at the nature of the cognitive activity, which is occurring during the participants’ conceptualisations using the synchronisation/de-synchronisation data. As was presented previously, there is evidence to support a relationship between the conceptualisation of a task and the overall cognitive approach taken to the problem-solving episode. Therefore, it is important to explore the nature of the activity to gain an understanding of the relationship to efficacy of performance.

All tasks were analysed originally using the topographic outputs. For the purpose of clarity, a selection of three tasks will be presented in this section. In selecting the tasks for analysis the hypothetical approach groupings (mathematical, visual and dual approach) were considered. In total six tasks were selected for analysis, two from each grouping. This allowed the researcher to investigate the nature of the cognitive activity occurring during different tasks.

4.4.2 Mathematical Category

4.4.2.1 Application of Theorem Task (A)

This task required students to calculate the height of a television screen when given a width and diagonal length. See Appendix 1 for a full set of tasks. The most effective solution would be the application of Pythagoras’ theorem to calculate the missing variable. The performance stats for task A indicate that there was a 75% success rate.

4.4.2.1.1 Successful Approach

Participant 08 was selected for analysis as they succeeded at the task and recorded an efficiency score of 5. This indicates that this participant was effective, showcasing
high performance for low mental effort. Figure 49 illustrates the EEG synchronisation data for theta and alpha for participant 08. This graph is taken from the same larger data set located in Volume 2 Appendix 4, which contains all EEG synchronisation data for all participants.

Immediately noticeable is the complete desynchronisation (decrease) of theta activity as shown on the left of Figure 49. Activity in the theta frequency has been shown to be strongly associated with memory functions and in particular working memory (Klimesch 1999). This indicates a low level of cognitive load exerted on this participant's working memory system.

Looking to the alpha frequency now, it is evident that there is a significant amount of desynchronisation (decrease) of activity. This is notable as the desynchronisation of locations within the alpha frequency is known to be correlated with the activation of specific cognitive functions (Fink et al. 2009). Within alpha, desynchronisation is shown to correlate with semantic memory performance, which relates to the
recollection of specific facts and knowledge (Klimesch 1999). Activity in the left centrotemporal area is most notable as this supports the use of semantic memory as is indicated in the topographic diagram in Figure 49. As is also clear in the topographic plots for this participant, cognitive activity remains similar through all stages of the problem-solving episode (See Figure 50 and Figure 51). The activity in the left centrotemporal area remains highly active during the entirety of the task.
Figure 50: Theta Activity across Application of Theorem Task (A) for Participant 08

Figure 51: Alpha Activity across Application of Theorem Task (A) for Participant 08
The predominance of activity in the left hemisphere supports the use of a semantic memory process. The left frontal and central areas have been shown to be activated during semantic memory tasks (Klimesch 1999). This possible reliance on memory is also evident when looking at the participant’s solution (Figure 52). Illustrated is a competent application of a known theorem.

Looking at this participant’s commentary during the interview sessions a reliance on memory was evident in many of the problems. When asked during the post task interview about the general approach adopted to solving the tasks the participant states:

"...I probably knew that answer at the start but then probably do a bit of maths..."

(Participant 08)
There was also a suggestion of an element of conditioning in the individual’s conceptualisation potentially as a result of school experience.

"...you’d be doing a lot of maths problems even in secondary school..."

(Participant 08)

In the follow up interview using a stimulated recall approach the participant described the overall approach adopted as generally visual:

"...my first port of call probably for all the problems was visualisation..."

(Participant 08)

This statement is actually contradicted by the EEG evidence presented in Figure 49 as there is no indication of a visuospatial process being engaged. As is evident in this comment, it would seem that the particular conception this participant had of the tasks was focused on recalling past information of a semantic nature.

Evidence of a reliance on previous experience and in particular school experience was found in a number of participant commentaries. Participant 01 was asked about the familiarity of the tasks and whether this might have had an effect on the approach adopted:

"Yeah maybe from school you kind of go into a bank of memory rather than maybe trying to work it out..."

(Participant 01)

Participant 02 indicates a strong influence of the nature of learning within second level on the current performance:

"...I suppose it was...driven into me from that stage (school)..."

(Participant 02)

This reliance on past memory was most clear in discussion with participant 06 who was referencing the overall approach to the 15 assigned tasks.

"Parts of it I just couldn't remember I don't know why..."

(Participant 06)
A reliance on past experience is a common occurrence among many participants as is evident by the commentaries discussed. Looking at participant 09 (Figure 53) a slightly different pattern of cognitive activity is seen during the conceptualisation. Participant 09 was selected for displaying the highest efficiency value of 9 during the task. Within theta, there is significant activity in the centrotemporal areas and the left parietooccipital area. The left parietooccipital area has been shown to incorporate various retrieval functions in long-term memory (Banich and Compton 2011). The type of memory activated during this participant's conception is likely different to that of the participant 08. The memory function associated with synchronisation of the theta frequency is known to be related to either working memory or episodic recollection (Klimesch 1999).

![Participant 09 Task A](image)

![Breakdown of Cognitive Processes](image)

**Figure 53: Participant 09 Application Theorem Task (A) Synchronisation Data**

However, a significant difference in this individual’s conception is the desynchronisation of alpha activity in the right parietooccipital areas. The right parietooccipital area is significantly involved in visuospatial processes, which have
been known to be a key component of successful mathematical performance (Tversky 2005b). The left frontal area is a known area for functions of working memory and in particular mathematical and analytical processes (Houdé and Tzourio-Mazoyer 2003). This would be expected in a task of this nature.

Theta activity shows activation in the left parietooccipital area (Figure 54). This activation of the left parietooccipital area indicates the recollection of Pythagoras’ theorem as is shown in the hard copy solution (Figure 56Figure 54). However, noticeable in Figure 53 is the activation of the right parietooccipital area within the alpha frequency. This is especially noticeable at the higher end of the frequency band in the topographic maps which is known to be implicated in specific cognitive processes such as visualisation (Rescher and Rapplesberger 1999). The nature of the memory implicated in this participant’s approach could be episodic given the relationship of theta to episodic memory (Klimesch 1999).
Figure 54: Theta Activity across Application of Theorem Task (A) for Participant 09

Figure 55: Alpha Activity across Application of Theorem Task (A) for Participant 09
Looking at the solution in Figure 56 it is immediately noticeable that the hard copy reflects a larger emphasis on the use of a visual representation prior to application of a formula.

![Participant 09 Solution for Application of Theorem Task (A)](image)

**Figure 56: Participant 09 Solution for Application of Theorem Task (A)**

The use of a visual approach is more likely when the commentary from this participant’s interviews is taken into account. There is evidence to suggest that a visuospatial approach was taken during the problem-solving episode:

"I didn’t even look at the question first I just looked at the pictures. And then I looked at the question, once I read the question I kind of had the answer in my head"

*(Participant 09)*

When asked to describe the overall approach adopted to the 15 tasks there is again a strong indication of a visuospatial approach. The approach seems to take the form of a "bottom-up" process where a visual representation is used to facilitate further reasoning (Tversky 2005b).
"...Just drawing them out basically, just putting it straight from what’s in my head to paper and work from that..."

(Participant 09)

The previous comments were extracted from both of the participant’s interview sessions. Both indicate a reliance on a visual approach during the conceptualisation stage of the task. This supported the student in progressing the solution for this particular task possibly through access to episodic memory as is alluded to in the EEG data.

4.4.2.1.2 Unsuccessful Approach

Looking specifically at an unsuccessful approach now, Figure 57 illustrates the cognitive activity for participant 03 during task A. This participant displayed an efficiency score of just 0.71, which was very poor. There is again a different pattern of cognitive activity being displayed for this participant. The majority of theta is demonstrating a pattern of de-synchronisation apart from the left centrottemporal area. This is indicative of a memory function as it is the sole synchronised activity for theta in this task. As it is not located in the frontal areas, which are the known seat of working memory (Stillings et al. 1995), it is likely an episodic style of memory. The predominant activity in the alpha band is a de-synchronisation in the frontal areas with increased activity in the left frontal area. This points to the expending of effort on an analytical function of working memory. This is supported in the interview commentary, which is presented later in the section.
Looking at the topographic maps for this participant in Figure 58 and Figure 59 it can be seen that theta activity shows a large trend of activation in the left centrotemporal and parietooccipital areas throughout the entirety of the task. This would align with the previous hypothesis of a reliance on recall. Alpha activity (Figure 59) displays some activation in the right parietooccipital area which indicates a visual element of cognition. It could also indicate the blocking of visual strategies as alpha activity has been shown to block specific cognitive functions depending on task demands (Klimesch 1999) and is synchronised in Figure 57.

**Figure 57: Participant 03 Application of Theorem Task (A) Synchronisation Data**
Figure 58: Theta Activity across Application of Theorem Task (A) for Participant 03

Figure 59: Alpha Activity across Application of Theorem Task (A) for Participant 03
As already stated, this participant was unsuccessful. One of the core reasons for this lack of success is an inability to accurately recall the procedure. This is reflected in the participant’s hard copy solution (Figure 60) where it is clear that the formula was applied incorrectly.

![Participant 03 Solution for Application of Theorem Task (A)](image)

**Figure 60: Participant 03 Solution for Application of Theorem Task (A)**

Participant 03 was unsuccessful at the task and the cognitive evidence points to the role of a memory function during the conception and subsequently throughout the entire task.

“And then there was another one where it was a square you were given the diagonal length or a rectangle length but if you misjudged it and didn’t see that you could make it into Pythagoras theorem and make it into a triangle”.

*(Participant 03)*

As is evidenced in this comment by participant 03, there was a clear recognition that the solution to the task would involve application of a theorem. So the conception was based on a mathematical approach but involves a great deal of memory in recognising Pythagoras’ theorem. This is an appropriate conceptualisation of the
task but could not be completed as the student could not recall correctly the application of the formula. Participant 03 alluded to a higher level of complexity in the tasks when the theorem could not be recalled:

"...I suppose unless you didn't know...basic formulas of area conversions or whatever you might have a very low score"

(Participant 03)

This recognition of the importance of knowing the exact theorem and recognising it for the tasks prescribed was evident in a number of participants' commentaries.

"You would have to know what kind of formulas or what way you are going to go about the actual question"

(Participant 11)

"...questions that I would have had to think about...and recall what I have learnt before would have taken more mental effort"

(Participant 02)

So as can be seen in the evidence presented in this section there are a variety of cognitive approaches evident in participant solutions. These approaches relate predominantly to functions of memory where episodic and semantic evidence has been presented.

4.4.2.2 Algebraic Task (D)

Task A was completed with a reasonable pass rate of 75%. As was presented in the previous section, there were a number of variances evident in participants’ cognitive patterns. However, a general reliance on memory during the conceptualisation was found. It is now worth considering a task where the majority (92%) displayed an unsuccessful approach.

This algebraic task (D) asked students to calculate the area of a lawn after it had been extended under certain conditions (See Appendix 1). The most effective approach to obtain this solution was the application of a binomial function using algebra to obtain the missing variables. This is a common concept, which is taught in second level mathematics courses.
4.4.2.2.1 Unsuccessful Approach

As all but one of the participants failed, the unsuccessful approaches will be considered first.

Figure 61: Participant 07 Algebraic Task (D) Synchronisation Data

Figure 61, illustrates the synchronisation data of participant 07 during the task. This participant illustrated an efficiency value of .43. As presented, there is a significant amount of synchronisation within the theta frequency located in the left parietooccipital area. This area has already been presented as a key region within the theta frequency in recalling past information (Banich and Compton 2011). Again, there is synchronisation evident in the left centrotemporal area, a key location for processes of long-term memory. There is a similar level of synchronisation evident in the frontal areas within theta. These are key regions for working memory processes (Cabeza and Nyberg 2000).
This pattern of activity indicates a focus on long-term recollection of information and given the high level of theta synchronisation it is likely episodic in nature. The focus was potentially on trying to recall a past occurrence of a similar situation. There is also notable de-synchronisation in the right parietooccipital area within the alpha frequency. This indicates the involvement of a visuospatial cognitive process during the conceptualisation stage.

This particular cognitive process is also evident throughout the duration of the task as can be seen in the topographic plots in Figure 62 and Figure 63. This is particularly noticeable by the right hemisphere activity in the alpha frequency. Notable within the theta frequency is the constant activation of the left parietal areas throughout the entirety of the task. This data and previous research (Cabeza and Nyberg 2000) would indicate that this participant was attempting to recall a process from memory.
Figure 62: Theta Activity across Algebraic Task (D) for Participant 07

Figure 63: Alpha Activity across Algebraic Task (D) for Participant 07
Evidenced in the hard copy solution produced by participant 07 (Figure 64) is a significant amount of sketched representation. This sketch behaviour is potentially the manifestation of the visuospatial process alluded to in the EEG synchronisation data (Figure 61). Considering the solution produced and the nature of the theta synchronisation it is probable that the visuospatial representation process used facilitated an episodic process. To clarify the visual process activated an episodic recall for the participant where he recognised the situation but could not recall the exact process (semantically).

“Well I got the garden that...increased it in size by three and two. And then I knew that the top right hand corner of the garden it was going to be two metres by three metres... probably towards the end I was probably looking more into a quadratic equation...”

(Participant 07)
As can be seen in the commentary for this particular question there is an emphasis on utilising a visual approach to build a representation of the problem. After this was built, it the participant was trying to recall a process from past experience ("quadratic equation"). This suggests that the visual approach used in building the conceptual model was utilised to aid in recollection from memory.

The EEG synchronisation data for participant 10 is shown in Figure 65. This participant achieved only slightly better with an efficiency score of 0.5. Again, this participant was also unsuccessful at the task but interestingly displayed a relatively short time on task of 97 seconds. This is unusual as one would expect a participant who is having difficulty with a task to expend a larger amount of time on task. Another notable fact is the low mental effort rating of 2 which this participant ascribed to the task.

![Figure 65: Participant 10 Algebraic Task (D) Synchronisation Data](image)
Indicated in Figure 65, there is significant theta synchronisation in the left parietooccipital area. Again, this is an indicator of recollection from memory (Cabeza and Nyberg 2000). Notably, there is significant de-synchronisation in the alpha band particularly in left frontal and centrotemporal areas. These are regions associated with analytical or logical approaches to thinking (Razoumnikova 2000) and also semantic memory (Klimesch 1999). The de-synchronisation of the parietooccipital areas could be as a result of an element of visual cognition. This would suggest that there was a visuospatial component of cognitive activity evident in the construction of the conceptual representation.

The pattern of cognitive activity evidenced in the topographic plots for this participant (See Figure 66 and Figure 67) display similar patterns of cognitive activity throughout the task. Therefore, the conception this participant constructed was misconstrued and the approach was inappropriate for the task. The evidence presented in the synchronisation data highlights an involvement of visuospatial cognition. This pattern is echoed in the topographic plot for alpha which shows activation of the parietooccipital areas as well (Figure 67). This evidence indicates that a reliance on a visual representation of the task led to a misunderstanding for this participant.
Figure 66: Theta Activity across Algebraic Task (D) for Participant 10

Figure 67: Alpha Activity across Algebraic Task (D) for Participant 10
As is evident in the solution produced by participant 10 (see Figure 68) there is scant evidence to suggest a significant amount of reasoning in the task. It is possible that this participant misconceived the problem entirely and assumed that the mental representation constructed was effective. It must be remembered that these participants volunteered willingly for the study and displayed genuine attempts to solve the tasks. This lack of appropriate engagement in terms of cognition is not a result of lack of motivation.

![Rough Work](image)

**Figure 68: Participant 10 Solution for Algebraic Task (D)**

In the post-task interview sessions, participant 10 did not make direct reference to this algebraic question. However, indication that the individual approached all the tasks with a mathematical conception was provided. When asked directly what the predominant strategy adopted during the tasks was:

*Participant 10: "Maths"

*Researcher: "Could you elaborate....."*

*Participant 10: "...I was trying to work on numbers straight away"

*(Participant 10)*

This is interesting as it suggests an unawareness of the actual approach that was adopted to the task. In the follow up interview session which used stimulated recall for reflective purposes there was a slight shift in perception of approach.
"...yeah I said yesterday it was a maths approach....I was just thinking over the past day I would visualise something before I just went and done the maths...."

(Participant 10)

Clearly, this indicates a lack of awareness directly following the task but when given the time to reflect, this changes to a more accurate recollection. This also illustrates the importance of metacognitive reflection on performance. So the commentary indicates that a visual conception was first utilised to progress the solution. This is also represented in other participant commentaries:

"...I could picture that straight away but then....you kind of tend towards leaning towards doing it mathematically"

(Participant 08)

"...I just drew the rectangle out and I knew it was extended by 3m in one direction and 2m in the other....I wasn't one hundred percent sure to work back from that..."

(Participant 03)

This participant illustrates the same reliance on a graphical representation of the task but once this is constructed, faces an impasse in the problem. The visual conception was an attempt to understand the task and then there was a failure to recall an approach from past experience. The activation of theta discussed earlier indicates an episodic component of memory so it suggests they recognised the situation but could not access the semantic content of memory.

4.4.2.2.2 Successful Approach

One participant did display a successful approach to the task. The synchronisation data for participant 04 can be seen in Figure 69. Again, there is significant synchronisation of theta in the left parietooccipital indicative of long-term memory processes. This is coupled with a de-synchronisation in alpha of the frontal areas in conjunction with synchronisation in theta of the frontal areas. This pattern is indicative of a higher cognitive load and possibly increased cognitive engagement. The nature of theta activation in the left parietooccipital area is likely a relation to recollection process memory. Alpha displays de-synchronisation in the left
hemisphere and this is tied to semantic or linguistic processing (Cabeza and Nyberg 2000).

Figure 69: Participant 04 Algebraic Task (D) Synchronisation Data

The overall pattern of cognitive activity does not change during the task as can be seen in the topographic maps for this participant (Figure 70 and Figure 71). So the initial conception of the task again determined the approach. As is clear in Figure 71, there is significant activity in the alpha frequency located in the left occipital area throughout the task. This indicates a visual process as the occipital areas cater for visual mental imagery in particular (Kosslyn et al. 2001).
Figure 70: Theta Activity across Task D (Algebraic) for Participant 04

Figure 71: Alpha Activity across Task D (Algebraic) for Participant 04
As can be seen in this participant’s solution, which is shown in Figure 72, there is a strong emphasis on mathematical reasoning. This, along with the EEG synchronisation data, points to a reliance on semantic memory for the approach. Again, the use of a sketch and the de-synchronisation of alpha in the right parietooccipital region (Figure 69) indicate an involvement of a visual representation during the conception of the task. Similar to participant 07, the visuospatial process could have been used to aid memory.

![Participant 04 Solution for Task D (Algebraic)](image)

Figure 72: Participant 04 Solution for Task D (Algebraic)

In addition, the use of a visual representation to support memory functions is supported in this participant’s commentary.
"Like to answer you need both the question and the schematic if you like...I think you wouldn’t have answered any of them without the diagram”.

(Participant 04)

Interestingly this participant indicated a high mental effort for this task (9) coupled with a high task time of 284 seconds. This would indicate a significant cognitive load was involved as a result of this conceptualisation. Visualising the task requirements does not appear to have been an issue for this participant according to the solution presented. Therefore, it is plausible that the mental effort was allocated to the algebraic reasoning involved.

4.4.3 Visual Category

The previous section presented a sample of analysis completed on tasks, which were grouped in the mathematical category. This section will focus on those from the visual category. It is important to remember that these groupings are hypothetical and it is possible they can be solved in various manners.

4.4.3.1 Dynamic Imagery (K)

Task K asked students to calculate the shortest distance between two points along the surface of the cube. This is shown in Appendix 1. The most effective solution would be to use a development of the cube to obtain a straight line between the points and then map this back to the pictorial view. The necessity to mentally manipulate the cube places this task in the “dynamic imagery” category of visuospatial reasoning (Gaughran 1990). This task was poorly answered with a failure rate of 58% being recorded.

4.4.3.1.1 Unsuccessful Approach

The EEG synchronisation data for participant 06 is shown in Figure 73. This participant was unsuccessful at the task and recorded an efficiency score of 0.5. There is notable synchronous activity within the theta frequency across the parietooccipital areas. This would indicate a cognitive process based on
phonological encoding due to left hemispheric locations (Cabeza and Nyberg 2000). It also indicates an element of episodic recollection given the relationship of theta with this function. The data indicates that the student is recalling familiarity with the geometric object (cube) but is treating it in an analytical manner indicated by the phonological style encoding. Noticeably the right frontal area is also synchronised in theta.

![Participant 06 Task K](image1)

**Figure 73: Participant 06 Dynamic Imagery Task (K) Synchronisation Data**

Alpha is demonstrating a pattern of synchronisation across the task in the frontal and right parietooccipital regions. This indicates a low level of specific cognitive engagement (Fink et al. 2009). Considering this, along with the performance of the participant it is likely that a misconception has occurred. This also supported by the style of activity presented in alpha, which indicates analytical cognitive processes, located in the left hemisphere as de-synchronisation patterns (Figure 73). The topographic maps are depicted in Figure 74 and Figure 75.
Figure 74: Theta Activity across Dynamic Imagery Task (K) for Participant 06

Figure 75: Alpha Activity across Dynamic Imagery Task (K) for Participant 06
These topographic plots indicate a consistent pattern of cognitive processing across all stages of the task. The theta map supports the evidence presented earlier, with a left hemispheric dominance indicating a phonological or analytical style conceptualisation. There are slight variations towards the latter stages of the task with activity becoming more pronounced in the left hemisphere with traces in the right parietal and frontal regions. This is possibly the participant converging on the representation, which is shown in Figure 76, which would require visuospatial cognitive processing. The solution supports the over analytical nature of the process.

![Rough Work](image)

**Figure 76: Participant 06 Solution for Dynamic Imagery Task (K)**

It is probable that the participant misconceived the problem leading to an inadequate representation and cognitive approach. This occurred due to an inappropriate encoding process based on phonological or analytical representation as opposed to visuospatial encoding during the conceptualisation. The episodic experience,
indicated by the theta synchronisation, suggests recalled information affected the encoding process.

Interestingly the task time recorded by this participant was very low as was the rated mental effort. Therefore, this participant believed the conceptualisation of the task and subsequent approach was effective. This participant's approach is representative of a number of the participants who were also unsuccessful. The similarity of the solutions is apparent in Figure 77 and Figure 78.

Figure 77: Participant 05 Solution for Dynamic Imagery Task (K)

Figure 78: Participant 03 Solution for Dynamic Imagery Task (K)
The adoption of a mathematical/analytical approach is also supported in the participants' interview commentary.

“I think looking back, the general approach for all of them was work it out maths for nearly everything. I don’t think there was anything really, well there was one question obviously that I drew out the rotating one and nearly everything else then was nearly working with figures”.

(Participant 06)

"I would say a logical mathematical approach to most of the questions and some of them required to actually just draw them out on paper and see them...just logical mathematical approach"

(Participant 01)

It is plausible to assume that an over reliance on the analytical style of approach influenced the nature of the conception of the task. This was found in many participants' approaches.
4.4.3.1.2 Successful Approach

The EEG synchronisation data for participant 12 is displayed in Figure 79. This participant was successful at the task recording the highest efficiency score of 2.

![Figure 79: Participant 12 Dynamic Imagery Task (K) Synchronisation Data](image)

There is significant synchronisation of activity, within the theta frequency, in the right centrotemporal and parietooccipital regions. This is coupled with a desynchronisation in the alpha frequency in the same areas. This indicates that significant cognitive engagement occurred in these cortical areas. Theta synchronisation in coincidence with alpha desynchronisation is known to be associated with high levels of cognitive engagement (Antonenko et al. 2010). Given the role of the right hemisphere in visual processes (McGilchrist 2009), it is likely that this participant conceptualised the problem in a visuospatial manner. Again, the pattern of cognitive activity exhibited by this participant did not vary throughout the duration of the task. This can be seen in the topographic plots in Figure 80 and Figure 81.
Figure 80: Theta Activity across Dynamic Imagery Task (K) for Participant 12

Figure 81: Alpha Activity across Dynamic Imagery Task (K) for Participant 12
The topographic maps presented on the previous pages, further support the use of a visuospatial cognitive process. As depicted in this participant’s solution (Figure 82) a visual approach to representation is evident. However, it is just the final solution that is represented which suggests that this participant completed the majority of reasoning processes internally. This points to the use of a visual mental representation of the task during the problem-solving episode.

**Figure 82: Participant 12 Solution for Dynamic Imagery Task (K)**

The use of visuospatial strategies is supported in some of this participant’s interview commentary.

"...originally I was just trying to visualise everything from what I was given and then I suppose am (pause) categorising it in my head and working a strategy around it...".

*(Participant 12)*

It is probable that this participant conceptualised the problem in a more visuospatial manner than the previous participants.

**4.4.3.2 Image Holding and Comparing Task (L)**

The previous section presented evidence in relation to a visual task where participants generally did not perform well. This section will look at task L where a success rate of 92% was recorded. The task asked students to determine how many
times bigger a container was compared to another. It could have been solved using the application of a formula for volume but it was posited to be most effectively solved using a visual mental image.

4.4.3.2.1 Successful Approach

Shown in Figure 83 is the EEG synchronisation data for participant 11 during this task. This participant was successful at the task recording an efficiency score 3.33 which was one of the highest.

There is significant synchronisation evident in the left parietooccipital region within the theta frequency (Figure 83). This is suggestive of a long-term memory process (Banich and Compton 2011). It would also indicate of some element of analytical or logical reasoning (Cabeza and Nyberg 2000) and this could be the case given the style of task.
Looking at the alpha frequency (Figure 83) a large amount of de-synchronisation is evident in many areas. Most notably right centrotemporal and parietooccipital areas as well as right frontal regions. This is a strong indicator of a visual approach being adopted during the conceptualisation phase (McGilchrist 2009). Given that a visuospatial cognitive process was not recorded in the breakdown of cognitive activity in Figure 83 it is likely that there was a low level of cognitive load during this task. This is plausible as this task is ranked the lowest in terms of complexity according to Gaughran's (1990) spatial factors framework. This visuospatial process is also supported by the evidence provided in the topographic plots indicating activity in the right parietooccipital region (See Figure 84 and Figure 85).
Figure 84: Theta Activity across Image Holding and Comparing Task (L) for Participant 11

Figure 85: Alpha Activity across Image Holding and Comparing Task (L) for Participant 11
The solution for this participant is shown in Figure 86 and indicates a numerical representation process. Even though the data presented previously indicates a strong element of visuospatial cognition, it is evident that the participant has externalised this as a mathematical concept.

![Rough Work](image)

**Figure 86: Participant 11 Solution for Image Holding and Comparing Task (L)**

There is evidence in the external representation of the task (see Figure 86) to suggest a mathematical approach. The strong evidence of a visuospatial cognitive process evident in the synchronisation data suggests that a visual conception was used to support mathematical/analytical type reasoning.

"It was yeah it was a maths based one, solely maths. By looking at it I wasn’t able to tell. There were a few that you kind of had to look at them before you could go away off and do the maths one."

*(Participant 11)*

As can be seen in the commentary for this participant, there was a strong belief in utilising a mathematical approach. The EEG evidence would indicate a contradiction however. This data suggests that at a perceived level the approach was visual first, which allowed the task to be solved mathematically. This possibility is supported by the topographic plots for the duration of the task and particularly the alpha band shown in Figure 85.

As depicted in Figure 85, alpha (in the 11Hz range) displays a slight variation in the latter stages of the task. The activity in the right occipital area, which is known to be
associated with visual mental imagery (Kosslyn et al. 2001), becomes less evident. This is coupled with a slight increase in the left hemisphere activity, which indicates a switching of cognitive strategies. It would appear that there is a strong likelihood of a mixed cognitive approach to this task.

The implication of visuospatial cognitive areas (namely the right parietooccipital areas) is evident in a number of participant's topographic plots for this task. These can be found in Volume 2 Appendix 2. Similarities in participants' solutions are clear in Figure 87 and Figure 88.

![Rough Work]

Figure 87: Participant 07 Solution for Image Holding and Comparing Task (L)
The hard copy solutions reflect an approach based on mathematical reasoning. It is probable that this task was predominantly visual during the individuals' internal representative process and was externalised numerically. This hybrid approach is supported in participants' commentary.

*Researcher:* “If you could describe overall the general strategy to solving these tasks yourself what would it be? What was your general strategy?”

*Participant:* “Am maths based and visualisation but mostly kind of bringing it down to maths and using formulas and equations.”

(Participant 07)

"Just drawing them out basically just putting it straight from what's in my head to paper and work from that”

(Participant 09)

4.4.3.2.2 Unsuccessful Approach

As discussed, this task was successfully completed by 92% of participants. In fact just one participant did not succeed. Participant 12 was not successful but recorded a
short time spent on the tasks and a low mental effort rating. This suggests that the task was perceived as low in terms of complexity.

As depicted in Figure 89, all areas show a de-synchronisation within the theta frequency. This suggests a lack of engagement in working memory resources and points to a misconception of the task. Again, it must be remembered that this participant volunteered for the study so motivation was not an issue.

The right parietooccipital region is desynchronised within the alpha band and this indicates involvement of a visuospatial process. In terms of complexity, there is a low level of cognitive activity evident by the single desynchronised area in alpha coupled with total de-synchronisation in theta. This is also supported in the breakdown of cognitive processes as all processes are indicating zero values.
Looking at the topographic plots for theta in Figure 90 a slight variation in cognitive activity can be seen. Theta displays a variation in the latter stages of the task particularly within the 4 and 8 hertz frequencies. There is a shift of activity to left centrotemporal regions at these stages (75-100%) which indicates the activation of long-term memory (Cabeza and Nyberg 2000), which was possibly semantic in nature, or analytical resources. This is potentially the point where the past experience of the participant was influencing the approach.
Figure 90: Theta Activity across Image Holding and Comparing Task (L) for Participant 12

Figure 91: Alpha Activity across Image Holding and Comparing Task (L) for Participant 12
Alpha (Figure 91) also illustrates a pattern of variance during the task. The activity in the parietooccipital regions in the early stages of the task becomes less active in the latter stages. This activity is replaced by increased activity in the left hemisphere suggesting analytical or convergent style cognitive processes (Razoumnikova 2000). Interestingly, widespread synchronisation of alpha is indicative of low level of cognitive processing which can occur as a result of conditioning (Cabeza and Nyberg 2000). The task was likely familiar (as is indicated in the commentary below) to the participant and was conceptualised with this conditioned approach and executed procedurally. This is supported by the short time on task and low mental effort scores.

This is also reflected in this participant’s external representation where a single figure is presented (See Figure 92). It is quite likely that this participant misconceived the task.

Figure 92: Participant 12 Solution for Image Holding and Comparing Task (L)

It would appear looking at the hard copy solution that the majority of the reasoning conducted in this task was internal. Given the occurrence of significant activity in
the right parietooccipital region within the alpha frequency, this student relied on a visual representation of the task.

Participant 12: "Yeah when I got this question and I saw it initially I just I saw the two boxes and kind of visually I was just didn’t make anything of it. Then I read the question see how many times container A would fit into container B...automatically I thought twice in my head even before I went about it"

Researcher: "And why was that?"

Participant 12: "I don’t know I think it’s just logically the way my brain works from so many times doing it 2,4,6,8, and so on all this in school for so many years I automatically said it must go twice..."  
(Participant 12)

As can be seen in the extract of commentary above, there is significant evidence of elements of visualisation in this participant’s approach. However, there is also data to suggest that an element of conditioning was influencing the approach as is evidenced in the reference to school. This suggests that past experience was intruding on the conceptual process here and caused some element of misconception.

As can be seen in the evidence presented in this section, there are varying ways that participants have approached the tasks. The use of a visual strategy is indicated in the cognitive activity of all participants presented, which is to be expected given the nature of the task. It is probably the case though that some participants are unaware of this as is evident in the example of participant 11.

4.4.4 Dual Approach Category

The previous sections dealt with the theoretical task groupings of mathematical and visual approaches. This section will present a brief analysis of the dual approach category where tasks were posited to be effectively solved either visually or mathematically.
4.4.4.1 *Simple Arithmetic/ Image Holding and Comparing Task (G)*

Task G was completed successfully by all participants so represents the strongest evidence of performance. This task required students to fit boxes of specified dimensions into a minimum number of compartments. See Appendix 1 for a full set of these tasks. All participants were successful in this task.

Figure 93 illustrates the EEG synchronisation data for participant 02. This participant recorded an above average time on task and an average mental effort.

![Participant 02 Task G](image)

There is a significant synchronisation of activity in the left frontal and centrotemporal areas for this participant within the theta frequency. Theta in the frontal areas is known to be an indicator of working memory processes (Klimesch 1999) and the left hemisphere is associated with analytical type functions (OECD 2007). There is a significant de-synchronisation of alpha within the right frontal area, which is an indicator of some visuospatial components of working memory.
(Kilmesch 1999). De-synchronisation in alpha is known to be associated with specific cognitive activity in regions of the hemisphere. Activity is also desynchronised in the right centrotemporal area so this pattern of activity indicates a visual approach to the conception.

Looking at the topographic plots for this participant’s approach (See Figure 94 and Figure 95), it is clear that there is no significant variation in cognitive activity from the conceptualisation through the entirety of the task. There is a slight variation in the theta frequency at 6Hz between the conceptualisation period and the latter stages. The initial activity implicates more posterior and central regions but this quickly moves to frontal and left central areas in the next stages of the task. This illustrates a variance in cognitive activity however, there are no such alterations in the other frequencies, which suggest this is minimal. There is significant activity, within the alpha frequency, in the right parietooccipital areas, which points some involvement of a visuospatial process (See Figure 95).
Figure 94: Theta Activity across Simple Arithmetic/ Image Holding and Comparing Task (G) for Participant 02

Figure 95: Alpha Activity across Simple Arithmetic/ Image Holding and Comparing Task (G) for Participant 02
As can be seen Figure 96, the participant’s solution indicates and attempt at ordering the various box combinations using numerical values. However, this could just be the external representation format chosen while still relying on a visual conceptualisation of the problem.

Figure 96: Participant 02 Solution for Simple Arithmetic/ Image Holding and Comparing Task (G)

“I don’t know why it’s just strange considering that if I had have been asked the question before I would have said I would have had a graphical approach. Reading the questions my initial reaction was to jump to maths.”

(Participant 02)

As is evidenced in the above comment extracted from this participant’s post-task interview, there is a significant belief in a mathematical approach. This comment indicates that the student is unsure of his cognitive preference after completing these tasks. The data indicates that he was utilising a visual approach during the task but
was not aware of it. This is supported by the nature of the external representation (See Figure 96).

Taking another example, cognitive activity for the conceptualisation period of participant 06 is shown in Figure 97. This graph displays a slightly different cognitive pattern.

![Participant 06 Task G](image)

*Figure 97: Participant 06 Simple Arithmetic/ Image Holding and Comparing Task (G) Synchronisation Data*

Again, looking at the theta band it can be seen that there is synchronisation in the left and right frontal areas as well as the left centrottemporal zone. A notable difference, when compared to participant 02, is the stronger increase in activity for the left parietooccipital area. This area is also desynchronised within the alpha band (Figure 97) so it can be seen that there is an element of cognitive activity occurring here during the conception. This area of the cortex has been shown to be involved in visual tasks such as mental rotation (Gill et al. 1998). A similar frontal activation to participant 02 is noticeable within both frequencies where the left frontal area is
playing a large role. Again, this indicates an analytical process, possibly planning the approach, which is being undertaken within working memory.

Figure 98: Participant 06 Solution for Simple Arithmetic/ Image Holding and Comparing Task (G)

Again, the external representation takes the form of a numerical notation (see Figure 98). This suggests that the participant used a numerical approach to the task but the cognitive activity from the conception indicates that the participant needed a visual conception to achieve this approach. The use of a visual approach is supported in the post task commentary of this participant.

"...what I should have done was calculate you know add up all the boxes and see if they fit in the first place. And I didn’t do that I just started kind of picking ones and choosing ones and seeing what was going on."

(Participant 06)

As is presented in the above commentary, the participant alludes to the use of a visual strategy. However, he seems to lack confidence in this stating that he should have actually adopted a mathematical approach. Interestingly, this participant rated the mental effort on this task as reasonably high and the time spent on the task was
also very high. So even with a visual conception this task was a challenge for the participant.

Figure 99: Participant 04 Solution for Simple Arithmetic/ Image Holding and Comparing Task (G)
Similar to the previous participants there is again a numerical representation of the task evident in Figure 99 and Figure 100. The cognitive activity evident in the topographic analysis (See Volume 2 Appendix 2) suggests a visuospatial approach indicated by parietooccipital involvement, was adopted by the majority of participants. The similarity of external representations evident in the hard copy solutions supports this. This suggests that the visuospatial processes were utilised during the internal representation to facilitate a numerical output.

"For all fifteen am going back through then probably one or two that could have been answered with just maths. You could have just answered with maths...But still you have to understand you would have to build a mental image first..."

(Participant 04)

The same participant was also asked if visualisation skills were important for solving these types of tasks
"... I think you need fairly good visualisation skills for them all... to understand what you been asked..."  

(Participant 04)

A similar importance was placed on the use of visual representations to aid in further reasoning by participant 08:

"...I find it easier when I have to sketch something out if I'm given the dimensions of something... and then you're able to see the relationships..."  

(Participant 08)

As can be seen in this participant’s commentary, the importance of being able to visualise the tasks is clearly stated. This would indicate that the use of a visual conception facilitated this student in completing the majority of tasks.

4.4.4.2 Probability/Image Holding and Comparing Task (J)

The previous task was approached correctly by all participants and as can be seen in their cognitive processing there was a good deal of evidence to suggest similar approaches using visualisation. In contrast, task J was not completed successfully by any of the participants. The task asked students to determine the number of possible routes between two points across a grid. The moves were permitted under directional constraints, which meant the most effective approach to solving the task was the implementation of a probability formula using the potential moves. It could potentially have been solved using a visuospatial approach as well. The task is presented in full in Appendix 1.

Figure 101 presents the EEG synchronisation data for participant 10. This participant recorded a high time on task. The mental effort ascribed to the task was also very high which indicated that there was a significant level of difficulty encountered.
There is significant synchronisation in the theta frequency located in the left centrotemporal area. This is indicative of a memory process being employed or potentially a phonological encoding strategy (Cabeza and Nyberg 2000). The large amount of de-synchronisation within the alpha frequency suggests a large amount of specific cognitive engagement. This is especially clear in the right frontal and parietooccipital regions, which indicates a visuospatial cognitive approach. In addition, the de-synchronisation of the left frontal and parietooccipital regions suggests an analytical or convergent set of cognitive processes being employed (Razoumnikova 2000). The pattern of visual activity is clearly indicated throughout the task with alpha activity being recorded in the right parietooccipital region. This can be seen in the participant’s topographic plots in Figure 102 and Figure 103. There is clear evidence of cognitive activity located in the right parietooccipital region within the alpha frequency in Figure 103. This evidence suggests a visuospatial cognitive process occurring throughout the task.
duration. There is also significant activity indicated within the left hemisphere for the theta frequency (Figure 102). This aligns with the data presented indicating the use of analytical type cognitive actions.
Figure 102: Theta Activity across Probability/Image Holding and Comparing Task (J) for Participant 10

Figure 103: Alpha Activity across Probability/Image Holding and Comparing Task (J) for Participant 10
As is depicted in Figure 104, there is a clear use of a visual representation during the reasoning process. This is likely the manifestation of the visual activity alluded to in the EEG synchronisation data during conceptualisation.

![Rough Work](image)

**Figure 104: Participant 10 Solution for Probability/Image Holding and Comparing Task (J)**

This is also corroborated in the participant's interview commentary:

_Researcher:_ "...when you read that problem what was the first thing that came into your head?"

_Participant 10:_ "How to get, or how many ways you can get down and you had to step like a step everyway rather than going the one direction...I was just kind of thinking about really do you know just about counting...I wasn’t thinking about doing any sort of maths and again I was thinking maybe there is some simple kind of maths solution..."

_(Participant 10)_

As can be seen in this participant’s commentary, a visual approach is clear. Although he acknowledges the fact that there may have been a mathematical approach to the task, he still pursued the approach he first conceived.
Shown in Figure 105 is the EEG synchronisation data for participant 09. This participant recorded a very short time on task of only 92 seconds and a low mental effort rating. This data suggests that this participant thought he was more effective in approaching the task than in reality. This possible misconception is supported in the EEG data gathered during conceptualisation.

Significant synchronisation was found within the alpha frequency (Figure 105). This suggests that the level of specific types of cognitive engagement for the task was quite low for this participant’s conceptualisation. This is also supported in the breakdown of cognitive processes, which indicates a zero value for visuospatial processes typically associated with alpha. There is significant synchronisation of theta in the left parietooccipital and right centrotemporal areas. This is related to episodic style encoding (Klimesch 1999). This could suggest an element of visuospatial cognition, which is analytical in nature as well. Overall, there is a
different pattern of activity than in the previous participant’s data and this suggests a misconception of the task’s complexity.

This misconception is supported by the evidence produced in the hard copy solution by this participant (See Figure 106). The representation presented is quite sparse and suggest an inadequate reasoning process.

![Rough Work](image)

**Figure 106: Participant 09 Solution for Probability/Image Holding and Comparing Task (J)**

Again, the representation points to the use of a visual process but is far less substantial than the previous participant’s solution.

“I read over them two or three times, then started to get a picture in my head of what was happening and then looking back at the question again making sure I was reading it properly, and then just thinking about the approach then I would actually use to solve it and whether or not I need to use extra things or whether I need to draw it out...”

*(Participant 09)*
There is a suggestion of a visual approach evident in the overall strategy to the tasks as indicated in the participant's commentary. These two participants are representative of a similar visual strategy being adopted by the majority of the participants. This is indicated by the activation of visuospatial cortical areas as illustrated in the complete set of topographic plots located in Volume 2 Appendix 2. The similarity of external representations produced by participants also supports this common approach. Figure 107 and Figure 108 present further examples of this similarity.

Figure 107: Participant 05 Solution for Probability/Image Holding and Comparing Task (J)

Figure 108: Participant 02 Solution for Probability/Image Holding and Comparing Task (J)
“I think I would have used maths like, honestly, I would have used maths say whenever I had a chance to think...if I saw numbers I went straight for them, I found the questions without the numbers a little harder”

(Participant 05)

As referenced in this comment, participant 05 displayed a preference for mathematical reasoning. This was what was most familiar and when faced with an unfamiliar task then a failure to engage with appropriate cognitive processes occurred. Therefore, it may not have been entirely a misconception.

As is clear in this section, there is a similar approach among participants to solving this task. The majority of solutions, which can be seen in Volume 2 Appendix 1, display schematic style sketches. It is clear from the cognitive data and interview data that a visual conceptualisation is most prevalent during this task.

4.5 Specific Patterns

The previous sections delved into the particular cognitive patterns exhibited during participants’ conceptualisation processes when faced with a particular task. Although there were a variety of different cognitive processes evidenced across the twelve participants there were some commonalities found in particular tasks. In the mathematical category, there was a strong reliance on the use of long-term memory functions. Moreover, when this could not be enacted effectively, the success levels were poor.

The use of visual strategies was common in the visual and open categories and there is some evidence to suggest that these strategies were used to support other more analytical functions including memory. It is worth considering the approach of individual participants now in more detail.

Specifically, what is noted in the general cognitive data is the lack of significant differences between successful tasks and failed tasks. This is quite clear in the topographic maps for all participants which are located in Volume 2 Appendix 2.
The maps show little variance throughout the duration of the task periods and this is surprising if failure is considered. If a student were not succeeding at a task a re-conceptualisation or change in cognitive pattern would be expected at some stage during the task (Midouser 2009). The evidence presented so far suggests this is not the case. The following sections will present a detailed analysis of a selection of participants using the lens of performance.

Participants 01 and 05 were selected for this detailed analysis. Participant 01 displayed one of the poorest performance rates failing 53% of the tasks. Participant 05 was selected as they performed reasonably well scoring a 73% success rate.

4.5.1 Participant 01

Participant 01 displayed a poor performance only achieving a pass rating of 47% in the applied tasks. This participant was ranked among the poorest performers within the study. Despite this it is interesting to note that this participant’s mean time spent on task was 95.8 seconds and this was lower than the majority (See Appendix 3). This coupled with a median score of 4 for mental effort suggests that the participant may have assumed an effective performance during the tasks.

Figure 109 and Figure 110 present the EEG synchronisation data for the Theta and Alpha bands respectively. Looking at Figure 109, it can be seen that the Theta frequency in the left centrotemporal area displays the highest amplitude for all successful tasks. This is an interesting finding as the Theta band has been shown to be reliably correlated with memory functions and in particular episodic memory (Klimesch 1999). The location of this activity is notable as the centrotemporal areas are known to play a role in memory functions (Stillings et al. 1995).

These areas of the brain also play a role in mathematical and logical cognition but significant activation of the parietooccipital areas in the right hemisphere would be expected as well if this was the function (Houdé and Tzourio-Mazoyer 2003). In addition, it is also noticeable that the left parietooccipital area also shows a pattern of
increase. This area of the cerebral cortex has been shown to cater for the retrieval of long term information (Banich and Compton 2011). A Spearman correlation on the percentage synchronisation values revealed a strong statistically significant relationship between the left centrotemporal and parietooccipital areas $r = .964$, $n=6$, $p < .001$. This increases the likelihood that a memory based approach was taken during the construction of this participant’s conceptualisation.
It is worth noting that the frontal regions are also synchronised for the majority of these successful tasks. This is not surprising as the role of Theta in these areas has been shown to support working memory processes (Gill et al. 1998, Klimesch 1997).
Any task is going to involve some activation of working memory resources but the small percentage synchronisation during this participant’s problem solving episode is worth noting. One would expect Theta in this area to increase exponentially with increasing task complexity. But if cognitive load were high during these tasks Alpha would display a large de-synchronisation (Antonenko et al. 2010). As can be seen in Figure 110, this is not the case as Alpha has shown a synchronisation pattern in the majority of tasks that this participant completed successfully. The data suggests a reliance on memory of an episodic nature. This is supported by the high synchronisation of left centrotemporal areas in the theta frequency (Klimesch 1999).

To take a specific example, the formulaic task (C) indicates significant activation of the left centrotemporal and parietal areas within theta (Figure 111). This task required participants to calculate the area of a figure consisting of a series of triangles and a square (see Appendix 1). This participant’s solution displays a correct approach with competent application of a known formula for area.

![Figure 111: Participant 01 Solution for Application of Formula Task (C)](image)

It is reasonable to infer that the high levels of synchronisation in the left centrotemporal and parietooccipital areas were indicative of recall behaviour. The
participant likely recognised this style of problem during the conceptualisation period and was able to successfully retrieve the formula from memory.

As discussed, Alpha activity displays a predominant pattern of synchronisation. What this immediately indicates is that the complexity of the task was considered low according to this person’s conceptual representation. Generally, desynchronisation is considered an indicator of cognitive function within the Alpha band (Neubauer et al. 2006). Generally, alpha synchronisation has been shown to indicate cortical idling which has been linked to creative thought processes (Fink et al. 2009). However, as these tasks were convergent in nature it highlights a lower level of cognitive engagement for this participant.

The EEG synchronisation activity of participant 01 indicates a memory dominated approach during the conceptualisation stage, which largely leads to his success. It is now necessary to consider this same activity when failure was the result.

Figure 112 and Figure 113 illustrate the EEG synchronisation activity for participant 01 across all tasks where a failed approach was the outcome. It is immediately noticeable that once again activity in the left centrotemporal area within theta displays the highest synchronisation pattern. There is a similar trend of synchronisation in the alpha frequency. Again, this indicates high levels of cortical idling illustrating a low level of cognitive engagement. Within the successful tasks, the left parietooccipital area also displayed a high level of synchronisation. Examining the relationship between synchronisation activity in the left centrotemporal and parietooccipital areas within the theta frequency for the unsuccessful tasks did not reveal any significant association, $r = .452, n = 8, p = .260$. This is a noticeable difference between theta activity during the successful condition and indicates either an inability to recall information or a choice not to use that strategy during conception.
Figure 112: Participant 01 EEG Synchronisation for Theta on Unsuccessful Tasks

Figure 113: Participant 01 EEG Synchronisation for Alpha on Unsuccessful Tasks
Interestingly, theta activity in the left centrotemporal area shows a marked reduction in the formulaic/visuospatial - representation (I) and visuospatial - representation (O) tasks. In these, the right parietooccipital area displays one of the highest synchronisation percentages. This particular area of the cortex has been known to be involved in visuospatial cognitive processes and suggests an alternative cognitive approach (Razoumnikova 2000, Ward 2010). Alpha activity in this region for the visuospatial - representation task (O) shows only a slight synchronisation. One of the core indicators of cognitive engagement in a task is a marked increase in theta synchronisation compared to alpha de-synchronisation (Antonenko et al. 2010). Alpha has not desynchronised in this instance but theta is markedly higher. The solution this participant produced is displayed in Figure 114 and demonstrates an approach which would support the use of a visuospatial approach.

Figure 114: Participant 01 Solution for Kinetic Imagery (O)

Generally, looking at the graphs for theta and alpha frequencies during the successful tasks compared to the unsuccessful tasks there are few differences. The correlation between theta activity in the left centrotemporal and parietooccipital areas during the successful tasks is the most noticeable differentiator. This data indicates an ability to
successfully recall information during the conceptualisation stage during these tasks, which could have been a key factor in this participant's success.

Further investigation of possible differences in EEG activity between the pass and fail conditions was conducted using an independent-samples t-test. Exploration of the data for normality revealed a number of outliers for activity located in the left centrotemporal area for both frequency bands. Two sets of statistical analysis were conducted and results are as follows:

- With the outliers included there was no statistical difference in synchronisation activity for theta in the pass ($M = 91.66$, $SD = 143.3$) and fail ($M = 103.9$, $SD = 5.71$; $t(88) = - .437$, $p = .663$ two-tailed) conditions. This was the same for alpha where no significant differences were found between the pass ($M = 55.79$, $SD = 70.09$) and fail ($M = 73.37$, $SD = 80.05$; $t(88) = - 1.1$, $p = .274$ two-tailed) conditions.

- With the outliers removed from the data there was no statistical differences in synchronisation activity for theta in the pass ($M = 48.69$, $SD = 62.56$) and fail ($M = 73.34$, $SD = 55.8$; $t(79) = -1.873$, $p = .065$ two-tailed) conditions. This was the also the same for alpha in the pass ($M = 43.04$, $SD = 40.67$) and fail ($M = 53.73$, $SD = 42.44$; $t(82) = -1.175$, $p = .243$ two-tailed) conditions.

These statistical results confirm that for the majority of tasks this participant engaged a similar cognitive approach during the conceptualisation of the problems. This was also true regardless of whether the end condition was deemed successful or unsuccessful.

### 4.5.2 Participant 05

Participant 05 displayed a reasonable level of performance relative to the majority of participants. In total this participant achieved a successful approach of 73% and spent an average of 144 seconds per task. This is markedly higher than participant 01 who displayed a mean time of 95.8 seconds. Participant 05 recorded a median score of 2 for mental effort and a range of 8. This would indicate that overall this
participant exerted a small amount of mental effort to achieve success in the tasks. The large range score would also indicate that this varied during the 15 tasks where some required a larger amount of effort than others.

Figure 115 and Figure 116 illustrate the EEG synchronisation activity in the theta and alpha frequencies for all successful tasks.
Figure 115: Participant 05 EEG Synchronisation for Theta on Successful Tasks

Figure 116: Participant 05 EEG Synchronisation Data for Alpha on Successful Tasks
As evident in Figure 115, theta activity is showing a significant pattern of synchronisation across both centrotemporal areas. However, as in the previous participant’s cognitive analysis, the left centrotemporal area is demonstrating the higher synchronisation values. Again, this is indicative of a memory function being employed during the conceptualisation and representation of the problems. Given the activation of the right centrotemporal area in apparent conjunction with the left it is possible that visual memories were evident in the conception (Houdé and Tzourio-Mazoyer 2003). As already discussed, de-synchronisation in the alpha band is a typical indicator of cognitive function (Klimesch 1999) and as can be seen in Figure 116, the activity in these areas is synchronous in nature indicating low levels of specific cognitive engagement.

Further investigation of possible associations between the left and right centrotemporal areas was conducted with a Spearman correlation. There was no significant association found for these two areas within the theta frequency \((r = .473, n = 11, p = .142)\) or in the alpha frequency \((r = .445, n = 11, p = .170)\). There was a significant correlation found between the right centrotemporal and parietooccipital areas in the alpha frequency \((r = .727, n = 11, p < .05)\). But as can be seen in figure 12 these areas are predominantly synchronised so it can be inferred that these regions were not necessarily cognitively engaged during the conceptualisation.

Theta also displays a synchronisation pattern over the frontal areas in both hemispheres. This again is not a surprising occurrence as these frontal regions are known to be the seat of working memory, which would be activated for most applied tasks (Banich and Compton 2011, Ward 2010). As theta is predominantly associated with memory functions and given that the majority of alpha activity is demonstrating a synchronisation pattern, there is strong evidence to support a memory-focused conception.

In the arithmetic/visuospatial - representation (G), formulaic/visuospatial - representation (H) and formulaic/visuospatial - representation (I) tasks alpha displays a de-synchronisation pattern in the left parietooccipital area of the cortex.
This pattern would indicate that the participant was utilising this area in these tasks, as de-synchronisation is associated with cognitive function (Klimesch 1999). The left parietooccipital area is known to be a key area in visuospatial cognition and in particular mental rotations (Gill et al. 1998). As shown in Figure 117, this participant has implemented quite a visual approach to solving task H. This task could have been solved mathematically using area formulas but this participant adopted a visual approach and counted the occurrences.

![Figure 117: Participant 05 Solution for Application of Formula/Image Holding and Comparing Task (H)](image)

In this particular case, the high level of synchronisation in the theta frequency indicates an occurrence of memory. This data only accounts for the first 32 seconds and it took 76 seconds for this participant to complete the task (see table 2). This indicates that the first step in conceptualising this task was to refer to experience.

Shown in Figure 118 and Figure 119 is the EEG synchronisation data for theta and alpha when the outcome of the task was an unsuccessful approach. Again there is significant synchronisation in theta located in the left centrotemporal area for the
application of formula (D) and simple arithmetic/image holding and comparing (F) tasks. Some minor synchronisation in this area can be seen in the other tasks. This points to the involvement of a long-term memory function during the conceptualisation. As it is within the theta frequency, it is likely episodic in nature (Klimesch 1999).
Figure 118: Participant 05 EEG Synchronisation Data for Theta on Unsuccessful Tasks

Figure 119: Participant 05 EEG Synchronisation Data for Alpha on Unsuccessful Tasks
As is evident in the alpha data (Figure 119) there is a majority pattern of synchronisation. This immediately indicates that the student was not significantly cognitively engaged during the task. It points to a misconception of the tasks complexity. Specific de-synchronisation occurs in the left parietooccipital regions which are known to be involved in mental rotation processes (Gill et al. 1998).

Possible differences evident in cognitive activity between the successful and unsuccessful conditions were investigated using an independent samples t-test. Again, exploration of the data revealed a number of outliers in both frequency bands and predominantly located in the left centrotemporal areas. Two rounds of tests were conducted and results are as follows:

- With the outliers included there was no statistical difference in synchronisation activity for theta in the pass ($M = 70.80, SD = 100.22$) and fail ($M = 38.76, SD = 56.45$; $t (88) = 1.48, p = .117$ two-tailed) conditions. Alpha displayed a significant difference between the pass ($M = 32.74, SD = 52.24$) and fail ($M = 7.62, SD = 37.18$; $t (88) = 2.159, p < .05$ two-tailed) conditions.
- With the outliers removed from the data there was no statistical differences in synchronisation activity for theta in the pass ($M = 38.32, SD = 43.87$) and fail ($M = 38.77, SD = 33.22$; $t (80) = -.038, p = .970$ two-tailed) conditions. This was the also the same for alpha in the pass ($M = 20.02, SD = 33.22$) and fail ($M = 12.03, SD = 30.99$; $t (81) = .997, p = .322$ two-tailed) conditions.

The significant difference in the alpha frequency was only found when the outlier data was included. Therefore, in the majority there is no cognitive difference between successful and unsuccessful approaches. The fact that the sample size here was small may also have been a factor in this statistical finding.

Evident in these two participants’ approaches, there is strong evidence of a reliance on memory during the conceptualisation of tasks. In addition, it also seems as if regardless of the success in approach students are conceptualising tasks in the same manner. This has been shown by the lack of statistical difference in the EEG data
between successful and unsuccessful approaches. This finding aligns with the data produced in the topographic analysis and indicates the possibility of cognitive entrenchment.

4.6 Summary of Key Findings

The key findings arising from the research study are presented below and will form the basis for the discussion, which is located in the next chapter.

- Generally, performance in the prescribed tasks was poor with the highest level of performance occurring in the non-specific category for the simple arithmetic/image holding and comparing task (G). A 100% success rate was recorded for this task. The poorest performance was evidenced during the probability/image holding and comparing task (J) in the non-specific category.

- The efficiency of participants when engaging these prescribed tasks was also poor as indicated by the scores provided in table 3.

- A general unawareness of personal efficacy during the problem solving episodes was also found. This is strongly indicated in the time and mental effort data where participants who performed poorly on tasks but rated the effort low and recorded a low time on task (See Appendix 3). This was also echoed in participants comments under the section on perception of performance (1.2.3)

- A strong reliance on memory of past experiences in problem solving was found during the study. This is indicated by the commentaries provided throughout the study and especially in reference to school experience. Examples can be found in section 4.2.3 and 4.4.2. The statistical relationship between low levels of mental effort and high performance supports this finding. When participants were able to remember an approach the effort was low and the outcome was successful.

- The reliance on memory during the conceptualisation stage of the problem-solving episode is also supported in the EEG data presented throughout section 4.4. This is particularly clear in tasks in the mathematical category.
(4.4.2.1) where high levels of left centrottemporal activity in the EEG data are presented. The data indicates the existence of different types of memory or encoding processes such as episodic and semantic processes.

- Visuospatial cognitive processes were found during many of the tasks but they were primarily used in a representative manner to interpret information. Most of these tasks also exhibited significant activation of areas related to memory and analytical type reasoning.

- Most participants believed that their overall approach involved a mathematical strategy as opposed to a visuospatial one. The EEG data collected (See Volume 2 Appendix 2) indicate that the majority of participants adopted a visuospatial process for the majority of the tasks. This suggests an element of misunderstanding in terms of their personal cognitive approaches to tasks. It also suggests that the use of a visuospatial strategy allowed students greater flexibility to access further cognitive processes. In contrast, when the conceptualisation was overly analytical or phonological, participants were more rigid in their approach and were restricted to using past episodic experience to guide their approach.

- A large amount of fixation and rigidity was found during the cognitive analysis of participants' approaches. This is clear in the topographic plots for the entire participant sample located in Volume 2 Appendix 2. It is clear that in general, cognitive activity does not vary throughout the tasks suggesting fixation on approach following the conceptualisation.

- This rigidity is also supported by an inability of participants to see alternate approaches to tasks in the interview commentary (See Volume 2 Appendix 1).

- Conceptual entrenchment was found across many of the participants where there was clear evidence that tasks were conceptualised similarly regardless of performance outcomes. The lack of statistical differences in the cognitive activity between successful and unsuccessful conditions (see section 4.5) indicates that participants are conceptualising tasks similarly despite their differences in intent.
5 DISCUSSION
5.1 Overview

This study did not set out to prove definitively the benefits or detriments of certain cognitive approaches to solving problems. Instead, the core focus was on exploring the area of conceptualisation during the solving of prescribed convergent tasks that are typical of those used in STEM education. This was completed in order to present a number of key areas for future research.

With the recent renewed interest in the promotion of STEM education on a global scale (Clark 2012), there is a necessity to investigate the teaching and learning activities within the area. One of the core activities which STEM education is concerned with is the development of advanced problem solving abilities (Williams et al. 2008). The flexible adaptive development of these skills is something, which must be of concern given the dynamically shifting face of contemporary society and the workplace. As Pink (2008) discusses, we have moved away from the era of acquiring information and are now in the “conceptual age” where these flexible problem solving skills are necessary.

Within STEM education, there exist different epistemological assumptions of the nature of learning related to each area (Science, technology, engineering and mathematics). What is a core underlying facet of each of the epistemological assumptions is the nature of the problem or the situation for which knowledge must be adapted (Williams 2011b). This is a very important consideration as now it becomes critical that students develop the ability to frame problems and situations in order to optimise effectiveness. This is also a crucial skill for educators to be adept at when considering the design of instructional interventions. Optimising effectiveness of learning situations for given contexts can only increase the developmental potential of the educational intervention.

This chapter will discuss the research findings which are directly associated with the conceptual framing of convergent problems typical of STEM education. The chapter is presented in key sections for clarity. Firstly, it is necessary to explore the role of
memory and past experience in the conceptualisation process and this will lead onto to a discussion of the main themes uncovered regarding the manner in which pupils conceptualise these style of tasks. The relationship between the conceptualisation and the subsequent approach on a cognitive basis will then be explored. Thirdly, the role of visuospatial cognition will be discussed focusing on its role in the conceptualisation of convergent tasks. Fourthly, the implications for teaching and learning in the area will be considered. The chapter will conclude with some key recommendations for the area.

5.2 The role of memory and past experience

It is widely known that the influence of past experiences can have profound effects on present performance (Tulving 2001). It is therefore not surprising that the cognitive evidence in this study indicates a large activation of processes associated with various functions of memory. What is interesting is when the categories of tasks are taken into account. For the mathematical tasks utilised within this study, the majority of evidence presented in the findings indicates a significant reliance on memory. Delving deeper into this evidence it is clear that both elements of episodic and semantic memories are involved.

Semantic memory relates to memory of knowledge and facts that are abstract and general in nature, whereas episodic memory refers to memory of specific events that an individual has experienced (Baddeley 2001). Consequently, semantic memory is an important component of all problem-solving episodes within STEM education. Within STEM there are specific levels of content knowledge which would be expected of students for example within mathematics or science. The ability to call upon that knowledge and utilise it in solving new problems is clearly an important skill across all disciplines of STEM education.

From the findings of this study, it is clear that the past experiences of the participants had an influence on the nature of the conceptualisation constructed for various problems. If a task was conceptualised semantically from the outset then the
successful performance on that task would depend on the alignment of the semantic memory with the current task. This was the case for participant 08 during the application of theorem task (A). This was evident with a much higher level of activity in the alpha frequency, a known indicator of semantic processes. The participant clearly recalled the theorem from the beginning and did not encounter any issue with the execution. This is evident by the relatively high efficiency value of 5 out of 10, which the participant recorded. The semantic frame, which constituted this participant’s conceptualisation of the task, was clearly appropriate for this situation. However, if this process formed the predominant type of activity during conceptualisation of tasks in general for this participant, then there will be occurrences when the semantic frame will not align with a prescribed task. This style of conceptual process described for participant 08 reflects a type of “noetic” consciousness where no episodic event in particular is tied to the process (Baddeley 2001). It is possible given the evidence here, that this participant has engaged with these types of tasks so often in the past that they are now automatic. This is supported by the lack of theta activity for this participant, which would be a strong indicator of the activation of working memory resources.

This type of activity during the conceptualisation process has implications for the nature of learning which could occur during future applied problem solving tasks. If the conception is an automatic construction for the participant, then there will be occasions when this automatic construction does not align with the epistemic characteristics of further tasks. A surface characteristic of a task (descriptor, image etc.) can trigger a semantic conceptual frame, which is not adaptable to the current problem. This would result in poor performance or potentially performance, which does not align with the learning intent of the educational task.

An example where a conception based on memory actually failed the participant is that of participant 03 during the application of theorem task (A). In this case, there was again a low level of activity in the theta frequency suggesting a low load on working memory. There was one area within the theta frequency that displayed a high level of activity and that area is indicative of an episodic component of
memory. In this case, the evidence suggests that the participant recognised the application of the theorem but could not effectively recall the semantic content. This is a conceptualisation based on an “autonoetic” consciousness where the participant has recognised the familiarity of the situation (Baddeley 2001). In this case the familiarity of the situation could have caused a 'false' confidence in the conceptualisation of the task. As Kahneman (2011) discusses, the issue with relying on familiarity of situations as opposed to actual semantic content is the potential for bias in one's reconstruction of the context. This is referred to as "cognitive ease" (Kahneman 2011) and promotes a false belief in the memory of an event or in this case a past problem.

This is strong evidence pointing to the influence of past experience on the conceptualisation of current tasks. This is also supported in many of the participants’ commentary during the post task interviews. Here particular reference was made to second level school experience. For example, participant 01 stated: “maybe from school you kind of go into a bank of memory rather than trying to work it out...” This demonstrates a conceptualisation process, which was based on familiarity of school experience. This presents another important point for consideration. If the experience within the second level system of completing these styles of task was repetitive in nature then it is likely that strong traces have been built into their long term memory (Eysenck and Keane 2010). This will present an issue for future learning and problem-solving processes as the conception of further tasks will be influenced by the automatic reliance on those well-established traces. Again, this becomes a problem when the future tasks do not align with these types of experience from school.

Interestingly, the influence of episodic memory also occurred during a visual category task. During the dynamic imagery task (K), a number of students demonstrated visuospatial cognitive activity in association with high levels of left hemispheric activity indicating the possibility of episodic memory or phonological/analytical encoding. This is clear in the EEG data of participant 03 during this task. Overall, during the conceptualisation of the task there is little
evidence of a visuospatial approach. This accompanied with left hemispheric activity in theta points to the use of analytical reasoning or episodic memory. It is possible that the participant conceptualised the problem using their past experience of the geometry (cube) and this limited the approach taken thereafter. This was not the case for participant 12, who demonstrated activity typical of visuospatial cognition, with high levels of activation in the right parietooccipital region. This was the predominant process used during the conception of the task and this likely lead to a more flexible internal representation of the problem. This points to the possibility of an overemphasis on the use of analytical strategies as a result of schooling which can then effect the capacity of individuals to utilise a variety of cognitive functions. This was the case for participant 03.

The high level of reliance on memory indicated in both the cognitive activity and the commentaries is also supported by the statistical analysis on the relationship between effort and performance (p<0.0001). Here, low levels of effort were highly correlated with high levels of performance. This is quite logical if memory were the core processes that the effort was expended on. When the task was easy to recall effort was low but where it was not the converse occurred accompanied by lower performance. This raises concern as one (an educator) would expect that when the recollection of information is not possible the student would be able to adopt an alternative reasoning strategy. If the entirety of the problem-solving episode is spent on attempting to recall information then there is no evidence of adaptive and flexible behaviour. Given that these students have all been successful in second and higher education thus far, this raises serious questions about the nature of teaching and learning in their past experiences.

5.2.1 How pupils are framing problems?

Overall, the findings suggest that the mathematical category was most reliant on cognitive processes indicative of episodic and semantic memory. The semantic memories were appropriate when they could be successfully recalled and are a necessary component during the conceptualisation of these types of task. The
episodic memories on the other hand, seemed to be more restrictive in that they triggered automatic conceptualisations of tasks that were often not aligned with the intent of the task and are more susceptible to bias.

Tasks A and E were both problems that required the application of a theorem to solve. Therefore, the ability to access the semantic content of memory here would be advantageous. It is interesting to note that task A required a straightforward application of Pythagoras’ theorem. Whereas, task E required the identification of the need for Pythagoras’ theorem followed by application. The performance levels for A were lower than E despite the fact that the latter was the more complex task. The necessity to identify the application of the theorem initially may have led to a more active internal representation among participants. The task was clearly not as eligible to applying a theorem immediately which meant that the participants had to frame the task differently to task A. This initial identification stage could have forced students to construct a more situated representation before accessing the semantic content of memory. Therefore, it can be argued that their conceptualisation process in this case was less susceptible to biases from episodic memory.

It is clear that the findings support the influence of past experience on the conceptualisation process across the categories but most apparent in the mathematical category was that specific content knowledge is clearly needed. When looking at the categories in comparison to each other (Figure 31) it is noticeable that the cumulative performances in the mathematical and visuospatial categories are similar but much higher than the dual approach category. This is an interesting finding and may be due to the nature of the tasks. The fact that there are two possible approaches to each one of the dual approach tasks places the responsibility of framing the problem more so on the participants. The visuospatial and mathematical categories have a clear approach which is most effective for solving the problem so therefore are already partially framed for the students. As discussed, there is significant evidence within the findings to suggest the influence of school experience on the conceptualisation of problems for these participants.
These findings suggest that the repetitive use of single approach type tasks within STEM education has led to a phenomenon of conditioning during the conceptual process. The data suggest that students expect that the prescribed tasks utilised within the educational context will be already framed for them by the educator. The large body of research which suggests the adoption of surface approaches to learning in the face of high stakes terminal assessment (Bloxham and Boyd 2007, Entwistle 2000), supports this type of cultural framing or conditioning. In addition, it must be noted that these participants have been successful in such a culture of education to date. The evidence presented in the findings when performance is looked at across the three categories strongly supports this cultural framing effect. The students performed well when the task was partially framed but when the responsibility fell on them to conceptualise the task entirely, the performance was compromised.

The effect of this cultural framing on students' problem solving approaches could have significant implications. It may be encouraging the repetitive use of "system 1" type processes, which are automatic in nature and can lead to errors (Kahneman 2011). The evidence also supports this style of processing leading to rigid thinking and the prevalence of misconceptions. This is indicated in instances where the performance on a task was poor but the student rated the effort as low and/or the time spent on task was low. This indicates that the participant believed the approach adopted was effective possibly due to past successes with such a process. The other explanation is the impact of conditioning where the individual associates the current task with their school experience and are incapable of approaching the task in another manner. This possibility of conditioning is further supported when considering the relationship between an individual's conceptualisation of and subsequent approach to solving a task.

5.3 The relationship between conception and approach

One of the core aims within the current research study was to determine if there was an empirical relationship between the cognitive activity displayed during the conceptualisation of a task and throughout the entire task. This relationship is
clearly supported in the findings where the topographic maps show a consistent pattern of cognitive activity throughout all stages of the task. This is illustrated clearly in the topographic plots for each participant across an entire task located in Appendix 4. This is an important finding as it means that the cognitive activity, which constitutes the conceptual framing of the convergent task, determines the cognitive activity, which will be used for the remainder of the approach. The first few seconds of engagement with a convergent task determines the overall approach and ultimately the success or failure of the outcome.

What is more interesting when considering this finding is when performance is taken into consideration. The pattern of cognitive activity remains the same throughout the task despite the outcome being successful or unsuccessful. This raises questions about the flexibility of students' cognitive processing capabilities. Logically, one would expect that when a participant is not succeeding with their current approach that a re-conceptualisation of the task would take place. This would result in a change in cognitive pattern during the task but this was not recorded for the majority of participants' approaches. This supports a trend of cognitive rigidity and also a lack of ability to self-audit individual performance.

Further evidence, which supports this rigidity, can be seen in the detailed investigation of the approaches of participants 01 and 05. What is of core interest in these findings is the lack of statistical difference, in cognitive activity, between successful and unsuccessful performances in tasks. What this indicates is that despite the task, the conceptual framing of the problem was the same regardless of the performance. This supports this existence of cognitive rigidity during the conceptualisation of these STEM style convergent problems. Given the evidence presented on the influence of school experience on this process, it is plausible that at least some of this was caused by the participants' engagement in current educational practices. This is an important finding as it indicates a significant compromise in students' ability to flexibly conceptualise different problems.
The ability to self-audit one's performance during a task is a critical metacognitive component of problem solving (Kitchner 1983). The evidence presented here highlights a neglect of this ability among a sample of students who have been successful thus far in the education system. As the past experience and undergraduate experience of student teachers has been shown to influence their future practice (Williams 2011), such rigidity could negatively impact on future pedagogical practice. This presents core concerns for teaching and learning within STEM education. What will be necessary to consider as part of future research are the approaches one can take to better develop these flexibilities in conceptualisation. Some evidence for this development was uncovered during the study.

5.4 Visuospatial cognition and its role in conceptualisation

The findings support the use of visuospatial cognitive processes primarily in the visuospatial category of tasks. The tasks were chosen based on Gaughran's (1990) framework of hierarchical spatial factors. The performance scores indicate an accurate mapping of tasks to the framework where the tasks assigned to lower levels (e.g. image holding and comparing) recorded higher performance levels than those higher on the framework (e.g. dynamic imagery). It is surprising that these participants displayed such a poor performance during the visuospatial tasks and especially towards the higher end of the spatial factors framework, as all students were concurrently studying graphical education as a specific element of their degree programme and should have advanced visuospatial capabilities. Again, there is evidence in the findings to suggest inefficient cognitive approaches encroaching on the visuospatial conceptions.

This is most clear during the dynamic imagery task (K) for participant 06. In this case the participant conceptualised the task with elements of visual cognition but also evidence of episodic memory. The solution displayed an approach that was
quite analytical in nature and where the participant clearly could not manipulate the geometry. The evidence supports the likelihood that the episodic experience of the participant prevented a flexible visuospatial representation being constructed. It suggests that the participant conceptualised the geometry in relation to past familiarity with the object (cube) and this prevented further manipulation. This overly analytical conception is also presented in other participants' solutions. This reflects an element of conditioning encroaching on the visuospatial modality. The predominant style of activity within current educational systems is that of an analytical and convergent nature (McGilchrist 2009). As discussed earlier, the influence of past experience is supported in the findings so it is likely that this analytical manner of thinking is biasing the visuospatial cognitive processes in some cases. This is also supported in the work of (Van Sommers 1984) who demonstrated a restriction in pupils' visualising abilities as a result of the over development of analytical processes.

Interestingly, this conditioning effect can also hide the use of visuospatial processes from the participant. They can complete the task effectively but are convinced that the process they adopted was that of an analytical/mathematical approach. Participant 11 during the image holding and comparing task (L) is a good example of this. In this instance, the participant displayed a high level of cognitive activity indicating a visuospatial process. When questioned about the approach to the tasks a mathematical approach was stated. This highlights a type of metacognitive misalignment where the student did not realise the success they had was due to a different cognitive approach. This provides further evidence of a poor level of metacognitive skills among participants.

The findings support the effective use of visuospatial strategies in tasks outside the visuospatial category. This is evidenced most clearly by participant 04 during the algebraic task (D). The cognitive evidence gathered for this participant's conceptualisation process indicates a high level of visuospatial activity and this is supported by the significant amount of sketched representation evident in the solution (Figure 72). Interestingly, this was the only participant to solve this task
and did not directly rely on a process of recalling past instances of similar tasks. The visuospatial process here allowed the participant to understand the task first and then access the semantic information in long-term memory. This is supported by the high levels of alpha activity, which are known to be indicative of semantic processing.

Evidence of the use of visuospatial processes during conceptualisation to facilitate further reasoning capacities is present for participant 09 during the application of theorem task (A) as well. Here there was a significant amount of activity indicating a visuospatial process, which then facilitated access to the semantic content to complete the solution. This process facilitated a flexible conceptual frame on the problem, which allowed further access to other cognitive processes suitable to the task. This was likely a contributing factor in this participant achieving the highest efficiency value of all participants on this task.

This is an important finding as it affirms the importance of developing robust visuospatial skills as part of STEM education. This clearly added to the flexibility of participants’ conceptualisation processes and subsequently their ability to solve a variety of convergent problems. However, there is a cautionary point with regards the development of these skills to be found on further analysis of the findings. In particular, the probability/image holding and comparing task (J) where no participant produced a successful approach. In this case all participants relied on a visuospatial conceptualisation which resulted in a very high cognitive load, indicated by high ratings of mental effort (Figure 33). Just as an over reliance on mathematical/analytical approaches was discussed as effecting flexibility this can also occur with the over reliance on visuospatial skills. It is therefore important that there is a balance among the development of these capacities within the STEM disciplines. The findings do showcase the importance of developing visuospatial competencies for a variety of tasks within STEM education. The evidence presented highlights the increased flexibility a conceptual frame can have when the individual employs a visuospatial representation.
5.5 Conceptualisation leading to abstraction or authenticity

The type of cognitive processes which are dominant in the conceptualisation phase of the problem-solving episode have a significant impact on the outcome of the attempt. The reliance on episodic and semantic memory retrieval processes has its limitations as is illustrated in the findings. When the semantic content is the immediate focus this reflects a noetic consciousness where the participant automatically knows the approach to adopt. The impact of past school experience, as has been uncovered in the interview commentaries, supports the existence of conditioned approaches to the solving of some tasks (particularly mathematical) but also a rigid approach to conceptualising these tasks.

Episodic processes have been shown to be unreliable in a number of cases within the findings and were implemented when participants recalled familiarity with situation. Often these type of memories are highly susceptible to bias (Kahneman 2011) and the intrusion of these biases can occur during the reconstruction of the memory trace. It is important to note that memories are not crystallised entities, which are stored in the brain and are capable of being reproduced verbatim (Sutton 2009). They are reconstructed as and when needed by the individual so the question becomes what conceptual processes lend themselves to the effective reconstruction of long-term memory traces relevant to a current task?

It is useful at this point to consider Barsalou's (2009) theory of concept formation in long-term memory. Here he refers to two primary components of an individual's conceptual system: "simulators" and "simulations" (Barsalou 2009). Simulators refer to the collection of numerous memories relating to a particular category (e.g. Car) whereas simulations refer to a specific subset of information (e.g. BMW) within a simulator (Barsalou et al. 2003). The predominant use of memory processes during the conceptualisation stage of the task could be the participant accessing a simulation, which is abstracted from the present experience. This could be the result of repetitive promotion of this type of process (simulation) during past school
experience to the point that when the current task is associated with the simulation this is the automatic approach. For example, when faced with a task that demands the application of Pythagoras' theorem the problem is conceptualised as running the simulation associated with this. Whereas, ideally the conception would facilitate access to the entire simulator and activate the appropriate simulation(s) depending on the current situational problem.

This is exactly where the use of visuospatial cognitive processes during the conceptualisation phase can be an aid. The findings presented highlight the advantages a visuospatial conceptualisation offers in terms of flexibility. Considering this finding in light of the previous point on simulators and simulations leads to an interesting hypothesis. The findings suggest that visuospatial processes during the conceptualisation phase of a task allows greater access to a simulator for a given area. This facilitates a more authentic representation of the problem, which in turn directs the individuals' approach toward specific fit for purpose cognitive approaches to complete the task. However, care must be taken to achieve balance in the development of these abilities. This results in a more authentic conception of the problem, which is not as susceptible to bias from past experience and allows a greater level of adaptability in solving various problems.

This hypothesis is also supported within the pertinent literature on the development of spatial ability where it has been shown that developing spatial skills leads increased aptitude in areas such as science and mathematics (Sorby 1999, Sorby et al. 2005, Sorby 2009). The hypothesis presented here suggests that the development of spatial skills allows the construction of a more flexible conceptual frame, which then allows greater access to simulators within memory. This may explain why high levels of spatial ability are associated with gains in other areas of performance as shown by previous research.
5.6 Limitations of the Research

The study clearly highlights the complex relationship between the conceptualisation of a convergent STEM task and the nature of the engagement with that task. There are however, limitations with the current study that must be acknowledged.

- The study only focused on students of STEM education and there are limitations in generalisation associated with this. However, all students in the study were successful in the second level education system having performed well. Therefore, this did provide valid evidence relating to the influences of current educational practices.

- A further limitation relating to the sample of participants was the lack of female participation in the study. Given that ITTE at the University of Limerick is predominantly male, this was an unavoidable occurrence. The role of visuospatial cognition in augmenting the conceptualisation of convergent STEM problems was discussed. It is widely shown in research relating to spatial ability that there are significant differences between males and females in certain areas (Halpern and Collaer 2005). Therefore, investigating the existence of differences in the conceptualisation stages of problem solving is an important consideration.

- The sample size was relatively small (n=12) and this provides further limitations in ability to generalise. This was not a significant limitation overall as the mixed methods approach provided a large rich data set that was triangulated and from which conclusions were drawn. The focus of the study was also on STEM specific tasks and as these students are involved in ITTE they are representative of the typical STEM student population.

- The EEG headset is known for its poor spatial resolution in comparison to other techniques such as fMRI. However, this was carefully considered during the data analysis stages and particular care was taken in filtering the data in line with pertinent approaches in the research literature (Delorme and Makeig 2004) to ensure accurate data. As discussed, this method was also triangulated with qualitative data to increase reliability and validity.
6 CONCLUSIONS
6.1 Conclusions

The following conclusions were drawn from this research study:

- There is a significant relationship between the conceptualisation of a convergent task and the overall cognitive approach adopted to solving the task. The cognitive processes, which are utilised to form a conceptual frame for a task, remain crystallised throughout the entirety of the episode. This indicates that the first stages of an individual engaging with a convergent task are critical in determining the success of the outcome.

- Cognitive rigidity was found in many of the participants' approaches to various convergent tasks. This was indicated by the lack of variation in cognitive pattern throughout the problem solving episodes. Given the strong association uncovered between the conception of the task and the approach the rigidity could lie in the conceptual framing process. This was supported by the lack of statistical difference in participants' cognitive data during conceptualisation between tasks, which were successful and unsuccessful.

- The conceptualisation formed when engaging with a convergent task is strongly influenced by past experience. This takes the form of episodic or semantic memory processes, which have differential effects on the nature of the approach.
  - Semantic processes are appropriate when the semantic content of the task aligns with the memory but will lead to an unsuccessful approach when the task is not the same
  - Episodic processes trigger a familiarity between the participant and the task and are susceptible to cognitive biases leading to greater amounts of misconceptions

- The nature of the episodic experiences which was evident in many participants' cognitive data was linked to past school experience. This experience was presented as an underlying cause leading to rigid approaches
in conceptualising and approaching the convergent tasks. This suggests a conditioned approach to solving problems.

- Evidence of a cultural framing effect was uncovered when performance across the three categories of convergent tasks are considered. Performances in the single approach tasks were superior to that of the dual approach category. This suggests that students have increased levels of difficulty in solving a problem when required to frame the task themselves. This could be as a result of the conditioning alluded to earlier. This raises serious concerns for instructional design within the current system and suggests a need to consider framing tasks with students past experiences in mind.

- The role of visuospatial cognition in the conceptualisation process was delineated as a key component in accessing a wider variety of cognitive approaches to a task. This formed a key hypothesis emerging from the research study. This was discussed in relation to Barsalou's (2009) theory of simulators and simulations. The use of visuospatial cognitive approaches allowed participants to build more authentic representations of the problem during conceptualisation. This in turn lead to a greater access to cognitive resources (simulators) than semantic or episodic process which were more abstract in nature and likely allowed access to only simulations. This supports the need for developing these skills within STEM education.

- While acknowledging that further research is needed on this hypothesis, the role of visuospatial cognition in the conceptual framing of problems uncovered in this study may aid in explaining the relationship between spatial ability and success in other fields. The use of visuospatial processes during conceptualisation lead to more flexible approaches through increased access to simulators in long-term memory which ultimately facilitated greater success. This is important, as it is possibly one of the key factors in dealing with issues of cultural framing.
7 RECOMMENDATIONS
7.1 Recommendations

What has clearly been illustrated in the discussion of the findings of this research study is the relationship between the conceptualisation of a task and the overall approach adopted. This provides important evidence for instructional design relating to convergent style activities within STEM education. Essentially, it means the success a student will have in a convergent task is influenced by the nature of the conception. If the instructional design is intended to complement the development of a certain cognitive skill or skills then the conceptualisation of the activity must be considered.

The findings of this study have uncovered a number of elements, which affect the conceptualisation of convergent STEM problems. One of the strongest elements which has been found to impact on the conception of a task is the past experience of the participant. In particular, this study has demonstrated a strong link between past school experience and current approaches to problem solving indicating the potential existence of conditioned approaches. A key recommendation arising from the study is a necessity to consider how, as educators, tasks are framed to take into account past pupil experience. The tasks that the participants engaged with during the study triggered some sense of familiarity with past experiences in many cases. Therefore, it should be possible to alter the design of the intervention to utilise these triggers more effectively for current educational needs.

The overemphasis of particular approaches to tasks has created current inflexibilities within students' approaches to convergent STEM tasks. Therefore, there needs to be greater emphasis on a developing a variety of skills and this will have to be accompanied by using varieties of task styles. This will also aid in the development of flexible conceptualisation abilities, which are more authentic to the situational demands of the tasks as opposed to being abstractly stored in a simulation in long term memory.
This study also provides additional evidence to support the focus on developing robust visuospatial cognitive skills as part of STEM education. The theory that visuospatial cognitive processes implemented during the conceptual framing of problems allows greater access to simulators in long-term memory, is supportive of this focus. Ultimately, equipping students within STEM education with this core competency will likely lead to a more flexible ability to conceptualise problems in a variety of situations. This forms a key recommendation and aligns with the contemporary philosophy of developing adaptive learners (Claxton 2008, Robinson 2001).
8 FUTURE WORK
8.1 Future Work

This chapter will outline consideration for future work arising from the conclusions of the study:

- The study was initially conducted to determine how student teachers are framing convergent problems so was undertaken in a third level context. Past experience was indicated as one of the largest factors influencing the conceptualisation process and this lead to a trend of conditioning being uncovered. It would therefore be interesting to expand the scope of the study to encompass second level students and determine if these trends exist from an earlier stage in the current education system.

- The study provides empirical support for a relationship between conceptualisation and overall approach taken to solving convergent tasks. Convergent tasks are utilised as key interventions in the development of core competencies with STEM education, which then facilitate students advancing to more open ended divergent tasks (Kimbell 1994). The application of the method to divergent style tasks should be undertaken to explore the nature of conceptual framing when there is no obvious optimal approach or solution.

- The study provides strong evidence for the advantages of visuospatial cognition in constructing authentic conceptual frames for problems. Further research should be taken on this hypothesis with a larger sample size and considering the variable of spatial ability. Exploring the relationship between levels of spatial ability and conceptualisation of applied tasks would allow for a deeper understanding of this area. This could provide further evidence in explaining the relationship between high levels of spatial ability and achievement in other disciplines as uncovered by Sorby (1999).

- The influence of past experiences on the conceptualisation of the convergent tasks is supported in the evidence. Some of this has been discussed as a negative in terms of the existence of conditioned approaches to learning
which ultimately lead to rigid framing of problems. Future research should focus on the nature of task design, which could ultimately aid students in framing problems in effective manners, which align with learning outcomes of the task.

- Certain conceptualisation strategies lead to more optimal problem solving approaches for participants, which was indicated by lower levels of cognitive load and greater efficiency. Future work should further investigate the relationship between conceptualisation and cognitive load to determine if there is a bi-directional effect.

- As this study only encompassed students from a STEM background, a question remains as to whether the findings are limited to this context. Future work should therefore consider investigating the conceptualisation and subsequent problem solving approaches of students within different disciplines.
9 PUBLICATIONS
9.1 Associated Publications

**Peer Reviewed Conference Publications:**


Peer Reviewed Journal Publications:


10 REFERENCES


Kosslyn, S. M. and Pomerantz, J. R. (1977) 'Imagery, Propositions and the Form of Internal Representations', *Cognitive Psychology*, 9, 52-76.


Steinhauer, H. M. (2011) 'Graphical Communications: A Concept Inventory', in 118th ASEE Annual Conference and Exposition, Vancouver, B.C Canada,


11 APPENDICES
11.1 Appendix 1

This appendix contains all 15 tasks that were selected for use in the study. These tasks were taken from the "INULIS" database and are presented here in their respective categories.

**Task A**
A TV measures 26 inches across the diagonal of the screen, which is 20 inches wide. What is the height of the screen? (Answer to the nearest half inch)

ANS: 16.5 Inches

Figure 120: Task A - Application of Theorem (Mathematical Category)
**Task B**  
The recommended sizes for goals for mini-soccer are 3.66m wide by 1.83m high.

Approximately how much lightweight tubing would be used to construct the front frame of the goal? (Answer to one decimal place)

ANS: 7.3m

![Figure 121: Task B - Simple Arithmetic (Mathematical Category)](image1)

**Task C**  
The diagram shows the net of a pyramidal chocolate box. How many square centimetres of cardboard is needed to make the box?

ANS: 220cm squared

![Figure 122: Task C - Application of Formula (Mathematical Category)](image2)
**Task D**
A square lawn was extended in width by 2m and in length by 3m. The area of the new lawn is twice as big as the area of the old lawn. What are the measurements of the old lawn?

ANS: 6m x 6m

Figure 123: Task D - Algebraic (Mathematical Category)

**Task E**
What is the length of the diagonal of the largest square-shaped piece of paper you can tear from the sheet of paper in the diagram below? (Answer to 1 decimal place)

ANS: 11.3cm

Figure 124: Task E - Identification and Application of Theorem
**Task F**
Kitchen cupboards come in the following widths:
- 400 mm
- 500 mm
- 600 mm
- 750 mm

Which of the following combinations of cupboards exactly fit a wall that is 2.6m wide?

<table>
<thead>
<tr>
<th>Combination A</th>
<th>4 x 400 mm</th>
<th>2 x 500 mm</th>
<th>0 x 600 mm</th>
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<td>Combination D</td>
<td>0 x 400 mm</td>
<td>1 x 500 mm</td>
<td>1 x 600 mm</td>
<td>2 x 750 mm</td>
</tr>
</tbody>
</table>

**Figure 125: Task F - Simple Arithmetic/Image Holding and Comparing (Dual Approach Category)**

**Task G**
The rack in which the boxes are stored while awaiting collection has compartments of the correct width and length but is only 1 metre high. How can the boxes be packed so as to use only 3 compartments?

**Figure 126: Task G - Simple Arithmetic/Image Holding and Comparing (Dual Approach Category)**
**Task H**

Drinks cans are made by stamping out circular discs from a sheet of metal. Ans: 50

The rectangular sheet from which the circles of 10cm radius are stamped out measures 1m by 2m. How many can tops can be made from this sheet?

Figure 127: Task H - Application of Formula/Image Holding and Comparing (Dual Approach Category)

**Task I**

How many square boxes with a volume of 343cm cubed will fit an open shelf 1.2m long with a width of 10cm?

ANS: 17

Figure 128: Task I - Application of Formula/Image Holding and Comparing (Dual Approach Category)
**Task J**
How many ways can you travel from A to B in the diagram if you can only proceed eastwards and southwards at every intersection?

![Diagram](image)

Ans: 35

Figure 129: Task J - Probability/Image Holding and Comparing (Dual Approach Category)

**Task K**
Imagine an ant walking across the cube from points A to B. Illustrate the shortest path for the ant to walk from A to B along the surface.

![Diagram](image)

Ans:

Figure 130: Task K - Dynamic Imagery (Visuospatial Category)
**Task L**
How many times greater is the volume of container B when compared to that of container A?

ANS: 8

Figure 131: Task L - Image Holding and Comparing (Visuospatial Category)

**Task M**
Illustrate the following square abcd after it has been rotated clockwise through an angle of 90 degrees.

Figure 132: Task M - Planar Rotation (Visuospatial Category)
**Task N**
Which of the following pentominoes will make an open topped box?

A  

B  

C  

Ans: All

*Figure 133: Task N - Dynamic Imagery (Visuospatial Category)*

**Task O**
One view of a cube which has been cut by a single plane is shown. The plane cuts two edges of the cube in their mid-points and one edge of the cube at a one-third point.

Reconstruct a pictorial image of the cube showing where it is sliced.

*Figure 134: Task O - Kinetic Imagery (Visuospatial Category)*
11.2 Appendix 2

This appendix contains the interview schedules for the post-task and follow-up stimulated recall sessions respectively.

**Post-Task Interview Schedule**

1. Overall, how did you find the tasks?
   a. Probe – e.g. could you elaborate a little more on that?
2. In general, could you describe the amount of effort you needed to give to complete the tasks?
   a. May have to explain here – so the amount of mental effort you had to exert to progress the task
3. Were there any tasks that you had to use a lot of effort on?
4. What was your approach to this problem?
   a. What was the first thing that went through your head when you began this task?
      i. Probe – could you be more specific/elaborate....
   b. Reflecting on it now, is there any other way you could have approached the problem?
      i. Another strategy?
5. Were there any tasks that you found particularly easy or that you had to exert minimal effort on?
   a. What was your approach?
   b. Could you have done this another way?
   c. If so why did you choose the approach you did?
      i. Probe if needed!
6. Could you describe your general strategy to solving all of these tasks?
   a. Probe – could you be more specific/what do you mean exactly by ....
   b. Why do you think, did you adopt such a strategy?
   c. Would these styles of problem be something you encountered in the past?
7. Is there anything else you would like to talk about that I haven’t asked?
8. Are there any questions which you would like to revisit?
9. END.
**Follow-Up Stimulated Recall Interview Schedule**

The core aim of utilising a stimulated recall (SR) approach is to facilitate a reflective discussion on yesterday’s problem solving activities. One of the primary purposes of employing a stimulated recall approach is to ground the interview in a particular situation and stimulate further reflection (Bryman 2008). It is particularly useful for triggering participants’ reliving of and reflections of particular episodes. For the purpose of this study three episodes within a participant’s problem solving session were identified as follows:

A task where the participant displayed a:

1. Maximum efficiency
2. Medium level of efficiency
3. Poor level of efficiency

As one of the core aims of the study is to investigate task conceptualisation and its relationship to efficiency (capacity) in problem solving performance, these episodes were determined based on calculations of efficiency proposed by Hoffman and Schraw (2010). This model consists of calculating the ratio of performance to effort or time. As this study focuses on the conceptualisation process which is highly subjective in nature, it was decided to employ subjective ratings of mental effort as a calculating variable. The use of subjective measures is in line with previous literature on cognitive load theory (Sweller et al. 2010, Sweller et al. 1998). The formula for the calculation of efficiency is displayed below.\(^8\)

\[ E = \frac{P}{R} \]

Equation 3

The performance scores were computed based on a scale of professional judgement ranging from 0-10.

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\(^8\) Where E = efficiency, P = performance and R = effort
Once the values of efficiency for all 15 tasks per participant were calculated the three matching the criteria explained above were selected and the video segments were marked for the interview.

**Questions:**

1. Just before we begin looking at specific tasks, could you comment on what you thought was expected of you during the tasks yesterday?
   a. May have to explain here – so when you came in and the headgear and video camera were introduced what did you think was expected of you?
   b. Were you to just get to a solution or was your approach more important?

2. Select the tasks (order as above):
   a. Can you describe your approach and what you were thinking as the video plays – feel free to stop at any point!
   b. Reflecting on this task, could you have done anything differently?
   c. Why then did you choose the approach you did
      i. Efficiency?
      ii. Minimal effort?
      iii. Easier to remember?
   d. May have to present an alternative if the participant can’t think of one

3. Repeat step 2 for the next two tasks

4. Reflecting on the 15 tasks, can you classify your general approach to these problems?

5. Do you think that some of the problems you engaged with this approach may have been solved more efficiently using a different strategy?
   a. (If so) why did you use the one you did?
   b. Is it an approach that you are just familiar with?
   c. Where would you have used such an approach before?
   d. Can you give specific examples?

6. Are there any other tasks that you would like to look at?

7. Is there anything else you would like to talk about that I may not have asked?
8. Do you want to revisit any of the questions in this interview once more?
11.3 Appendix 3

Contained in this appendix are all the tabulated data relating to performance scores (gained from scale of professional judgement), performance times spent on task and mental effort scores.
Table 6: Resultant Scores After Applying Scale of Professional Judgement

<table>
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<th>PART</th>
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<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
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Table 7: Time Spent on Each Task

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*Note.* Blank cells indicate a missing effort value
11.4 Appendix 4

This appendix contains a sample of topographic scalp plots produced during EEG analysis for a single task for all twelve participants. The complete set containing all participants and every task are located in volume 2, appendix 2 on the attached CD.
Participant 07 Task H - Theta

Conception Period (19%)

50%

75%

100%

Participant 07 Task H - Alpha

Conception Period (19%)

50%

75%

100%