Expertise and Reasoning: Dual Process versus Modular Approaches

Zoe Purcell

First Class Honours BA in Psychology, Macquarie University, 2014

Dissertation submitted in fulfilment of the requirements for the degree of Masters of Research.

Macquarie University, Human Sciences, Psychology

Submitted On: 9 October 2015

Table of Contents

Declaration....4

Acknowledgements....5

1. Introduction....7

1.1 Overview....7

1.2 Dual-Process Theories....8

1.3 Modularity Theories of Reasoning....14

Carruthers' cognitive architecture for dual-process reasoning....15

Complex Emergent Modularity Model....18

Global workspace theory....20

1.4 Summary....24

2. General Method....24

2.1 Overview....24

2.2 Participants....25

2.3 Materials....26

Cognitive Reflections Test....26

Problem Solving Test....26

2.4 Procedure....27

3. Experiment 1....28

3.1 Rationale and Hypotheses....28

3.2 Design....29

3.3 Method....30

3.4 Results ... 30

3.5 Discussion ... 32

4. Experiment 2 ... 33

4.1 Rationale and Hypotheses ... 33

4.2 Design ... 35

4.3 Method ... 36

4.4 Results ... 39

4.3 Discussion ... 41

5. General Discussion ... 43

Cognitive load ... 47

Expertise. ... 51

Future directions. ... 54

Appendix A ... 63

Appendix B ... 65

Declaration

The work in this dissertation has not been submitted for a higher degree at any other university or institution. All intellectual property belonging to any person other than myself has been cited appropriately throughout the dissertation. Ethics committee approval has been obtained the study that was completed for this dissertation; the protocol numbers is 5201500347, see Appendix B.

Acknowledgements

I would like to sincerely acknowledge my supervisor Associate Professor Colin Wastell for providing me with unwavering support and encouragement, and invaluable guidance throughout this process, without him this project would not have been possible. I would also like to thank my family and friends who went above and beyond to support me over the past year.

Abstract

Dual process theories suggest that reasoning involves autonomous (Type 1) processes and effortful (Type 2) processes. In contrast, modular theories of reasoning assert that the mind consists of a multitude of in- out- information processors (modules). The Cognitive Reflections Test (CRT)(Frederick, 2005) contains three worded maths problems for which the intuitive answer is incorrect. It has often been used to support dual process theory. This thesis contains two experiments that examine the influence of font fluency (Experiment 1) and cognitive load (Experiment 2) on the CRT, and how these effects vary between participants with different levels of mathematical expertise (math and non-math participants). Changes in font fluency had no effect on CRT performance. Performance of math participants decreased under load but remained higher than non-math participants. Cognitive load did not affect the performance of non-maths participants who performed consistently poorly compared to math participants. In both experiments, math participants outperformed non-math participants. The results suggest that expertise is a key factor in problem solving and that both dual-process and modular theories can support the present finding. However, this thesis suggests that research investigating the role of expertise in reasoning may benefit from using a modular reasoning framework.

1. Introduction

1.1 Overview

Gilbert (1999) observed that under behaviourism, psychology produced “a generation of disaffected cognitive revolutionaries and an extraordinary number of well-trained pigeons” (p. 8). Gradually these disaffected revolutionaries moved away from behaviourism and began to examine the internal processes of thinking. Questions such as “Are humans rational?” and “What is consciousness?” were no longer philosophical mysteries, but topics for empirical investigation. With rationality under examination, a large body of evidence emerged indicating that humans make errors and are influenced by biases in decision-making (e.g. Kahneman & Tversky, 1979; Tversky & Kahneman, 1974). In an attempt to account for this evidence, a number of dual-process theories of reasoning emerged and gained substantial traction (e.g. J. Evans, 2010; J. S. B. T. Evans, 1984; Petty & Cacioppo, 1986).

The premise behind dual-process theories is that the mind consists of two separate sets of reasoning processes: one responsible for decisions that are easy, automatic and nonconscious, and the other for decisions that are difficult, deliberative and conscious. However, these theories have been heavily criticised as unscientific models and for their insufficient explanation of key phenomena such as interaction and coherency that is, how would two neurologically separate processes interact so as to form one coherent reasoning experience? (Keren & Schul, 2009; Kruglanski & Gigerenzer, 2011; Wastell, 2014). Alternative models have subsequently arisen, some of which incorporate elements of theories of cognitive architecture (Carruthers, 2009; Wastell, 2014). The incorporation of cognitive theories, in particular the modular (Fodor, 1983) and global workspace hypotheses (B. Baars, 1988), has helped to address a number of the weaknesses in the preceding reasoning models. However, they have received little empirical investigation.

This thesis offers a brief outline of reasoning literature, highlighting the key themes and contrasting predictions, and then examines some of these predictions over two experimental studies. It is focussed on dual-process theories, in particular that proposed by J. Evans and Stanovich (2013), and modular models of reasoning, in particular those hypothesised by Carruthers (2009) and Wastell (2014). The experimental component of this thesis first examines the dual-process assertion that a supervisory reasoning process, when active, can override incorrect default responses. Building on the finding in Experiment 1, that skill levels had strong effect on reasoning, the second experiment explores the role of working memory in reasoning and whether this relationship differed on the basis of expertise.

The present thesis explores formal (rather than experiential) reasoning processes as defined in the *Encyclopaedia of Cognitive Science* (2003). Reasoning refers to the cognitive processes in which "information is combined, in an inference, to yield new information" (p. 863). Problem-solving is a form of reasoning involving the "analysis and transformation of information towards a specific goal" (p. 728). Problem solving involves three general stages: understanding, production, and judgement. First, the criteria for a solution is established; second, the relevant information is manipulated by an appropriate procedure; and third, the candidate solutions from the second stage are compared to the solution criteria from the first stage, if they match, a solution has been reached. A number of procedures may be required to reach the goal solution; this can be conceptualised as a chain of procedures.

1.2 Dual-Process Theories

There are many dual-process theories of reasoning (also known as dual-systems theories) (e.g. Evans St & Over, 1996; Sloman, 1996, 2002; K. Stanovich, 1999). These theories delineate the properties of Type 1 and Type 2 processes (summarised in Table 1) and their underlying neural mechanisms (Lieberman, 2009; Smith & DeCoster, 2000; for a critique Kruglanski, 2013). This thesis will refer to the dual-process model from the default-interventionist approach as outlined by Evans (2010; see also Evans & Stanovich, 2013) as it is representative of the main dual-process theories and facilitates engagement with the most recent debate. Dual-process theories are widely accepted but have also attracted criticisms that question the scientific validity of the model and highlight conceptual gaps in the model. The present thesis focusses on working memory, cognitive de-coupling, autonomy, consciousness and cognitive ability (see Table 1). These factors play a deterministic role in dual-process theories, are prominent themes across theories of cognitive architecture and present opportunities for empirical investigation.

Table 1. *Cluster of attributes frequently associated with dual-process and dual-systems theories of higher cognition.*

Type 1 Processes (Intuitive)	Type 2 Processes (Reflective)
Defining features	
*Does not require working memory**	*Requires working memory**
*Autonomous**	*Cognitive de-coupling: mental simulation**
Typical correlates	
Fast	Slow
High capacity	Capacity limited
Parallel	Serial
Nonconscious*	Conscious*
Biased responses	Normative responses
Contextualised	Abstract
Automatic	Controlled
Associative	Rule-based
Experience-based decision-making	Consequential decision making
Independent of cognitive ability*	Correlated with cognitive ability*

System 1 (old mind)	**System 2 (new mind)**
Evolved early	Evolved late
Similar to animal cognition	Distinctly human
Implicit knowledge	Explicit knowledge
Basic emotions	Complex emotions

Note. Italicised attributes are interpreted as the key defining characteristics of Evans and Stanovich's (2013) dual-process theory. * focussed on in this thesis.

Evans (2010) used the term 'intuitive mind' to describe Type 1 processes which he summarised as fast, intuitive and with the capacity to process large amounts of information in parallel, and the term 'reflective mind' to describe Type 2 processes summarised as slow, reflective and with limited information capacity. Evans (2007) explored three potential ways that the separate processes might interact: pre-emptive conflict resolution; parallel-competitive; and default-interventionist. In spite of finding all three solutions unsatisfactory and experimental evidence not ruling decisively against any one solution, Evans and Stanovich (2013) adopted the default-interventionist model. This default-intervention view suggests that Type 1 processes generate an initial default response, that Type 2 processes can intervene to override this response if necessary and capable, and that Type 2 processes win out when no Type 1 response is selected.

Evans and Stanovich (2013) assert that the default-interventionist model is supported by previous studies that suggest the disposition to override incorrect intuitive responses is a function of other factors such as feelings of rightness during the initial intuition (Thompson, 2009; Thompson, Turner, & Pennycook, 2011). For example, Thompson et al. (2011) found that people who are more confident of their initial intuitive response are less likely to change their answer after reflection. However, as Thompson et al. (2011) note, this finding not only advocates for the alteration of the default-intervention model (by including a metacognitive mechanism) but can also be interpreted within other decision making theories. As with many of the findings used to support the dual-process theories, the correlational nature of the evidence weakens any subsequent deterministic or directional claims.

Kruglanski and Gigerenzer (2011) criticised dual process theories, and in particular Evans and Stanovich's (2013) model, because the definitions offered were vague and multiple. Evans and Stanovich (2013) therefore clarified the 'defining characteristics' from those that were merely correlational in nature (see Table 1). However, this clarification seemed only reinforce another criticism – that the theory is based on circular restatement (Gigerenzer, 2010). Evans (2010; Evans & Stanovich, 2013) asserted that autonomous processes can operate and control behaviour without working memory. Evans & Stanovich (2013) distinguished Type 2 processing from Type 1 as Type 2 processing involves cognitive de-coupling and hence requires working memory. These assertions lead to two problems. First, the suggestion that Type 1 processes can operate with or without working memory makes this claim seemingly untestable in that the presence of working memory cannot distinguish Type 1 from Type 2 processes. Second, describing one type of reasoning in terms of the other does not aid our understanding of the constructs.

As highlighted by Thompson (2013), these definitions imply that the delineation of processes may only require a single point of differentiation for example where one type is autonomous and the other is not. However, a complementary autonomy solution falls into another theoretical problem, that of using one-word definitions. As Gigerenzer (2009, 2010) states, the use of one-word explanations are so flexible that they can explain almost any phenomena. One-word explanations can account for phenomenon any *A* and it's opposite, *non-A*. Although Evans and Stanovich (2013) describe Type 1 processes in terms of autonomy and Type 2 processes in terms of working memory, these two descriptors are inextricably linked because an autonomous process is defined as occurring without working memory; because they describe one in terms of the other, it is akin to a one-word and circular definition. Although a complementary distinction can be useful as a descriptor for differentiating subjective reasoning experiences, one-word definitions can be neither proven nor disproven and so do not aid our understanding of the mind (Gigerenzer, 2010). To illustrate this issue, imagine that a person seeking medical attention, was advised that the problem does not lie in their kidney, rather it lies in their 'not-kidney'. This does not help the patient to isolate or explain the problem. Similarly, to define a process by the absence or presence of a single feature, does little to aid our understanding of the underlying phenomena.

Another criticism of dual-process theories is that they rely on continuous characteristics to assert a dichotomist model. Keren (2013) noted that working memory has been identified as continuous mechanism (Baddeley, 2012). Which leads to the question: at what point of working memory engagement is a reasoning process qualified as Type 1 or Type 2? Returning to the default-intervention hypothesis, the continuous nature of defining characteristics also raises the issue that, if Type 2 processes can intervene to inhibit Type 1 processes, there must be a line (and accompanying measurement) that predicts at what point on the continuum this intervention becomes possible and/or likely. Even if the point at which Type 2 process were differentiated from Type 1 processes was clarified, this does not solve the interaction problem.

The default-intervention model suggests that the way the two processes interact is that Type 2 processes play a supervisory role and can override default Type 1 errors. However, as Thompson (2013) acknowledged, this does not always happen, even when working memory is involved. For example, when offered the opportunity to rethink their initial (incorrect) answers, many participants do not change their response (Shynkaruk & Thompson, 2006; Thompson, 2009, 2013; Thompson et al., 2011). However, observed changes in confidence after reconsideration of the initial response (even when the respondent does not change his answer) indicates that some sort of additional thought had been executed and presumably involved working memory (Thompson et al., 2013). Given that active working memory does not ensure the override of Type 1 errors, dual-process advocates must explain how and why this happens on some occasions and not others.

Evans and Stanovich (2013) claim that “intervention will only occur when difficulty, novelty, and motivation combine to command the resources of working memory” (p. 237). The requirements for intervention remain unclear. For example, what combination of difficulty, novelty, and motivation, and how much of each factor is necessary, and, what mechanism makes this assessment? However, there is some evidence to support this claim. Alter, Oppenheimer, Epley, and Eyre (2007) conducted a study in which participants were required to complete the CRT which consists of three items that have intuitive responses that are incorrect. The items were presented to the participants either in difficult-to-read font (disfluent condition) or easy-to-read font (fluent condition). The participants in the disfluent condition performed significantly better on the task than those in the fluent condition, suggesting that intervention is more likely when there are metacognitive experiences of difficulty during reasoning. However, replication attempts have been inconsistent (Thompson et al., 2013).

Alter, Oppenheimer, and Epley (2013) reconcile the contrasting findings, asserting that disfluency prompts analytic thinking but that analytic thinking can only lead to improved performance for those who possess sufficient cognitive ability to do so. An alternative explanation comes from Kahneman and Klein (2009) who maintain that when there are cues that an initial judgement may be wrong, System 2 can override and replace this response with more careful reasoning. However, they suggest that the effect of cues for analytic thinking are dependent on the relative skill and expertise of the reasoner specific to the task at hand.

Dual-process theories including the default-interventionist perspective have been highly influential and offer intuitive models of thinking from the perspective of the individual reasoner. Although there is merit in describing the dichotomous subjective experience of reasoning, current dual-process theories seem limited in their ability to provide testable models for the processes that underlie reasoning. Moreover, conceptual issues such as how two separate processes interact and how they generate a coherent sense of reasoning, have not been sufficiently explained or adequately supported by empirical evidence. In order to advance our understanding of key issues, such as interaction and coherency, some theorists have begun to incorporate models of cognitive architecture.

1.3 Modularity Theories of Reasoning

Fodor's influential book *The Modularity of Mind* (1983) suggested that the human mind is made up, to some extent, of domain-specific information processors which he called modules. Since then various modules have been proposed such as a face-recognition and theory-of-mind (for a list see Stanovich, 2004, p. 44). More recently, albeit with a slight semantic change (see Carruthers, 2006), the concept of modularity has been used to assist our understanding of higher level functions. Advocates of massive modularity assert that the mind is entirely modular including processes responsible for problem solving and decision making (e.g. Carruthers, 2006; Cosmides & Tooby, 1992; Pinker, 1997). One of the benefits of incorporating modularity into theories of reasoning is that a modular structure does not require additional mechanisms for executive control, such as supervisory or monitoring mechanisms. Rather their operation is determined by the modules' specific input requirements.

Modules, according to massive modularity proponents, are "functionally specialised mechanisms with formally definable informational inputs" (Barrret & Kurzban, 2006, p. 630). A module is triggered by specified informational inputs. If the trigger criteria for a module is met, its operation is mandatory. That is, given the trigger criterion are present, a module will generate an output regardless of the individual's intent. Hence a modular structure does not require an additional mechanism to determine whether this operation will occur because modules contain built in gating systems by way of specific input criteria. The challenge for proponents of a modular cognitive architecture is to allow for flexibility and coherency (Roberts, 2007). That is, how can a cognitive architecture built on processes with predetermined input criteria allow for reasoning in novel situations, how can new modules be developed, and how can a multicomponent architecture allow for a coherent sense of reasoning?

To address these questions, modular theories of reasoning often focus on the roles of working memory, learning, and expertise. There are a number of modular models of reasoning (e.g. Mercier & Sperber, 2011; Barrett & Kurzban, 2006). However, the present thesis focusses on the perspectives of Carruthers (2009) and Wastell (2014) because together, they provide a helpful bridge between dual-process theories and cognitive theories of working memory, and in particular the Global Workspace Theory (GWT)(Baars, 1988). This thesis also gives an outline of the GWT because although it does not centre on reasoning and problem solving, its hypotheses for working memory and consciousness have significant implications for reasoning and problem solving. The predictions within these models have implications for findings and predictions made by dual-process theories.

Carruthers' cognitive architecture for dual-process reasoning. Carruthers (2009) presented perhaps the most comprehensive integration of modularity and dual-system reasoning theories[1]. He presents an argument for the delineation of the systems by nature of their processes rather than physical or mechanistic realisations. Potential solutions to the interaction and coherency issues in dual-process theories are inherent in his model. Rather

[1] He refers to System 1 and System 2 in accord with earlier dual-systems models (e.g. Evans & Over, 1996; Sloman, 1995, 2002; Stanovich, 1999). In case of unexpected theoretical ramifications, the present thesis will use the terms as he has done. However, for the arguments presented here they can be understood as akin to Type 1 and Type 2 processes respectively.

than postulating that the systems compete or that one system can override the other, he asserts that the underlying structures of reasoning processes are the same. In line with Stanovich's TASS theory (2004), Carruthers (2009) asserts that System 1 is comprised of semi-independent modules. However, he suggests that dual reasoning experiences are the result of different patterns of activation rather than separate mechanisms. System 1 and System 2 do not exist separately, rather, System 2 is realised through the cycles of operations of System 1. This is also the position taken by a number of cognitive and computational psychologists (e.g. Faghihi, Estey, McCall and Franklin, 2015).

The mental rehearsal of an action leads to the generation of a mental representation which can, in turn, be broadcast via cyclical realisations of System 1 processes (Carruthers, 2009). The global broadcast of representations facilitates communication between modules because the representations can then be received as input by other modules. The GWT, originally proposed by Baars (1988), asserts that broadcast occurs via the repetition and increased activation of representations, and is intimately linked with conscious awareness. Some theorists assert that representations become conscious by virtue of global broadcast (Dretsch, 1995; Tye, 1995, 2000). Others maintain that broadcast allows the 'mind-reading system' access to representations (and subsequently conscious awareness of them) but that broadcast and consciousness are not the same phenomenon (Lycan, 1987, 1996; Carruthers, 2000; 2005). Broadcast allows mental rehearsals to access multiple knowledge sources and procedures, and arrive at novel solutions to problems. The global broadcast of representations can hence facilitate flexibility within a modular cognitive architecture. It should be noted that the issue of conscious versus nonconscious processing is akin to the interaction problem in dual process theories (how the two systems interact) addressed earlier. However, within the GWT, conscious and nonconscious processes are not separate or competing processes, rather processing becomes conscious when the patterns of activation stabilise in a regular cycle.

While Carruthers’ (2009) model affords flexibility and communication for the purpose of solving immediate novel problems, there is little explanation for the way that modules can be developed through training or learning. Carruthers asserts that modules are designed for learning and suggests that because System 2 is action-based, reasoning processes can be learned in the way that action processes are learned. Motor skills are learned through imitation, instruction, and beliefs about how one should perform an action; System 2 thinking skills should therefore be learned through imitation, instruction and beliefs about the way one should reason. While this is not a comprehensive account of the underlying process of module development, it does imply that, just as behavioural skills can be, modules can be developed to the point of automation.

There are a number of limitations in this account of reasoning. The role of consciousness remains unclear. If conscious awareness occurs by virtue of global broadcast it may lead to the redundancy of dual theories of reasoning (beyond a convenient metaphor), as consciousness would then appear to be the major underlying distinction, rather than any associated phenomena (e.g. working memory, automation and cognitive de-coupling). Consciousness may also be related to the way that we come to a coherent experience of reasoning. If one postulates that the mind is made up entirely of modules, there must be an accompanying solution for coherent sense of reasoning. By incorporating cognitive theories of consciousness, in particular the GWT, more comprehensively a modular architecture may be able to account for coherency.

In sum, Carruthers’ (2009) asserts that System 1 is semi-modular and System 2 is realised through cycles of System 1 operations. In doing so, he provided a defence for one sort of dual system theory. However, it could be argued that this approach is best reflected as a multi-component or modular account for reasoning, in that the repeated activation of a module may not warrant the distinction of the process as different type of decision. The shift from the use of terms such as dual-systems to dual-process seems to reflect a shift in the general assumptions of dual reasoning theories toward a more process based distinction. The defining aspects in Evans and Stanovich (2013) (refer to Table 1) also seem to reflect process driven dualism (albeit with the limitations highlighted earlier). However, this seems to be the extent of the inclusion of this notion in the model. If they concur with a process based distinction like Carruthers' they need to explain how a Type 2 decision might override a Type 1 decision within a modular, process-distinguished framework.

Complex Emergent Modularity Model. Wastell (2014) asserted that previous reasoning theories do not sufficiently account for humans' sense of coherency in reasoning, how the proposed dual-processes interact, or how they deal with novel situations. He proposed a new theory to address the shortcomings of dual- and single- process models by combining aspects of complexity, emergence, and modularity theories. Wastell's (2014) complex-emergent-modularity model (CEM) accounts for reasoning in novel situations with the inclusion of 'virtual modules'. Wastell introduces virtual modules to distinguish learnt from innate modules. A virtual module is "a learnt mental representation that is triggered automatically by specific information characteristics of the task or problem… experienced as mandatory and often without conscious awareness" (Wastell, 2014, p. 11).

Virtual modules allow for flexibility within a massive modular framework in three ways. First, virtual modules can execute abstract operations – that is, they can deploy an operation such as addition with varying input (e.g. different numbers) provided they satisfy the trigger conditions of the module (e.g. numeric and operational information). In other words, the input criteria are loosened somewhat to allow more flexible activation. Second, practiced chains of procedures can become a new virtual module (or modules) such that it can operate automatically. Third, virtual modules are dynamic when interacting consciously, for example, when under explicit instruction. That is, modules can be combined to perform more complex information processing when the output from one module can be received as input for another.

Under the CEM, virtual modules can be created through experience in the form of explicit instruction and practice or, through repeated exposure and feedback on success. This assertion suggests that the underlying structure of processing units remain the same, but the mandatory execution of a process is possible through learning. However, the way that virtual modules are created is not inherent in the structure proposed by CEM, and requires further clarification. The CEM emphasises the role of learning in developing virtual modules and recognises it as an important query for future research.

Another way that the CEM allows for flexibility in a modular mind is the inclusion of consciousness as a key component, particularly for reasoning in novel or infrequent situations. McGovern and Baars (2007) assert that consciousness facilitates the access to, and recruitment of, multiple knowledge sources which can be adapted and reconfigured to broader circumstances. Similar to Carruthers (2009), Wastell (2014) suggests that when a novel task or problem becomes conscious it can be addressed by utilising knowledge and operational resources (i.e. modules) which were not originally developed for that task. These novel procedures may become virtual modules over time but for the purpose of solving immediate problems consciousness may be required for reorganisation and flexibility. The potential for consciousness to allow the flexible combination of modules is understated in the CEM but presents an interesting avenue for further investigation within the development of models of reasoning. The implications of consciousness in the CEM map closely onto the GWT which offers key insights that may assist models of reasoning to incorporate consciousness more comprehensively.

In addition to predictions for the flexible operation of a modular architecture of reasoning, the CEM also addresses the issue of coherency. The CEM utilises complexity theory (Mitchell, 2009) to explain how a multicomponent modular mind could interact to form a coherent sense of reasoning. Wastell (2014) uses Reynold's (1987) 'Boids' program as an example of complex emergent behaviour in which notional birds, each following a simple set of rules, can create apparent complex unified flock behaviour without any central control. He likens this to modules, proposing that they operate according to simple, automatic processes and come together to form coherent reasoning.

Wastell's (2014) theory provides a plausible alternative to previous models and incorporates key themes such as automaticity, learning and expertise, and consciousness. Like Carruthers (2009), the major strength of this model is that it incorporates a cognitive structure wherein the outcome (whether a certain decision is made or not) is built in rather than requiring another mechanism that performs this function. The CEM addresses issues of flexibility and coherency in a modular approach. However, an explanation of how new virtual modules are created is needed, as well as a more comprehensive account of flexible reasoning under consciousness. Most importantly, the claims made by Carruthers (2009) and Wastell (2014) require experimental evidence based on *a priori* hypotheses.

Global workspace theory. A major challenge for modular reasoning theorists is to explain how a modular architecture can integrate information in such a way that it enables reasoning in novel situations and accounts for a coherent reasoning experience. A number models of reasoning have referred to the GWT for potential solutions to this challenge or allude to similar hypotheses (Carruthers, 2009; Wastell, 2014). Baars (1988) refers to a global workspace as a functional hub which has the limited, but dynamic, capacity for the binding and broadcasting of specialised knowledge or operations (i.e. modules). The GWT asserts that consciousness reflects a global workspace function when multiple input streams stabilise on a winner-takes-all gestalt. Although the primary aim of the GWT is to distinguish conscious from unconscious phenomena which is not a central element of the empirical aspect of this thesis, the model complements modular theories of reasoning by incorporating a neural model for a modular architecture of mind, and addressing key themes such as solving novel problems, automaticity, and feelings of knowing.

Shanahan (2010) proposed a neural structure which can facilitate the predictions from the GWT with multiple scales of small-world networks. The brain can be conceived of as a network of nodes (neurons) and links (synapses) (Franklin, Strain, Snaider, McCall, & Faghihi, 2012). A module can be thought of as a number of nodes which are densely connected internally, but sparsely connected externally. Small-world networks have dense local connections and sparse global connections. Shanahan (2010) proposed a hierarchical modular cognitive architecture in which smaller cell assembly modules are nested within larger cognitive modules. Additionally, he postulated a core network of connective hubs through which information between modules pass. In line with the limited capacity of the global workspace, the connective core can only process one combination of processes at a time. Shanahan's (2010) structure is supported by evidence from neuroscience, for example for a connective core (Hagmann et al., 2008) and hierarchical small-world modules (van den Heuvel & Sporns, 2011). This structure would facilitate the communicative assumptions of the GWT while maintaining the ability of smaller processes to have a global influence via broadcast.

Conscious moments are thought to hold only 1-4 unrelated items simultaneously; Baars et al. (2013) asserts that the limited capacity of consciousness, may be "the biological price to pay for global access" (p.1). This model suggests that only a single representation can be conscious at one time, other active representations may reach consciousness after some delay if the preceding conscious information drops below threshold. However, many active representations may never reach consciousness as their activation may decay over time and fail to reach the threshold for occupation of a global workspace. The GWT suggests that access to a global workspace is necessary for solving novel problems because it allows the combining and reorganising pre-existing knowledge and operations (Baars et al., 2013). Therefore, when solving a novel problem, performance would be expected to decline when an additional cognitive load is occupying the global workspace.

The GWT also asserts regarding the role of consciousness and automation. The GWT predicts that consciousness is associated with learning, and that novel skills can be automated with practice (Baars, 2002). Once automated, processes do not require the dynamic capabilities of a global workspace to operate effectively. This is supported by evidence that patterns of brain activity become less widespread after practice (e.g. Raichle et al., 1994). The assertion that new skills can be automated after practice, and hence do not require occupation of the global workspace, implies that experts would be less influenced by additional cognitive loads than novices. However, the GWT does not extrapolate on how a process is automated beyond the assertion that it is linked with consciousness and practice. Automation is a key phenomenon which requires further explanation and empirical investigation particularly in the area of problem solving.

It is widely accepted that an individual's unique experience and practice, and subsequent expertise, will affect their cognitive processing for tasks related that to that area of expertise (e.g. Ericson & Smith, 1991; for reviews specific to mathematical problem solving and cognition see Baroody & Dowker, 2003, and Campbell, 2005). The GWT implies that differing levels of expertise would impact the way a particular problem is solved. Novices, who do not possess the appropriate pre-existing knowledge, or operations which could be effectively combined to reach an accurate solution, would not be expected to perform any differently given the flexibility of a global workspace or not. Intermediate problem solvers who possess the appropriate pre-existing knowledge and operations, but have not practiced the problem or problem type to the point of automaticity, would be expected to be able to solve novel problems given the flexibility of the global workspace. Experts who have practiced the problem or type of problem to the point of automaticity do not need the flexibility of the global workspace to solve the problem.

The GWT does not restrict conscious representations to sensory concepts involved with working memory such as phonological and visual representations. For example, the GWT also incorporates an emotional component of consciousness in what Baars (2013) refers to as feelings of knowing (FOK). Baars acknowledges that FOKs are subjectively vaguer than sensory experiences which have easily discernable physical and temporal properties but asserts that the underlying structure is precise. FOKs can be bound and propagated in the global workspace but originate in the non-sensory regions of the cortex (e.g. frontoparietal region and anterior temporal cortex). Examples of FOKs like the tip-of-the-tongue experience indicate that FOK exists and can become active to the extent of a conscious awareness of it. However, it is unclear if or how FOKs interact with sensory information, and whether they can influence practical reasoning. The idea that there is an emotional component to reasoning is acknowledged in dual-process theories (e.g. Evans & Stanovich, 2013). However, in both the GWT and dual-process theories, the relationship between metacognition and reasoning requires further clarification and empirical investigation.

The GWT is the most widely accepted theory for the role of consciousness in cognition (Franklin et al., 2012) and has been applied to a number of basic visual, motor and speech based phenomena. However, there is little research which explicitly explores the implications of this model for complex problem solving and decision making. The combination of modular reasoning models with the GWT has been sparse and largely superficial (e.g. Carruthers, 2009). An extensive integration of these models may assist our understanding of the mechanisms which underlie the behavioural and subjective differences observed in reasoning and decision making research. It would help to address gaps in previous theories by incorporating elements such as consciousness, individual differences in cognitive ability (both general and specific), and learning. The incorporation of these elements could help to solve the issues of interaction and coherency faced by dual-process and modular theories of reasoning. Further, the development of a comprehensive model of decision making which integrates and relates these phenomena is likely to be more conducive to empirical investigation with the removal of circular definitions, one-word definitions, and testable predictions, this is, in part, the motivation behind the present thesis

1.4 Summary

This thesis presents two experiments which examine problem solving from the perspectives of dual-process theories, modular reasoning theories and the GWT. The experiments focus on prominent factors across reasoning research including metacognitive cues, working memory and expertise. The empirical investigation of these factors supplements the existing body of reasoning research and provides preliminary findings which have promising implications for future research.

2. General Method

2.1 Overview

Experiment 1 focused on the role of metacognitive cues. Experiment 2 focused on the role of working memory. To engage directly with the previous reasoning research and generate comparable findings, both experiments measured performance on the CRT as the dependent variable (e.g. Alter et al., 2007). The experiments included a quasi-experimental factor of expertise based on the participants' major area of study which were used to categorise the participants as 'math' and 'non-math'. Math participants included those undertaking university courses with a high level of focus on mathematical skill such as engineering and actuarial studies. Non-math participants were first-year undergraduate psychology students whose studies had less focus on mathematical skill. Students whose studies were mathematical in emphasis were pooled together to allow sufficient power for data analysis. Extended rationale and hypotheses specific to each study are presented in sections 3 and 4.

2.2 Participants

The study included 162 participants; 80 in Experiment 1 and 82 in Experiment 2. All participants were undergraduate students from Macquarie University, Sydney, majoring in psychology, finance, engineering, science or actuarial studies. Psychology students were recruited through the Macquarie University subject pool website and received course credit for their participation. Other students were invited to participate during lectures and could access the study through their specific course websites; these participants had the opportunity to enter a draw for one of three $50 department store vouchers. Before consenting to participate, all participants indicated that English was their first language and that they were over 18 years.

Response patterns indicating non-compliance were removed before data analysis. Non-compliance was indicated if more than ten percent of the responses were missing. Participants who did not respond to one or more dependent variable items (CRT questions) were also excluded. Participants who indicated at the end of the experiment that they had experienced technical issues or interruptions (e.g. images not loading, internet disruptions) were also excluded.

2.3 Materials

Cognitive Reflections Test. The CRT was developed by Frederick (2005) as a simple measure of one type of cognitive ability. The CRT consists of three questions which all have tempting incorrect responses (see Figure 1). Frederick (2005) interpreted the results from a largely dual-process perspective asserting that the CRT was predictive of the types of choices that people make, particularly in regard to the problems that feature prominently in heuristics and biases research. Correct answers were interpreted as an indication of a higher degree of deliberative thinking and incorrect answers as an indication of more impulsive thinking. The Cronbach's alpha for the CRT test pooled across both experiments was .67 which is comparable to values reported in previous studies involving the CRT; for example, Campitelli and Gerrans (2014) α = 0.66; Weller et al. (2013) α = 0.60.

1) A bat and a ball cost $1.10 in total. The bat costs $1.00 more than the ball. How much does the ball cost? _______ cents

2) If it takes 5 machines 5 minutes to make 5 widgets, how long would it take 100 machines to make 100 widgets? _______ minutes

3) In a lake, there is a patch of lily pads. Every day, the patch doubles in size. If it takes 48 days for the patch to cover the entire lake, how long would it take for the patch to cover half of the lake? _______ days

Figure 1. *The Cognition Reflection Test (CRT). The correct responses are 5 cents, 5 minutes and 47 days, respectively*.

Problem Solving Test. The PST included 12 worded mathematics problems. Participants were presented with each question one by one. An example of an item in the PST is "At Woolworths, milk costs 65 cents per litre. This is 2 cents less per litre than milk at Coles. If you need to buy 4 litres of milk, how much will you pay at Coles?" This test was used in the present study due to the similarities the items have with the CRT. The CRT and PST both contain worded mathematics problems which are written in a way that reflects a real-life situation. Further, they both require similar levels of mathematical skill. Once translated into algebraic form the CRT and PST problems contain a similar number of basic mathematical operations with the exception of the first CRT item which requires substitution.

Hegarty et al. (1995) found that people who were successful at solving these problems showed behavioural differences to those who were unsuccessful, such as eye movements, which suggested the use of different solution strategies. The questions were presented in the same order as they were in the original study to increase the likelihood that the present use of the scale reflected true differences in problem-solving strategies, without measuring observed behavioural differences. Previous Cronbach's alpha were not available. However, in the present study Cronbach's alpha pooled across both experiments was .71 showing acceptable reliability. Further, all items were correlated with the total scores by more than .3. The validity of the scale is supported by the differences observed between maths (M = 10.10, SD = 2.25) and non-maths students (M = 9.07, SD = 2.01). An independent samples t-test confirmed this difference (t = 3.11, p = .002, d = .48).

2.4 Procedure

The experiments were hosted by Qualtrics online survey software (version 2013). Participants accessed the study using their own electronic devices. In both experiments participants initially provided informed consent and demographic information. General instructions were then presented in which participants were advised that they could use a pen and paper where necessary, to respond as quickly as possible and with only their final answer. Participants then completed the CRT and the PST. Participants were then asked to report if they experienced any disruptions or technical issues during the experiment. Finally, non-psychology students were required to indicate their major area of study and were offered the chance to go into a draw to win one of three $50 vouchers for department store vouchers.

3. Experiment 1

3.1 Rationale and Hypotheses

Models of reasoning and cognition suggest that metacognitive cues may influence the reasoning process, for example, they include factors such as feelings of rightness (Thompson, 2009; Thompson, Turner, & Pennycook, 2011), emotion mechanisms (Carruthers, 2009) and FOKs (Baars, 2013). The GWT suggests that there is an emotional component to reasoning and that affective information can influence reasoning processes via the global broadcast of FOKs. Carruthers (2009), similarly suggested that broadcast provides access to emotion generators in System 1 which influences the judgment of a potential act (i.e. mental rehearsal), and then whether or not to action that rehearsal. However, while they acknowledge the importance of affective aspects of reasoning, neither Baars (2013) nor Carruthers (2009) make clear predictions for the way affective components of reasoning might be operationalised and tested.

The dual process model proposed by Evans and Stanovich (2013) postulated that incorrect default Type 1 responses can be overridden by Type 2 processes, but that the tendency to do so is a function of several factors including feelings of rightness and cognitive ability. Cues of difficulty which decrease feelings of rightness reduce an individual's confidence when solving a problem, increasing the likelihood of more reflective Type 2 processing. Metacognitive factors like lowered feelings of rightness may increase the likelihood of Type 2 processing, but, for Type 2 processing to lead to correct responses, the individual must have sufficient cognitive ability to perform the task at hand (Alter et al., 2013). The inclusion of expertise as a factor in Experiment 1 was a largely exploratory addition. Given the importance placed on expertise, which is skill level in a specific area or for a specific task, in reasoning research and theory (e.g. Kahneman & Klein, 2009; Wastell, 2014) an additional quasi-experimental factor for mathematical skill was included in the experimental design. Alter et al. (2013) suggests that the effect of fluency is only possible when the individual possesses sufficient cognitive ability. Therefore, it was expected that if any fluency effect was found, the sample who possess higher math-based cognitive ability, would be more likely to demonstrate a fluency effect. However, it should be noted that these hypotheses were made tentatively and with an eye to explore new approaches to problem solving that include factors of expertise rather than to provide evidence for or against the theories aforementioned.

Experiment 1 aimed to test the replication of a previous study by Alter et al. (2007) while incorporating a factor of expertise. In accordance with preceding literature, the following hypotheses were made:

Hypothesis 1.1 Participants in the disfluent condition will perform better on the CRT than those in the fluent condition.

Hypothesis 1.2 Participants from courses with high mathematical focus will outperform participants from courses with low mathematical focus.

Hypothesis 1.3 The fluency manipulation will affect participants from courses with high mathematical focus to a greater extent than participants from courses with low mathematical focus.

3.2 Design

Experiment 1 assessed whether cues of difficulty, operationalised as changes in font fluency, interfered with the solution process and whether this effect differed between math and non-math participants. This study had a 2 x 2 between-subjects quasi-experimental design. The dependent variable was the number of correct responses on the CRT. There were two independent between-subjects factors with two levels: condition (fluent and disfluent) and participants' course focus (math and non-math).

3.3 Method

The experiment was comprised of two sections, the CRT in which fluency was manipulated with font changes, and the PST used to assess levels of pre-existing mathematical skills. These sections were counterbalanced. Participants were randomly allocated to either the fluent or disfluent condition. Those in the fluent condition completed a version of the CRT written in easy-to-read black Arial 12-point font, whereas participants in the disfluent condition completed a version of the CRT printed in difficult-to-read 10% grey italicised Times New Roman 10-point font (Figure 1). Previous research has shown that similar font manipulations effectively influence fluency (Alter et al., 2007; however, see Thompson, 2013). Expected response time for the CRT task was 30 – 120 seconds. The full procedure was designed to take approximately 15 minutes.

(a) Disfluent

> *A bat and a ball cost $1.10 in total. The bat costs $1.00 more than the ball.*
> *How much does the ball cost?*

(b) Fluent

> A bat and a ball cost $1.10 in total. The bat costs $1.00 more than the ball.
> How much does the ball cost?

Figure 1. *An example of CRT Question 1 for (a) participants in the disfluent condition and (b) participants in the fluent condition.*

3.4 Results

Results from 35 participants were excluded from the analysis due to non-compliance or technical issues. Participants were aged between 18 and 23 years. Forty-three were psychology students, and 37 were from mathematically focussed courses: actuarial (15), finance (1), science (3) or engineering majors (18). Condition allocations and demographics are summarised in Table 1.

Table 1

Allocation of Participants to Conditions by Course, Gender, and Age

Condition	N	Course Math : Non-Math	Gender Male : Female	Age M *(SD)*
Fluent	37	15 : 22	13 : 23*	19.08 *(1.50)*
Disfluent	43	22 : 21	25 : 18	19.07 *(1.42)*

*One participant did not wish to answer the item for gender.

Scores on the PST had a possible range of 0 - 12. Math participants scored higher (*M* = 10.73, *SD* = 1.19) than non-math participants (*M* = 9.30, *SD* = 1.97). An independent samples t-test showed that the difference between these mean scores was significant, t (78) = -3.84, $p < .001$. The statistical assumptions for this test were met. The Cohen's *d* indicated that this was a large effect size, *d* = .88. While this scale does not necessarily capture the underlying differences which lead to the hypothesised interaction effects, it does substantiate the separation of the sample by math and non-math participants as a reflection of mathematical problem-solving expertise. The difference in average PST scores, although statistically significant and strong in effect size, indicated that the non-numeric students were not innumerate. The average score for psychology students was 77.5% demonstrating that their mathematical capabilities were such that one would expect them to be able to understand and solve the CRT problems because the mathematical knowledge required in the CRT is similar to that required by the PST problems.

The differences between mean CRT scores were examined using a 2x2 ANOVA. The assumptions for this test were met. The analysis revealed that the main effect of condition on CRT while controlling for course was not significant (F (1, 78) = 0.296, p = .588, η^2_p = 0.004). The main effect of course on CRT while controlling for condition was significant (*F*

(1, 78) = 72.63, $p < .001$, $\eta^2_p = 0.489$). The interaction effect of course by condition on CRT was not significant (F (1, 78) = 0.027, $p = .870$, $\eta^2_p < 0.001$); this is displayed in Figure 3.

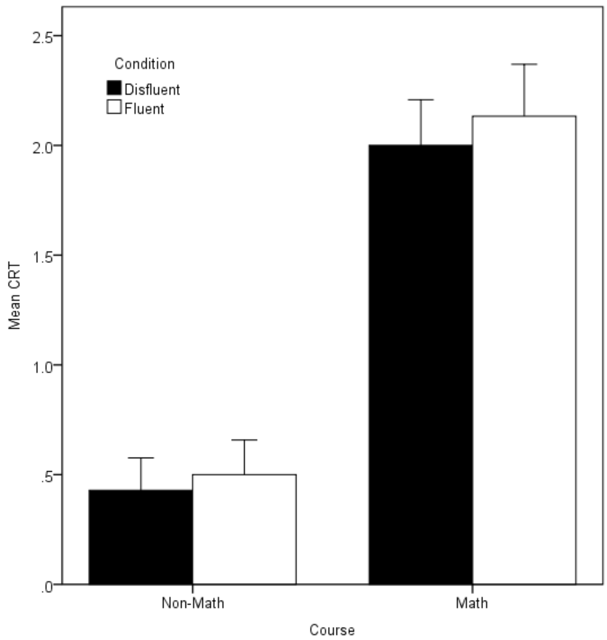

Figure 3. *Graphical representation of interaction effects. Error bars reflect +1 SE.*

3.5 Discussion

Hypothesis 1.1 predicted that participants in the disfluent condition would perform better on the CRT than those in the fluent condition. This hypothesis was not supported. The results in the present study, therefore, did not replicate the finding in Alter et al. (2007). These results do not lend support for the dual process hypothesis regarding fluency and the supervisory system (Toplak, West & Stanovich, 2011). The results do not support the justification by Alter, Oppenheimer and Epely (2013) for contrasting results in Alter et al. (2007) and Thompson et al., (2013). Alter, Oppenheimer and Epely (2013) suggested that the effect of fluency by font manipulation may only be present for individuals of higher cognitive ability. This study suggest that both math and non-math participants possessed sufficient ability to answer the CRT items. However, neither group were affected by font manipulation.

Hypothesis 1.3 predicted that the fluency manipulation would affect math participants to a greater extent than non-math participants from courses with low mathematical focus.

This hypothesis was not supported. The increase in relative mathematics skill between non-math and math samples did not predict changes in fluency effects. This indicates that the effectiveness of fluency manipulations may not be dependent on mathematical expertise.

Hypothesis 1.2 predicted that math participants would outperform non-math participants. This hypothesis was supported. The large difference in performance on the CRT observed between these two groups could indicate that there is a difference between the solution processes used by these groups. From a dual-process perspective, the relatively low performance of non-math participants on the CRT may reflect a tendency for these participants to use Type 1 processes and answer with a default intuitive responses. The relatively high performance by math participants might be attributed to the use of Type 2 processes wherein math participants had engage in more effortful thinking. From a default-intervention account, this may suggest math participants were more likely to override default Type 1 processes. If greater performance is a result of Type 2 processing, as defined by the requirement of working memory capacity, it follows that taxing working memory while undertaking this task should account for the difference on CRT performance between math and non-math groups.

4. Experiment 2

4.1 Rationale and Hypotheses

Dual-process and modular theories of reasoning emphasise the role of working memory in problem solving. The GWT asserts that working memory requires the global workspace and that the global workspace is essential for solving novel problems. In Experiment 1, math participants outperformed non-math participants, even though both groups possessed sufficient cognitive ability to solve the CRT items, as measured by the PST. To the extent that this performance difference was due to Type 2 processes, then one would expect that a memory load would be more disruptive to the math participants than the non-math participants. Evans and Stanovich (2013) assert that Type 1 processes do not require working memory but that Type 2 processes do. However, in the same paper they state that Type 2 processes can be practiced to the point where they are “processed in a Type 1 manner” (p. 236). This experiment adheres to the definition of Type 2 processes as requiring working memory because of the emphasis that Evans and Stanovich (2013) place on this definition. Under dual-process theories taxing working memory should reduce a person’s capacity for Type 2 reasoning. Therefore, the addition of a cognitive load should affect participants’ performance on the CRT to a greater extent for math participants than non-math participants.

Modular reasoning theories and the GWT suggest that working memory requires the global workspace for flexible integration of pre-existing knowledge and operations (Wastell, 2014; Baars, 1988). From a modular perspective, the addition of a cognitive load will reduce participant’s ability to combine pre-existing knowledge and operations, which will subsequently influence their performance on the CRT. However, modular perspectives predict that this effect will depend on the participant’s expertise. According to both the CEM and the GWT, adding a cognitive load will not affect the performances of novices as they do not possess the appropriate pre-existing modules to solve the problem. Adding a cognitive load will affect intermediates who possess the appropriate pre-existing knowledge but who need the flexibility of a global workspace. Adding a cognitive load will not affect experts who have automated the appropriate process and do not require the flexibility of the global workspace. Non-math participants were expected to possess sufficient pre-existing modules, based on the PST scores in Experiment 1, such that they might be classified intermediate problem solvers, whereas, math participants are expected to be more likely to have automated the necessary procedures for completing the CRT, potentially due to experience with mathematics problems, as such they might be classified as experts. It is not the aim of the present thesis to extrapolate upon which processes, of those required to complete the CRT, might have been automated (if at all) but rather, to explore whether the automation of reasoning procedures might be occurring and whether theories with the capacity to incorporate automaticity may provide more promising foundations for future research to build on.

The following predictions are made from a modular perspective because the CEM, in combination with the GWT, makes clearer predictions for CRT performance in relation to expertise which is a key component in this thesis. In accordance with this literature, the following hypotheses were made:

Hypothesis 2.1: Participants in the no-load condition will perform better on the CRT than those in the load condition.

Hypothesis 2.2: Math participants will outperform non-math participants. This is a test for the replication of findings in Experiment 1 under Hypothesis 1.2.

Hypothesis 2.3: The cognitive load manipulation will affect non-maths participants (intermediates) to a greater extent than maths participants (experts).

4.2 Design

Experiment 2 assessed whether an additional cognitive load which taxed working memory interfered with the solution process for CRT questions and whether this effect differed between math and non-math participants. This study had a 2 x 2 between-subjects quasi-experimental design. The dependent variable was the number of correct responses on the CRT. There were two independent between-subjects factors with two levels: condition (load and no load) and participants' course focus (math and non-math). As for Experiment 1, each participant's major area of study was recorded to determine the two different populations (math and non-math) and scores on the PST were recorded to assess levels of pre-existing skills in the domain of solving worded mathematical problems.

4.3 Method

Participants were randomly allocated to either the load or no load condition. Each of the three CRT questions were set up with elements, presented separately: an information component, a grid pattern to memorise, the full CRT question, and the response grid. The order of the elements differed between conditions such that participants in the load condition were required to solve the problem while remembering the grid pattern and those in the no load condition were not. A copy of the instructions provided to the participants can be found in Appendix B.

Subjects in the load condition were presented with the information component to read, followed by the grid pattern to memorise, then the full CRT question to answer, and finally an empty grid to recall the previously shown grid pattern (Figure 2). Participants had to complete the CRT question while remembering the grid pattern. Therefore, in this condition, the CRT questions were answered under increased cognitive load and with depleted working memory capacity. The information component of the task was presented prior to adding a cognitive load. This was done to minimise the effect of cognitive load on the comprehension process as opposed to the solution procedure as intended (Van Lier, Revlin, & De Neys, 2013). Figure 2 shows an example of the CRT section for a participant in the load condition completing the first CRT problem.

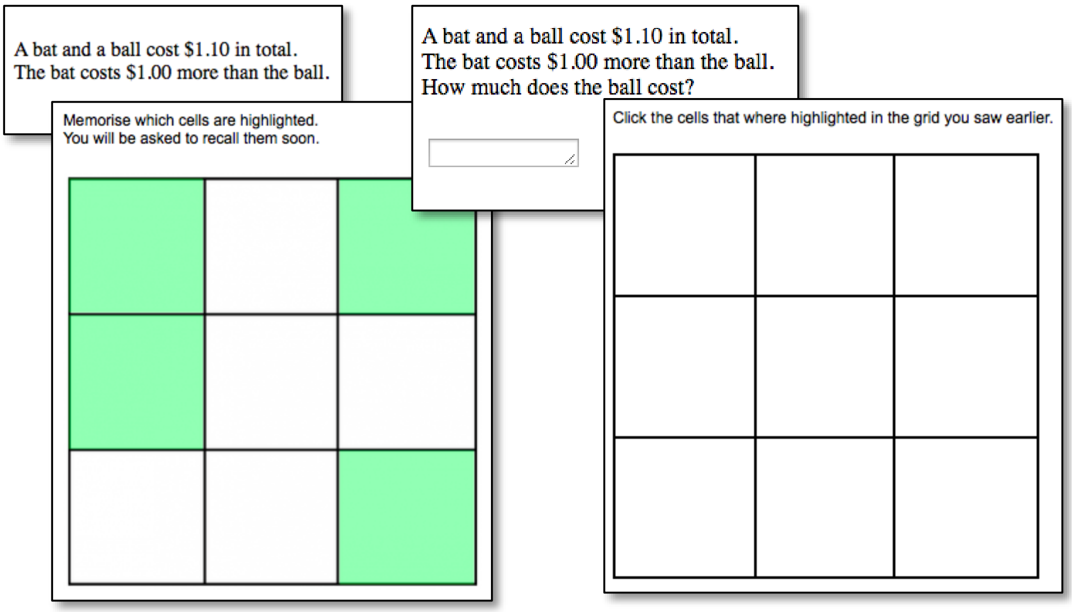

Figure 2. *A timeline of CRT Question 1 for participants in the load condition.*

Subjects in the no load condition were presented with the information component to read, followed by the grid pattern to memorise, then an empty grid to recall the previously shown pattern and finally the full CRT question (Figure 3). The CRT problems were therefore solved without an additional cognitive load. In the no load condition, the cognitive load task was not expected to affect comprehension of the problem information. However, the information element of the question was presented prior to the task reduce potential confounds. Figure 3 shows an example of the CRT section for a participant in the CRT control condition completing the first CRT problem.

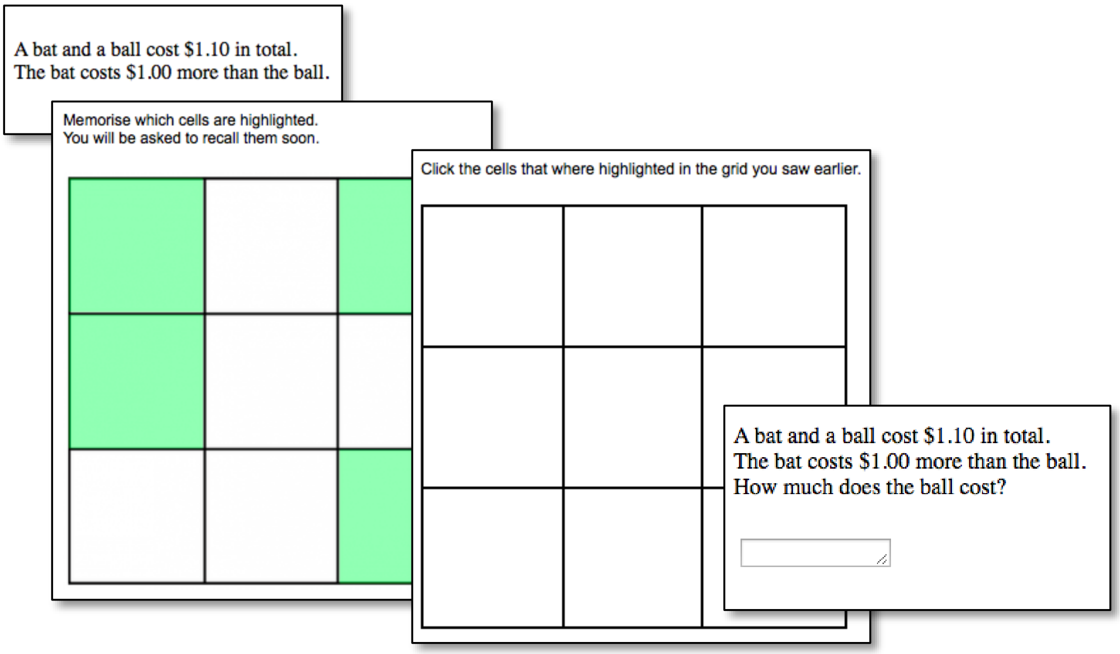

Figure 3. *A timeline of CRT Question 1 for participants in the control condition.*

The grid pattern memory task was based on Van Lier et al. (2013) memory dot-task and adapted to the capabilities of the Qualtrics survey software. A similar task was recently used in an experiment that effectively taxed working memory while participants completed the ‘bat and ball’ problem (CRT item 1; Johnson, Tubau, & De Neys, 2014). Participants were instructed to memorise the grid in the initial instructions and again when the grid was presented. When presented with the grid pattern participants had 8 seconds to memorise it before the survey automatically moved to the next component. They could not move on to the next component before 8 seconds. A count down timer was shown at the bottom of the screen. When presented with an empty grid, participants recalled the grid pattern by clicking the squares they believed they had seen highlighted in the pattern presented earlier. A square could be selected by clicking on it. Once selected, the square changed from white to green. Clicking on the square a second time would unselect it and return the square to white. Once the participant was finished they pressed “Next” to move on to the next part of the experiment. Expected response time for the CRT task was 1-3 minutes. The full procedure was designed to take approximately 20 minutes.

4.4 Results

None of the participants in Experiment 2 had participated in Experiment 1. Results from 37 participants were excluded from the analysis due to non-compliance or technical issues leaving 82 participants for inclusion in the data analysis. Fifty-one were non-numeric students with psychology majors and thirty-one were from numeric courses: actuarial majors (10) or engineering majors (21). A breakdown of condition allocations and demographics can be seen in Table 3.

Table 3

Condition allocation and demographics.

		Course	Gender	Age
Condition	N	Math : Non-Math	Male : Female	M *(SD)*
Load	36	13 : 23	16 : 20	19.08 *(1.50)*
No Load	46	18 : 28	25 : 21	19.07 *(1.42)*

Scores on the PST had a possible range of 0 - 12. Math participants scored higher (M = 9.90, SD = 1.72) than non-math participants (M = 8.92, SD = 2.09). An independent samples t-test showed that the difference between these mean scores was significant, t (80) = -2.203, p = .031. The Cohen's d indicated that this was a moderate effect size, d = .51. As in Experiment 1, this scale does not necessarily capture the differences which lead to the hypothesised interaction effects. However, it does in part validate the separation of the sample, by math and non-math participants, as a reflection of mathematical expertise. An average score of 74.3% for non-math participants also highlights that they demonstrated mathematical capabilities such that they possess the knowledge to be able to understand and solve the CRT problems.

The differences between mean CRT scores were examined using a 2x2 ANOVA. The main effect of condition on CRT was significant, F (1, 78) = 5.93, p = .017. η^2_p = .07. This indicates that when averaging across course participants in the no load condition performed significantly better than those in the load condition. The main effect of course on CRT was significant F (1, 78) = 27.85, $p < .001$, η^2_p = .26. This indicates that when averaging across condition, math participants performed significantly better than non-math participants. The interaction effect of course by condition on CRT was found to be significant [F (1, 78) = 5.19, p = .025, η^2_p = .06]. This indicates that the effect of condition was different for math and non-math participants. Follow up tests revealed that there was no significant difference between the load and no load conditions for non-math participants, F (1, 78) = 0.017, p = .899, η^2_p <0.001. There was, however, a significant difference between the load and no load conditions for math participants. Math participants in the no load condition outperformed those in the load condition (F (1, 78) = 8.899, p = .004, η^2_p = 0.102). These effects are demonstrated in Figure 7.

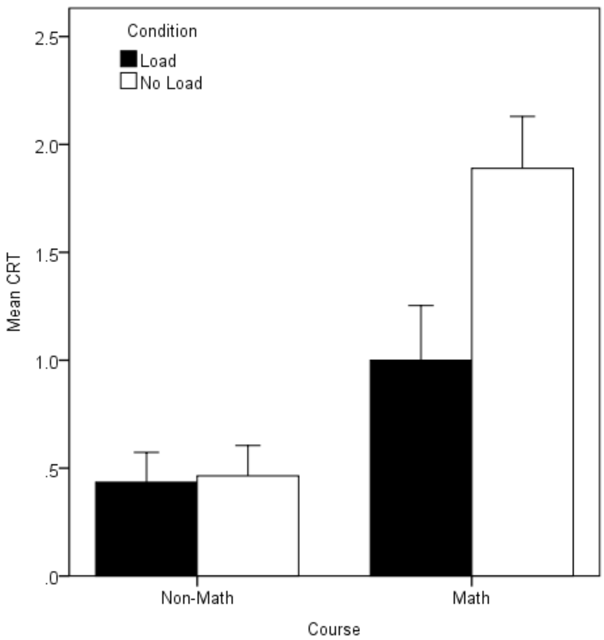

Figure 7. *Results from Experiment 1. Error bars reflect +1 SE.*

A post-hoc analysis was conducted to examine the unexpected finding that math participants' performance fell but that even with this drop in performance, average CRT scores were still higher for math participants in the load condition than non-math participants in no load and load conditions. This was unexpected given that Johnson et al. (2014) demonstrated a complete drop in performance on the bat and ball problem when participants were given a similar additional memory task, in line with Evans and Stanovich's (2013) assertions. Modular reasoning theories may explain this as a function of expertise. More expertise should predict less detrimental effects due to cognitive load. A moderate correlation was observed between CRT scores and PST scores for math participants in the load condition ($r = .49$, $p = .09$). There were 13 math participants in the load condition which may have resulted in insufficient power. The trend lends preliminary support for a modular theory of reasoning.

4.3 Discussion

Hypothesis 2.1 predicted that participants in the no-load condition would perform better on the CRT than those in the load condition. This hypothesis was supported. The results indicated that for this sample, working memory, as taxed by a visual memory task, was an essential factor for performance on the CRT. According to the dual-process theory, this suggests that higher performance on the CRT may have been due to the use of Type 2 processing. Under modular reasoning models and the GWT, it indicates that the global workspace was required for access to and flexibility between pre-existing modules, for increased performance on the CRT.

Hypothesis 2.2 predicted that math participants would outperform non-math participants. This was, in part, a test for the replication of findings in Experiment 1 under Hypothesis 1.2. The hypothesis was supported, indicating that the differences observed between math and non-math participants in Experiment 1 are reliable, and there are underlying differences between these groups that may account for different performances on the CRT beyond sufficient cognitive ability.

Hypothesis 2.3 predicted that the cognitive load manipulation will affect non-math to a greater extent than math participants. This prediction was made on the basis that both groups were expected to possess sufficient pre-existing mathematics skills to perform well on the CRT, which was supported by the PST results. The less practiced group (non-math) were expected to require the flexibility of the global workspace possible under the no load condition. Conversely, maths students, being well versed on these types of problems, were expected to have automated the appropriate procedures and therefore not require the global workspace (i.e. perform well regardless of load).

In contrast to the hypothesis, cognitive load had a significant effect on the performance of math participants but not non-math participants. Under the CEM and GWT, differences observed between math participants in the load and no load condition may indicate that math participants had not automated the appropriate module (or modules). One possible explanation is that for the correct solution to be reached, math participants required access to the global workspace in order to combine appropriate processes. In contrast, there was no difference between load and no load conditions for non-math participants. This indicates that even with access to the global workspace, non-maths participants were not able to effectively access or combine pre-existing knowledge to solve the CRT questions. The reason that non-maths participants were unable to use the global workspace as effectively as maths participants requires further explanation from modular theorists.

The interaction effect of condition (load or no load) by participants' area of study (maths or non-maths) on CRT performance can also be interpreted from a dual-process perspective. Previous interpretations of CRT results have suggested that higher performance is indicative of more reflective Type 2 processing and lower performance is indicative of more intuitive Type 1 processing (Toplak, West & Stanovich, 2011). Two populations that reliably achieve different performances on the CRT should therefore respond differently when Type 2 processing is restricted. The results from Experiment 2 support this prediction. The taxing of working memory through the addition of a cognitive load significantly lowered scores of the math participants indicating that higher performance on the CRT may be due to the use of a Type 2, working memory dependent, processes.

The interaction effect observed in Experiment 2 supplements the empirical investigations of both dual-process and modular models of reasoning by explicitly examining the roles of expertise and working memory on problem solving. Overall, the role of working memory in reasoning appears to differ according to the individuals relative skill level, in this case for worded mathematical problems. Additionally, an unexpected observation provides encouragement for a relatively new angle of reasoning research. The performance of math participants was significantly reduced with the addition of a cognitive load, however, it did not reduce performance to the level of performance observed for non-math participants. This is a preliminary indication that the relationship between higher performance on the CRT and working memory is not dichotomous. There are two possible explanations for this observation which centre on the continuous nature of working memory and the role of automation through expertise.

5. General Discussion

This thesis included two experiments which examined problem solving and the potential effects of a fluency cue (Experiment 1) and a cognitive load (Experiment 2) on the CRT. To examine if these effects were influenced by expertise, these effects were examined and compared for participants in courses that were more or less mathematical in emphasis. The findings in regard to fluency are interpreted from a dual process perspective. Those regarding cognitive load and expertise are interpreted from the perspectives of dual process theories (specifically Evans and Stanovich's 2013 model), modular reasoning theories and the GWT. The findings in the present thesis present interesting avenues for future research, particularly, surrounding the potential role of expertise in reasoning and problem solving.

Fluency. Contrary to what was hypothesised, the results observed in Experiment 1 suggest that changes in font fluency, a proposed metacognitive cue, do not affect performance on the CRT. The hypotheses for Experiment 1 were based on previous studies which suggest that the disfluent fonts increase CRT performance (Alter et al., 2007) but that this may be a function of cognitive ability (Thompson et al. 2013). Alter, Oppenheimer and Epley (2013) proposed that analytic reasoning prompted by font disfluency would only benefit individuals with sufficient ability to perform the correct solution procedure. The PST results for participants in Experiment 1 indicate that they had sufficient ability to solve the CRT items. However, contrary to Alter, Openheimer and Epley's (2013) assertion, they were not affected by font fluency. Further, following previous suggestions that reasoning processes are affected by expertise specific to the task at hand (Kahneman & Klein, 2009), the present study included a factor for the mathematical focus of the participants' studies. However, the findings suggested that font fluency effects were not related to the differences between participants whose studies emphasised mathematics or for those whose studies which did not.

There are a number of factors which may limit the conclusions made on the basis of observations in Experiment 1. The inability to replicate the findings that Alter et al. (2007) observed may be due to differences such as different font manipulation. For the disfluent condition, Alter et al. (2007) used 10% grey italicized Myriad Web 10-point font. However, subject to limitations in the host program, Qualtrics (2013), the present study used 10% grey italicised Times New Roman 10-point font. Further, the present study was conducted online and so the actual size and clarity of the font may have differed depending on the device the participants used. Additionally, the measure of sufficient cognitive ability was based on the PST. The skills required to solve the CRT questions may differ from those required to solve the PST items. Although, even with this difference, university students would be expected to have sufficient ability to solve the CRT items. Especially as the mathematics skills required (i.e. basic algebra and substitution) are included in the compulsory Australian national curriculum for Year 8 and Year 9 (ages 12 – 14 years). Perhaps more pertinent is the possibility that the differences between math and non-math participants may not have captured specific skill differences that may apply to the moderation of the fluency effect by cognitive ability. A future study could be conducted to establish if that was the case, for example by using more specific measures of expertise or recording participants' full enrolment details.

Conclusions from the results in Experiment 1, in regard to expertise effects are limited due to potential confounds: gender and motivation. The majority of math participants were male but the majority of non-math participants were female. Previous research has shown that males tend to outperform females on the CRT which is in line with the patterns observed here (Frederick, 2005). The unequal gender by course groups in this experiment meant that testing for gender effects was inappropriate. However, future studies should aim to clarify whether the patterns observed here are reflective of expertise rather than or in addition to gender effects. Similarly, maths participants may have been more motivated than non-math participants. It is likely that the math participants are motivated to perform well on mathematical tasks in comparison to non-math participants. Further, non-math participants were incentivised with course credit, and math participants were incentivised with the potential for monetary gain. It has been suggested that motivation affects intervention (Evans & Stanovich, 2013). These confounds may weaken the conclusions drawn from Experiment 1.

The findings in Experiment 1 may have been due to methodological issues. However, the results obtained are validated by research that has been recently released. A rigorous empirical examination of the effect on font fluency on CRT performance, was released after the hypotheses for the present study were generated (Meyer et al., 2015). Meyer et al. (2015) examined data from 16 replication attempts and concluded that font fluency did not affect performance even when controlling for cognitive ability, differences in font manipulation and experimental setting. Of particular relevance to the present thesis, two of the studies assessed whether fluency effects were dependent on sufficient ability to solve the CRT problems. In these studies, participants were given the CRT twice, the second version had an explicit hint (e.g. the answer is not 10 cents). Participants who could solve the second version of the problem were deemed sufficiently able, however, they too were not affected by fluency manipulations measured as measured in the preceding version. The paper also highlighted that fluency effects were not dependent on specific measures of mathematical expertise. For example, they demonstrated that SAT maths scores did not moderate the effect of font fluency across five different studies. These results are consistent with the findings in Experiment 1 and together it they support the conclusion that font manipulation does not lead to performance differences on the CRT through cueing Type 2 processes or otherwise.

Dual-process theories assert that that a supervisory reasoning process can override incorrect default responses (Evans & Stanovich, 2013). The override of a default response is said to be dependent on several factors such as metacognitive cues for disfluency. Font manipulation is one way that has been used in the past to examine this prediction. Experiment 1 did not find that disfluent fonts improved performance on the CRT. However, it is possible that other fluency manipulations or metacognitive cues may be able to produce this effect. The findings from the present study suggest that more research is required to establish whether metacognitive cues for difficulty affect problem solving and whether this might reflect the activation of different reasoning processes. These findings do not rule out that factors other than font fluency could influence reasoning under the default-intervention theory. Experiment 1 did not find evidence to suggest font fluency affects performance on the CRT. However, it did demonstrate a large difference between math and non-math participants on the CRT, which was examined further in Experiment 2.

Cognitive load. Toplak, West and Stanovich (2011) suggested that correct responses on the CRT are an indication that the person had overridden default responses and engaged in reflective thought. From this perspective, higher performance on the CRT might be indicative of Type 2 processing and lower performance on the CRT might be indicative of Type 1 processing. Type 2 processes are defined as requiring working memory (Evans & Stanovich, 2013). An additional cognitive load which reduces working memory capacity should therefore negatively impact CRT performance. This was found in to be the case in a study by Johnson et al. (2014) in a general undergraduate sample. Modular theories of reasoning suggest that the potential effect of cognitive load might be influenced by expertise and the automation of processes over time (Wastell, 2014). It was therefore important to examine whether the effect of cognitive load varied with expertise.

The hypotheses for Experiment 2 were based on the CEM and GWT. The CEM suggests that reasoning processes can become automated over time through the development of virtual modules. The GWT asserts that for modules to interact they require the flexibility of the global workspace. Novel problems can be solved by combining pre-existing modules but this requires the global workspace. The global workspace is proposed to facilitate working memory functions. Combining these assertions, one would expect that greater expertise in a specific area, leads to less dependence on the global workspace. It was therefore hypothesised that math participants would be affected by cognitive load to a lesser extent than non-math participants. This hypothesis was not supported. However, the results suggest that expertise plays an important role in problem solving, particularly in relation to the effect of cognitive load, and the present findings may still be explainable from a modular reasoning perspective.

In Experiment 2 the cognitive load reduced the performance of math participants but not non-maths participants. This could have been because of a floor effect for non-math participants. The inclusion of a larger scale in future studies would be ideal for testing whether this was the case. However, the unique nature of the CRT and the controversy around what it might be testing may render this is not an easily executed solution. Another option could be to use smaller intervals of expertise. However, it is unclear at this stage exactly which type of expertise (if any) is driving the difference between math and non-maths participants and so isolating and breaking down intervals may also be challenging. The potential of a floor effect may limit the strength of the interpretation of the results. However, the finding, that performance on the CRT may reflect expertise, is not jeopardised.

From a dual-process perspective, it may be that non-math participants were, for the most part, using Type 1 processes which do not require working memory. If that is the case, it is particularly interesting that the performance of math participants did not fall to the level of non-math participants which potentially reflects Type 1 processing capability. Previous findings that employed a similar cognitive load task found an almost complete reduction in performance on the bat and ball problem (Johnson et al., 2014). In contrast, for Experiment 2 there was only a partial reduction in performance for math participants. There was a reasonable difference between the mean score of math participants in the load condition (M = 1.00, SD = 0.91) and non-math participants in the no load condition (M = 0.46, SD = 0.74). This partial reduction effect was not formally hypothesised and requires further validation. However, the finding may have implications for both dual-process and modular models of reasoning and presents an interesting avenue for future research.

The partial reduction in performance may indicate that the cognitive load task did not tax all of the working memory capacity required for completion of the CRT items. It may be that some items required more working memory capacity than others. Those items requiring greater working memory capacity may have been responsible for the drop in performance, while items requiring less working memory capacity may not have been adversely affected. If this was the case, it may be that success on the CRT is due to Type 2 processing, and that the reduction of performance reflects the size of the additional cognitive load. This is supported by previous research.

Johnson et al. (2014) demonstrated that a high load task (a pattern of four dots in a 3 x 3 grid) was more effective than a low load task (a pattern of three dots in a 3 x 3 grid) for decreasing performance on the bat and ball problem (CRT Question 1). Conversely, it may be that individual differences in working memory capacity meant that some math participants could handle both the CRT and the load task but others could not. Future research should clarify whether the memory task used in the present study is equally effective for each CRT item, how changes in the demand of the additional load influences responses, and whether individual differences in working memory capacity complement these effects. The partial reduction might be a reflection of the use of Type 2 processes, as defined by the requirement of working memory. This does not clarifying why math participants outperformed non-math participants in the first place or why this might be a reflection of expertise.

The partial effect can also be explained from a modular reasoning perspective when integrated with the GWT. The observation that cognitive load only partially reduced the performance of math participants could be because some of the math participants had automated some or all of the modules used in the solution process, while others had not. Wastell (2014) suggested that virtual modules can be created through practice, and can interact when conscious. The GWT asserts that the global workspace is necessary for learning and integrating pre-existing modules. When presented with a novel problem, the global workspace can broadcast output from one module to be received as input for another, otherwise separate, module. This process may lead to the development of new virtual modules that can perform an operation that originally needed multiple modules. Expertise would therefore be reflected, psychologically, by a reduced dependency on the global workspace. It should be noted that the conclusions in regard to the partial reduction are made tentatively because although the difference between the performance of the math participants in the load condition and the non-math participants was not tested using a formal statistical test due to imbalanced cell sizes and lack of a priori hypotheses.

In Experiment 2, some math participants may have automated parts of the chain of processes necessary for solving CRT problems due to experience with worded maths problems. These parts would not be expected to require access to the global workspace and therefore, they would not be affected by the cognitive load task. The GWT asserts that the global workspace facilitates working memory functions like mental rehearsal of visual or phonological representations. The visual memory task in Experiment 2 was likely to require mental rehearsal, and subsequently occupy some of the cycles of the global workspace. The partial reduction observed for math participants in the load condition may reflect a number of reasons: some participants having automated the necessary processes and others not, leading to an average score for math participants falling somewhere between these groups; automation of some but not all the processes required for completing the CRT questions; automation of processes required by select items in the CRT but not others or; a combination of these. The moderate positive correlation between PST and CRT observed for math participants in the load condition lends preliminary support this possibility. In any case, it could be that the results in Experiment 2 reflect differences due to the automation and subsequent differences in dependency on access to the global workspace.

This interpretation requires further empirical investigation. One way to do this would be to include more variation in expertise particularly more advanced participants. If expertise is related to automation, you would expect that as mathematics skill increased, the effect of cognitive load would decrease without compromising accuracy. Future investigations like this should also aim to reduce confounds. As was potentially the case for this study, one difficulty that may be encountered in future experiments is that quasi-experimental measures of expertise are often confounded with motivation. For example, people who are expert mathematicians are likely to be more motivated to perform well on mathematics based tasks, which may be why they are expert mathematicians in the first place. The converse is likely to be true for those with less expertise. Expertise may also reflect individual differences, such as reasoning dispositions. One way to reduce possible confounds like these is to conduct within-individual experiments with random samples. For example, developing participants' skill base over time and measuring performance changes in relation to the effects of cognitive load. This type of experiment would require the use of an extended version of the CRT to prevent familiarity affecting responses. This presents a significant challenge however a recent paper by Toplak, West and Stanovich (2014) illustrates that progress is already being made to meet this task. The potential relationship between expertise and automation should also be investigated for areas beyond mathematics.

Expertise. The difference between dual-process and modular interpretations of the partial reduction in maths participants' performance is not merely semantic. Interpretations of the present findings, in particular the partial reduction effect, seem to suggest a similar capacity-based explanation for the effect of cognitive load, by way of a global workspace or working memory. However, they do not carry the same explanations for the processes that might underlie these results, particularly in regard to the potential role of expertise. Under the GWT working memory occupies part of the global workspace but is not the same construct. The differences between these approaches becomes more apparent when considering the possible explanations for the poor performance on the CRT overall, even with sufficient cognitive ability and no cognitive load, and why math participants outperformed their non-math counterparts.

Experiment 1 demonstrated a large main effect where math participants outperformed non-math participants. This effect was replicated in Experiment 2. This leads to the immediate question: why is this difference occurring? For dual-process theorists this is an issue of whether or not Type 2 processes are engaged. Evans and Stanovich (2013) assert that, in order for this to occur, intervention is required. That is, Type 1 default decisions must be overridden and replaced with Type 2 processing. Intervention is said to be dependent on several factors such as motivation and cognitive ability. Generally, dual-process theories suggest that a metacognitive mechanism and individual dispositions may be involved in detecting errors in initial responses and prompting Type 2 processes. The evidence put forth for the involvement of these factors is largely correlational such that it is difficult to understand the causal relationships that may exist between those factors and intervention. However, it is possible that they affect reasoning via a mechanism responsible for intervention.

There is evidence to suggest that expertise is might be the factor underlying the differences in CRT scores between math and non-math participants observed in Experiments 1 and 2. For example, Welsh, Burns and Delfrabbo (2013) found that performance on the CRT had a stronger association with specific measures of numeric ability than measures of inhibition tendencies. They found no relationship between the Sustained Attention to Response Task (SART) and performance on the CRT. The SART is a measure of an individual's ability to monitor performance for errors and inhibit incorrect responses (Robertson, Manly, Andrade, Baddeley & Yiend, 1997). The SART is based on a simple task in which the identification and correction of an error requires the inhibition of a repeated behavioural response. In contrast, corrections in the CRT are achieved with more complex processing. These differences may account for the lack of correlation, Welsh, Burns and Delfrabbro's (2013) claim that CRT performance is more reflective of a person's ability to detect numerical errors than the function of a general metacognitive mechanism or disposition. Explanation for the relationship between specific skill levels and performance on the CRT, observed in Experiments 1 and 2, is limited within a default-intervention dual-process model.

Modules have built in gating systems, realised through trigger criteria, such that a monitoring or supervisory mechanism may not be necessary for determining whether an action or solution is executed. Wastell (2014) asserts that errors on the bat and ball problem may occur due to the information in the problem triggering a virtual module for automatic subtraction (see also Dehaene, 2011). The difference between the math and non-math performance may reflect differences in modules' trigger criteria. The possibility that virtual modules can be developed with practice suggests the criteria for virtual modules may differ according to the person's prior experience, in this case with worded mathematics problems.

One way to reach a correct response on the bat and ball problem (CRT Question 1) is to translate the problem into algebra and solve via substitution. Assuming modules exist, the triggers for those responsible for processes such as substitution may differ for maths and non-maths students. For example, properties in the bat and ball problem may meet the trigger criteria for a substitution module for maths students, potentially as a result of their experience with solving worded maths problems in this manner. However, for non-maths students, properties in the bat and ball problem may trigger a subtraction module. This may be because the information imbedded in the problem, and particularly the phrase "more than", triggers the mandatory operation of a subtraction module. It is not clear which components of the problem might be acting as triggers. Future studies are needed to examine if and how changing aspects of the problem alters response patterns and whether this is reflective of experience and skill level.

Modular accounts for differences in performance seem more capable of incorporating effects of expertise on CRT performance than default-intervention dual-process models, however, however both approaches converge on a similar problem. Dual-process proponents face the difficulty of demonstrating how dispositions or monitoring mechanisms could cause some people outperform others and how these factors could reflect differences in expertise. Modular proponents are faced with demonstrating why more skilled participants would use a more complex module over a simpler one. For example, in the bat and ball problem, why do math participants opt for a substitution process when the criteria for a subtraction module may also be met? Is there a hierarchy of processes in which more complex modules are favoured over simple ones? From an evolutionary perspective it seems likely that the module(s) with more comprehensive criteria should be favoured over those that are less comprehensive. This would prioritise operations that take into account more information in the environment. This requires clarification with further empirical investigation.

Future directions. A number of studies have been suggested throughout the general discussion which may help to clarify and expand on the findings observed in the empirical component of this thesis. These include suggestions for reducing potential confounds; breaking down expertise into smaller and more varied differences; examining the effect of within-individual changes in expertise over time; altering the demand of the cognitive load task; and isolating potential modular triggers embedded in the CRT. Future studies should also aim to improve on the present design by including control measures to ensure the task was completed as intended, for example, checking the accuracy of recall on the memory task and conducting the study with a supervisor present to ensure no memory aids were used.

More generally, the results and subsequent theoretical implications advocate for a more comprehensive investigation into the potential influence of expertise and relative skill differences on problem solving and, if necessary, integrating the findings from this investigation into models of reasoning.

At this stage neither dual process nor modular accounts for reasoning provide a clear framework from which to interpret the present findings. However, for continuing the investigation into reasoning and expertise, a modular framework seems to offer clearer directions for future research than a dual process model. Evans and Stanovich (2013) maintain that Type 2 processes can become automated such that they resemble Type 1 processes, but that the "underlying neurophysiology and etiology might be quite different" (p. 236). This seems to contradict the definition of a Type 2 processes as requiring working memory. Subsequently it is unclear as to whether one should abandon the definition of Type 2 processes as requiring working memory, or, adjust the defining delineation of Type 1 and Type 2 processes to be based on neurophysiological factors. The default-intervention dual-process model does not ignore the potential for the automation of reasoning processes but in its current state, it is limited in its capacity to generate testable predictions that facilitate empirical investigation.

Modular models of reasoning seem to offer a clearer framework for examining the potential relationship between expertise and reasoning. Wastell (2014) explicitly identified the need to explain the transformation of reasoning experiences from effortful to automatic. The inclusion of virtual modules and predictions for the transformation process makes this model more appropriate for the examination of a potential transformation process. Key aspects of the CEM are dependent on complex phenomena like consciousness. However, the integration of such phenomena into the model is not comprehensive which limits the utility of the model. The advantage of incorporating an underlying modular architecture is that it can be mapped onto models of cognition. This facilitates the incorporation of findings from other areas of research that have a similar foundation in modularity theory.

The theoretical and experimental components of this thesis highlight considerable conceptual gaps in the current reasoning literature such as expertise and consciousness. It also exemplifies the state of the field as prime for the development of better models and investigation of unexplained phenomena. The traditional focus of reasoning research has been on heuristics and biases research which exposes errors in human judgement. The findings therein have fascinating implications for the way the mind may be reasoning and solving problems. However, in order to effectively explore the processes behind higher cognition, the field of reasoning and decision making could benefit from a broader approach to empirical investigation, in particular, through a more comprehensive integration with methodologies and theories from neighbouring fields of research such as those focussed on cognition, consciousness and expertise. The findings in this thesis suggest that modular theories of reasoning, such as the CEM, offer promising foundations for developing a more integrated approach to reasoning research.

References

Alter, A. L., Oppenheimer, D. M., & Epley, N. (2013). Disfluency prompts analytic thinking—But not always greater accuracy: Response to. *Cognition, 128*(2), 252-255. doi: 10.1016/j.cognition.2013.01.006

Alter, A. L., Oppenheimer, D. M., Epley, N., & Eyre, R. N. (2007). Overcoming Intuition: Metacognitive Difficulty Activates Analytic Reasoning. *Journal of Experimental Psychology: General, 136*(4), 569-576. doi: 10.1037/0096-3445.136.4.569

Baars, B. (1988). A Cognitive Theory of Consciousness. Cambridge University Press.

Baars, B. J., Franklin, S., & Ramsoy, T. Z. (2013). Global workspace dynamics: cortical "binding and propagation" enables conscious contents. *Frontiers in psychology, 4*. doi: 10.3389/fpsyg.2013.00200

Baroody, A. J., & Dowker, A. (Eds.). (2003). The development of arithmetic concepts and skills: Constructive adaptive expertise. Routledge.

Barrett, H. C., & Kurzban, R. (2006). Modularity in cognition: framing the debate. *Psychological review, 113*(3), 628.

Campbell, J. I. (2005). Handbook of mathematical cognition. Psychology Press.

Campitelli, G., & Gerrans, P. (2014). Does the cognitive reflection test measure cognitive reflection? A mathematical modeling approach. *Memory & Cognition, 42*(3), 434-447.

Carruthers, P. (2006). *The architecture of the mind*. Oxford, UK: Oxford University Press.

Carruthers, P. (2009). An architecture for dual reasoning. *J. St. BT Evans & K. Frankish*, 109-127.

Chaiken, S., & Trope, Y. (1999). *Dual-process theories in social psychology*: Guilford Press.

Cosmides, L., & Tooby, J. (1992). Cognitive adaptations for social exchange. In J. H. Barkow, L. Cosmides & J. Tooby (Eds.), *The adapted mind: Evolutionary psychology* *and the generation of culture* (pp. 163-228). New York, NY, US: Oxford University Press.

Dretske, F. I. (1997). *Naturalizing the mind*: mit Press.

Ericsson, K. A., & Smith, J. (1991). Toward a general theory of expertise: Prospects and limits. Cambridge University Press.

Evans, J. (2007). On the resolution of conflict in dual process theories of reasoning. *Thinking & Reasoning, 13*(4), 321-339. doi: 10.1080/13546780601008825

Evans, J. (2010). *Thinking twice: Two minds in one brain*. Oxford, UK: Oxford University Press.

Evans, J., & Stanovich, K. E. (2013). Dual-Process Theories of Higher Cognition: Advancing the Debate. *Perspectives on psychological science, 8*(3), 223-241. doi: 10.1177/1745691612460685

Evans, J. S. B. T. (1984). Heuristic and analytic processes in reasoning*. *British Journal of Psychology, 75*(4), 451-468. doi: 10.1111/j.2044-8295.1984.tb01915.x

Evans St, J. B. T., & Over, D. E. (1996). Rationality and Reasoning: Psychology Press Hove.

Faghihi, U., Estey, C., McCall, R., & Franklin, S. (2015). A cognitive model fleshes out Kahneman's fast and slow systems. Biologically Inspired Cognitive Architectures, 11, 38-52. doi: 10.1016/j.bica.2014.11.014

Fodor, J. A. (1983). *The modularity of mind: An essay on faculty psychology*. Cambridge, MA: MIT press.

Franklin, S., Strain, S., Snaider, J., McCall, R., & Faghihi, U. (2012). Global workspace theory, its LIDA model and the underlying neuroscience. *Biologically Inspired Cognitive Architectures, 1*, 32-43. doi: 10.1016/j.bica.2012.04.001

Frederick, S. (2005). Cognitive Reflection and Decision Making. *The Journal of economic perspectives, 19*(4), 25-42. doi: 10.1257/089533005775196732

Gigerenzer, G. (2009). Surrogates for theory. *APS observer, 22*(2), 21.

Gigerenzer, G. (2010). Personal Reflections on Theory and Psychology. *Theory & psychology, 20*(6), 733-743. doi: 10.1177/0959354310378184

Hagmann, P., Cammoun, L., Gigandet, X., Meuli, R., Honey, C. J., Wedeen, V. J., & Sporns, O. (2008). Mapping the structural core of human cerebral cortex. *PLoS Biol, 6*(7), e159. doi: 10.1371/journal.pbio.0060159

Hegarty, M., Mayer, R. E., & Monk, C. A. (1995). Comprehension of arithmetic word problems: A comparison of successful and unsuccessful problem solvers. *Journal of educational psychology, 87*(1), 18.

Johnson, E., Tubau, E., & De Neys, W. (2014). The unbearable burden of executive load on cognitive reflection: A validation of dual process theory. In Proceedings of the Annual Conference of the Cognitive Science Society (Vol. 36, pp. 2441-2446).

Kahneman, D., & Klein, G. (2009). Conditions for intuitive expertise: a failure to disagree. *American Psychologist, 64*(6), 515. doi: 10.1037/a0016755

Kahneman, D., & Tversky, A. (1979). Prospect theory: An analysis of decision under risk. *Econometrica*, *47*(2), 263-2922.

Keren, G. (2013). A Tale of Two Systems: A Scientific Advance or a Theoretical Stone Soup? Commentary on Evans & Stanovich (2013). *Perspectives on psychological science, 8*(3), 257-262. doi: 10.1177/1745691613483474

Keren, G., & Schul, Y. (2009). Two Is Not Always Better Than One: A Critical Evaluation of Two-System Theories. *Perspectives on psychological science, 4*(6), 533-550. doi: 10.1111/j.1745-6924.2009.01164.x

Kruglanski, A. W., & Gigerenzer, G. (2011). Intuitive and deliberate judgments are based on common principles. *Psychological review, 118*(1), 97-109. doi: 10.1037/a0020762

Lieberman, M. D. (2009). What zombies can't do: A social cognitive neuroscience approach to the irreducibility of reflective consciousness. *J. St. BT Evans & K. Frankish (Eds.), In two minds: Dual processes and beyond*, 293-316.

Mercier, H., & Sperber, D. (2011). Why do humans reason? Arguments for an argumentative theory. *Behavioral and Brain Sciences, 34*(02), 57-74. doi: 10.1017/S0140525X10000968

Meyer, A., Frederick, S., Burnham, T. C., Guevara Pinto, J. D., Boyer, T. W., Ball, L. J., . . . Schuldt, J. P. (2015). Disfluent fonts don't help people solve math problems. *Journal of Experimental Psychology: General, 144*(2), e16. doi: 10.1037/xge0000049

Mitchell, M. (2009). *Complexity: A guided tour*: Oxford University Press.

Nadel, L. (2003). *Encyclopedia of Cognitive Science* (Vol. 3): Nature Publishing Group London, United Kingdom.

Petty, R. E., & Cacioppo, J. T. (1986). *The elaboration likelihood model of persuasion*: Springer.

Pinker, S. (1997). *How the Mind Works*. New York, NY: W.W. Norton & Company.

Raichle, M. E., Fiez, J. A., Videen, T. O., MacLeod, A.-M. K., Pardo, J. V., Fox, P. T., & Petersen, S. E. (1994). Practice-related changes in human brain functional anatomy during nonmotor learning. *Cerebral cortex, 4*(1), 8-26.

Reynolds, C. W. (1987). *Flocks, herds and schools: A distributed behavioral model.* Paper presented at the ACM Siggraph Computer Graphics.

Roberts, M. J. (2007). Integrating the mind: Domain general versus domain specific processes in higher cognition (pp. 13-37). Hove, UK: Psychology Press.

Shanahan, M. (2010). *Embodiment and the inner life: Cognition and Consciousness in the Space of Possible Minds*: Oxford University Press.

Shynkaruk, J. M., & Thompson, V. A. (2006). Confidence and accuracy in deductive reasoning. *Memory & Cognition, 34*(3), 619-632. doi: 10.3758/BF03193584

Sloman, S. A. (1996). The empirical case for two systems of reasoning. *Psychological bulletin, 119*(1), 3.

Sloman, S. A. (2002). Two systems of reasoning.

Smith, E. R., & DeCoster, J. (2000). Dual-Process Models in Social and Cognitive Psychology: Conceptual Integration and Links to Underlying Memory Systems. *Personality and social psychology review, 4*(2), 108-131. doi: 10.1207/S15327957PSPR0402_01

Stanovich, K. (1999). *Who is rational?: Studies of individual differences in reasoning*: Psychology Press.

Stanovich, K. E. (2004). A brain at war with itself. KE Stanovich, ed. *The Robot's Rebellion*, 31-80. doi: 10.7208/chicago/9780226771199.001.0001

Thompson, V. A. (2009). Dual-process theories: A metacognitive perspective. In J. S. B. T. E. K. Frankish (Ed.), *In two minds: Dual processes and beyond* (pp. 171-195). New York, NY, US: Oxford University Press.

Thompson, V. A. (2013). Why It Matters The Implications of Autonomous Processes for Dual Process Theories—Commentary on Evans & Stanovich (2013). *Perspectives on psychological science, 8*(3), 253-256. doi: 10.1177/1745691613483476

Thompson, V. A., Turner, J. A. P., & Pennycook, G. (2011). Intuition, reason, and metacognition. *Cognitive psychology, 63*(3), 107-140. doi: 10.1016/j.cogpsych.2011.06.001

Toplak, M. E., West, R. F., & Stanovich, K. E. (2011). The Cognitive Reflection Test as a predictor of performance on heuristics-and-biases tasks. *Memory & Cognition, 39*(7), 1275-1289.

Tversky, A., & Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. *science, 185*(4157), 1124-1131. doi: 10.1126/science.185.4157.1124

Tye, M. (1997). *Ten problems of consciousness: A representational theory of the phenomenal mind*: mit Press.

Tye, M. (2000). Consciousness, Color, and Content (Representation and Mind).

van den Heuvel, M. P., & Sporns, O. (2011). Rich-club organization of the human connectome. *The Journal of neuroscience, 31*(44), 15775-15786. doi: 10.1523/JNEUROSCI.3539-11.2011

Van Lier, J., Revlin, R., & De Neys, W. (2013). Detecting Cheaters without Thinking: Testing the Automaticity of the Cheater Detection Module. *PloS one, 8*(1), e53827. doi: 10.1371/journal.pone.0053827

Wastell, C. A. (2014). An emergence solution to the reasoning dual processes interaction problem. *Theory & psychology, 24*(3), 339-358. doi: 10.1177/0959354314533442

Appendix A

Instructions for participants in the *no load* condition in Experiment 2

Instructions

You will be presented with 15 maths problems.

The **first** 12 problems will be presented one by one without a memory task.

The **last** 3 problems will be presented with a short memory task. These problems require you to:
1. Read the information component of the maths problem.
2. Memorise the 3x3 grid pattern in 8 seconds. After 8 seconds you will automatically move to the next page.
3. Recall the grid's pattern. Click the squares that were highlighted in the grid.
4. Solve the maths problem.

For all questions:

Please answer as accurately and quickly as possible.

Enter your final answer ONLY however you may use spare paper etc. to help you solve the problem.

Enter numbers to 2 decimal places (maximum) and exclude any terms such as cents or kilometres.

Thank you in advance for your concentration and participation.

Instructions for participants in the *load* condition in Experiment 2

Instructions

You will be presented with 15 maths problems.

The **first** 12 problems will be presented one by one without a memory task.

The **last** 3 problems will be presented with a short memory task. These problems require you to:
1. Read the information component of the maths problem.
2. Memorise the 3x3 grid pattern in 8 seconds. After 8 seconds you will automatically move to the next page.
3. Solve the maths problem
4. Recall the grid's pattern. Click the squares that were highlighted in the grid.

For all questions:

Please answer as accurately and quickly as possible.

Only enter your final answer however you may use spare paper etc. to help you solve the problem.

Only use numbers to 2 decimal places and exclude any terms such as cents or kilometres.

Thank you in advance for your concentration and participation.

Appendix B

Ethics Approval Received 1st May, 2015

Delivered-To: zoe.purcell@students.mq.edu.au
Received: by 10.79.75.7 with SMTP id y7csp63139iva;
Thu, 30 Apr 2015 18:31:31 -0700 (PDT)
X-Received: by 10.66.186.103 with SMTP id
fj7mr13251009pac.132.1430443891167;
Thu, 30 Apr 2015 18:31:31 -0700 (PDT)
Return-Path: <fhs.ethics@mq.edu.au>
Received: from netdnsprod1.mq.edu.au (netdnsprod1.mq.edu.au.
[137.111.226.226])
by mx.google.com with ESMTP id
k5si5889900pdo.20.2015.04.30.18.31.30
for <zoe.purcell@students.mq.edu.au>;
Thu, 30 Apr 2015 18:31:31 -0700 (PDT)
Received-SPF: pass (google.com: domain of fhs.ethics@mq.edu.au designates
137.111.226.226 as permitted sender) client-ip=137.111.226.226;
Authentication-Results: mx.google.com;
spf=pass (google.com: domain of fhs.ethics@mq.edu.au designates
137.111.226.226 as permitted sender) smtp.mail=fhs.ethics@mq.edu.au
Received: from mq.edu.au ([10.167.35.189])
by netdnsprod1.mq.edu.au (8.13.8/8.13.8) with SMTP id
t411VOJ9027444;
Fri, 1 May 2015 11:31:24 +1000
Message-ID: <488620155513124835@mq.edu.au>
X-EM-Version: 5, 0, 0, 4
X-EM-Registration: #0020530310231E005C00
From: "Fhs Ethics" <fhs.ethics@mq.edu.au>
To: "Associate Professor Colin Wastell" <colin.wastell@mq.edu.au>
Cc: "Miss Zoe Alexandra Purcell" <zoe.purcell@students.mq.edu.au>
Subject: RE: HS Ethics Application - Approved (5201500347)(Con/Met)
Date: Fri, 1 May 2015 11:31:24 +1000
MIME-Version: 1.0
Content-type: text/plain; charset=US-ASCII

Dear Associate Professor Wastell,

Re: "Is the role of supervisory reasoning different for experts and novices?"(5201500347)

Thank you very much for your response. Your response has addressed the issues raised by the Faculty of Human Sciences Human Research Ethics Sub-Committee and approval has been granted, effective 1st May 2015. This email constitutes ethical approval only.

This research meets the requirements of the National Statement on Ethical Conduct in Human Research (2007). The National Statement is available at the following web site:

http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/e72.pdf.

The following personnel are authorised to conduct this research:

Associate Professor Colin Wastell
Zoe Alexandra Purcell

Please note the following standard requirements of approval:

1. The approval of this project is conditional upon your continuing

compliance with the National Statement on Ethical Conduct in Human Research (2007).

2. Approval will be for a period of five (5) years subject to the provision of annual reports.

Progress Report 1 Due: 1st May 2016
Progress Report 2 Due: 1st May 2017
Progress Report 3 Due: 1st May 2018
Progress Report 4 Due: 1st May 2019
Final Report Due: 1st May 2020

NB. If you complete the work earlier than you had planned you must submit a Final Report as soon as the work is completed. If the project has been discontinued or not commenced for any reason, you are also required to submit a Final Report for the project.

Progress reports and Final Reports are available at the following website:

http://www.research.mq.edu.au/current_research_staff/human_research_ethics/application_resources

3. If the project has run for more than five (5) years you cannot renew approval for the project. You will need to complete and submit a Final Report and submit a new application for the project. (The five year limit on renewal of approvals allows the Sub-Committee to fully re-review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).

4. All amendments to the project must be reviewed and approved by the Sub-Committee before implementation. Please complete and submit a Request for Amendment Form available at the following website:

http://www.research.mq.edu.au/current_research_staff/human_research_ethics/managing_approved_research_projects

5. Please notify the Sub-Committee immediately in the event of any adverse effects on participants or of any unforeseen events that affect the continued ethical acceptability of the project.

6. At all times you are responsible for the ethical conduct of your research in accordance with the guidelines established by the University. This information is available at the following websites:

http://www.mq.edu.au/policy

http://www.research.mq.edu.au/for/researchers/how_to_obtain_ethics_approval/human_research_ethics/policy

If you will be applying for or have applied for internal or external funding for the above project it is your responsibility to provide the Macquarie University's Research Grants Management Assistant with a copy of this email as soon as possible. Internal and External funding agencies will not be informed that you have approval for your project and funds will not be released until the Research Grants Management Assistant has received a copy of this email.

If you need to provide a hard copy letter of approval to an external organisation as evidence that you have approval, please do not hesitate to contact the Ethics Secretariat at the address below.

Please retain a copy of this email as this is your official notification of ethics approval.

Yours sincerely,

Dr Anthony Miller
Chair
Faculty of Human Sciences
Human Research Ethics Sub-Committee

Faculty of Human Sciences - Ethics
Research Office
Level 3, Research HUB, Building C5C
Macquarie University
NSW 2109

Ph: +61 2 9850 4197
Fax: +61 2 9850 4465

Email: fhs.ethics@mq.edu.au
http://www.research.mq.edu.au/