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The Effects of Sleep on the Acquisition of Skill

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A Thesis Submitted in Partial Fulfillment of the

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The Use of Thesis statement is not included in this version of the thesis.

The Effects of Sleep on the Acquisition of Skill

Abstract

The current research was designed to evaluate the effect of sleep on memory for the declarative and procedural knowledge components of a cognitive skill. In a training phase, 17 participants in a no-sleep control group practised 120 repetitions of a simple algebra equation at 8am and 22 participants in a sleep group practised the task at 8pm. Novel task inputs were introduced within the same task structure in a transfer phase conducted 12 hours after training for each group. Overnight sleep conferred a 29% performance deficit on the transfer task compared to no-sleep controls. The results support the hypothesis that sleep consolidates declarative and procedural knowledge components of an acquired cognitive skill. The prediction that, when consolidated by sleep, knowledge acquired in training creates processing overheads that disrupt post-sleep transfer when task inputs are changed at transfer was upheld. Discussion considered the influence at transfer of three cognitive phenomena: proactive interference, inhibition, and facilitation developed in training. A basis for parsing the relative discrete effects of these phenomena is advanced and a novel framework for predicting skill acquisition and transfer across various training and transfer conditions is outlined. The present study extends support to sleep-consolidation of complex declarative knowledge as well as procedural knowledge, and has implications for theories of memory system dissociation as well as theories of skill acquisition and transfer.

Author: Peter G. Croy

Supervisor: Dr. Craig Speelman

Submitted: 27th October 2003

Statement

I certify that this thesis does not, to the best of my knowledge and belief:

1) Incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education;

2) Contain any material previously published or written by another person except where due reference is made in the text; Or

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Of my family at large, whose understanding was outstanding, I am proud. I will try to make up for lost time. In particular, to my Father who is in the grips of Alzheimer's and who failed to see me as often as he otherwise could ... I hope you don't remember Dad!

To Gail (my soul-mate), who supports me in everything and makes me very happy - this is for you.

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The Effects of Sleep on the Acquisition of Skill

There is a long history of behavioural research that has sought to demonstrate an innate role for sleep in memory consolidation. More recently, the field of neuroscience is contributing to an interpretation of sleep function through research on sleep related brain activity thought to represent *consolidation* of pre-sleep experience (for reviews of both behavioural and neuroscientific research see Maquet, 2001; Siegel, 2001; Stickgold, 2003; Stickgold, Hobson, Fosse, & Fossel, 2001; Vertes & Eastman, 2000). Together, behavioural and neuroscientific research claim strong support for the hypothesis that sleep promotes synaptic modification into a form that subsequently improves performance on skills acquired in waking hours (e.g., BuzsAk & Buzsaki, 2003; Hobson & Pace-Schott, 2002; Laureys, Peigneux, Perrin, & Maquet, 2002; Maquet, Schwartz, Passingham, & Frith, 2003; Pace-Schott & Hobson, 2002; Squire & Alvarez, 1995; Stickgold, 2003; Walker, Brakefield, Hobson, & Stickgold, 2003).

The *sleep-consolidation* hypothesis is supported by studies that demonstrate improved post sleep performance on several types of learning tasks. The majority of work in the field has centred on implicit learning tasks (e.g., Fischer, Hallschmid, Elsner, & Born, 2002; Stickgold, LaTanya, & Hobson, 2000; Stickgold, Whidbee, Schirmer, Patel, & Hobson, 2000; Walker, Brakefield, Hobson, et al., 2003), thus claiming strongest support for the acquisition of skills involving procedural learning. A lesser number of studies also support a role for sleep in the consolidation of declarative knowledge (e.g., Plihal & Born, 1997; Plihal, Pietrowski, & Born, 1999). However, some studies claim no support for sleep-consolidation of declarative knowledge (e.g., Smith, 1995). Thus, present opinion in the field differs regarding sleep's role in consolidating procedural versus declarative knowledge. Furthermore, much of the research in the field has focused on perceptual and perceptuomotor learning (e.g., Fischer, et al., 2002; Karni & Bertini, 1997; Karni, Tanne, Rubenstein, Askenasy, &

Sagi, 1994; Karni et al., 1998; Stickgold, LaTanya, et al., 2000; Stickgold, Whidbee, et al., 2000; Walker, Brakefield, Hobson, et al., 2003; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002). Less research has investigated sleep-consolidation of cognitive learning, an exception being Smith (1995). However, of the research on cognitive skill acquisition, no studies have been designed to enable a parsing of the separable effects of sleep on the declarative and procedural components of knowledge. In its present state of development, the sleep-consolidation hypothesis therefore appears to lack the practical utility needed to predict sleep effects on a broad range of knowledge and behaviour.

The purpose of the present study was to explore the effects of sleep on a cognitive skill acquisition and transfer task and to parse sleep's influence on separable declarative and procedural knowledge components of the task. In so doing, the present study directly addresses some of the principal contentions in the field and seeks to inform future sleep-consolidation research. The literature does not report any study that has attempted a parsing of sleep effects on the separable declarative and procedural knowledge components of cognitive skill acquisition. Accordingly, the present study expects to add meaningfully to the body of knowledge in the field.

Fields of endeavour that are complementary to sleep research include the study of human memory function and architecture, learning and skill acquisition, and cognitive neuroscience. Similarity to the debate within the sleep literature on the division between sleep-effects on procedural versus declarative knowledge, these fields of complementary research appear also to be presently occupied with reassessment of the merits of a memory model that attempts to account for a hypothesised dissociation in implicit and explicit memory function and architecture (e.g., Klein, Cosmides, Tooby, & Chance, 2002). While much of the literature continues to be guided by a declarative-procedural memory dichotomy, there appears to be growing appreciation of

a greater complexity in the encoding, storage and retrieval of human memory (e.g.,

Klein et al., 2002; Myers et al., 2003; Squire & Alvarez, 1995). The implication for the

sleep-consolidation field is that a growing appreciation of human memory complexity

is clouding the distinction between declarative and procedural knowledge systems (e.g.,

Stickgold, 2003). Accordingly, whether it is simply procedural memory that sleep

consolidates, or whether experience that is a composite of what has been termed

procedural and declarative memory is also consolidated by sleep, has become key to

achieving progress in the field.

Understanding sleep's role in enhancing memory is of obvious importance; such

a role for sleep might influence the way in which education and training programs

across a broad spectrum of human endeavour are structured and implemented. When

coupled with a complementary role for sleep, matters such as the intensity, timing and

duration of training necessary to optimise learning have clear practical implications.

Obvious stakeholders are students, teachers, athletes, and coaches – more generally, all

those whose work involves ongoing learning, and demands high standards of

performance, would stand to benefit from positive outcomes in this field.

The present review begins with a review of human memory systems and

architecture relevant to the present study, followed by an examination of the sleep-

consolidation hypothesis and related research. Finally, a review of the behavioural

models of skill acquisition is presented as a precursor to explication of the present

research.

Human Memory Systems

Memory was traditionally thought to be a unitary system. However, there are

now considered to be at least two kinds of memory in humans. The most commonly

used distinction concerns declarative versus procedural memory (e.g., Squire, 1986).

Declarative memory. Declarative memory has been described as *knowing that* and refers to knowledge that is explicitly, or consciously learned (Cohen, 2003; Schacter, 1996; Squire, 1986), and accessed with conscious awareness (Smith, 2001). According to Cohen (2003) and Cohen, Poldrack, and Eichenbaum (1997), declarative memory supports the on-demand accumulation, storage, and retrieval of new data about facts and events. It chunks, binds, and relates learned experience into flexible networks of knowledge representation, thereby providing a broad record of one's experience (Cohen, 2003). Declarative memory provides for representations of relations beyond the province of events, encompassing the relations among the facts that constitute one's knowledge of the world, providing the means for rapidly representing events and the spatial, temporal, and interactional relations among them. Moreover, declarative memory enables one to learn arbitrary, nonderivable associations through experience – for example, learning the names connected with people's faces or their addresses and telephone numbers (Cohen, 2003).

Procedural memory. Schacter (1996) describes procedural memory as characterised by unconscious, implicit, and usually, automatic knowledge (e.g., priming). Moreover, procedural memory has been described as *knowing how*, and comprises memories of skill sequences and problem solving processes (Smith, 2001). One of the key differences between declarative and procedural memory is that while declarative memory forms a flexible, relational database (Cohen, 2003), procedural memory is non-relational in nature, which results in inflexibility of procedural representations (Eichenbaum, 2001). This is because, according to Eichenbaum (2001), procedural knowledge is tuned and biased by experience - it represents the encapsulation of training sequences acquired through experience or practice. Furthermore, using the term *non-declarative* memory to describe all memory that is distinct from declarative memory, Viskontas and Knowlton (2003) maintain that non-

declarative memory refers to non-conscious memory of skills, habits, or other modes of learning that proceed beneath the surface of conscious awareness. Procedural memory, which Viskontas and Knowlton maintain is one component of non-declarative memory, describes the formation of skills and habits - a type of knowledge that, once acquired, often becomes difficult to articulate because of its implicit character.

The neuroanatomy of memory. The hippocampal formation and the basal ganglia are thought to play distinct roles in learning and memory. Traditionally, the hippocampus has been associated with declarative memory function in humans, while the basal ganglia are associated with procedural or habit learning (Cohen, Poldrack, & Eichenbaum, 1997; Graybiel, 2003; Myers et al., 2003; Swanson, 2003). According to Swanson (2003), the hippocampal system, being a closely related collection of structures in cerebral cortex, often referred to as the medial temporal lobe (MTL), is reciprocally connected with a wide variety of higher order association cortices representing all sensory domains. According to Cohen, Poldrack, and Eichenbaum (1997), the hippocampus drives the declarative knowledge binding process, forming reciprocal interconnections with all the higher order cortical networks of the brain. Activation of any element in the network triggers activation of related knowledge representations regardless of the context (Cohen et al., 1997). Cohen's view is consistent with Eichenbaum's (2000, 2001) claim that the hippocampus mediates the structuring of memory space composed of episodic (i.e., declarative) representations linked into a network – resulting in flexibility and promiscuity of explicit knowledge. By contrast, procedural memory is inflexible in that it is tied to a particular situation (Cohen et al., 1997).

According to Cohen et al. (1999), the hippocampus is not the repository or permanent storage site of all long-term memory. Instead, the reciprocal connections of the hippocampal system with all the higher order cortical processors allow it to mediate

storage in interaction with neocortical sites. After the various cortical processors identify the constituent elements of the event or experience, the hippocampal system binds together the multiple elements into long-term declarative memory representations that capture the relations among the elements, with the individual elements or attributes represented in distributed fashion in the relevant cortical processors (Cohen et al., 1999). According to Cohen et al., in functional neuroimaging studies of humans, hippocampal system activation arises whenever the task engages memory for the relations among items. Thus, Cohen et al. maintain that the interaction of the hippocampal system with neocortical processors and storage sites mediates the relational memory binding that allows the formation of declarative memory. Such memories are then flexibly accessible to various cortical processors in supporting cognitive processing and behavioural performance.

It has been widely accepted that the basal ganglia have a role in motor skill acquisition, which is largely implicit in character. However, more recently, a strengthening view that the basal ganglia are also involved in cognitive learning has emerged. For example, according to Graybiel (2003), the nuclei within the basal ganglia help to modify cortico-basal ganglia circuits because of experience, so that habits and procedures can be learned and produced as a whole sequence. Graybiel argues that such automatised behaviours free the brain to react to new events and to carry out many cognitive functions. By this account, Graybiel maintains that the basal ganglia may provide a base for cognitive activity as well as for motor activity.

There is an emerging view that the MTL can also store information independently (see Zola & Squire, 2003). Thus, an understanding the functionality of the MTL and the basal ganglia is still evolving. Whether the above accounts, that tend to indicate mutual exclusivity in the respective roles of the MTL and basal ganglia, can accommodate the idea that there is some form of binding of declarative and procedural

aspects of learning events was a question that is important to the conceptualisation and the interpretation of the present study. The task used in the present study has recognised declarative and procedural components. Sleep-consolidation effects on these knowledge components are dependent upon some form of mutuality in the encoding and storage of each, with respect to the overall representation of the task in memory.

Evidence of dissociation in memory systems. Evidence for dissociation between memory systems has accumulated largely through studies on brain-lesioned patents (e.g., Squire & Alvarez, 1995). Much of this work has pointed to dissociation in memory systems – that is, distinct declarative-explicit and procedural-implicit knowledge systems.

According to Cohen (2003), declarative memory differs from procedural memory in being a relational memory system. Declarative/relational memory impairment involves impairments in learning and remembering spatial relations among environmental cues and comparisons among temporally discontinuous events. According to Cohen, despite declarative memory impairment, animals can show normal learning and remembering of a large variety of conditioning, discrimination, and skill tasks, none of which requires a relational form of memory, but rather only gradual, incremental changes in bias or reactivity to individual items with repeated exposure. Similarly, according to Viskontas and Knowlton (2003), there is evidence that not only motor skill learning but also perceptual and cognitive skill learning can proceed in the absence of declarative memory (i.e., the absence of memory for the learning event). For example, it is believed that the acquisition of motor skills depends on the basal ganglia (e.g., Gabrieli, 1995), while the association of visual cues with motor actions depends on the cerebellum (e.g., Willingham, Koroshetz & Peterson, 1996). According to Viskontas and Knowlton (2003), in addition to having intact motor skill learning, patients with amnesia also have intact perceptual skill learning. Thus, while there is

some evidence for independent learning of perceptuomotor skills linked to an independence of basal ganglia functionality, the literature concerning evidence for independent basal ganglia involvement in cognitive skill learning is scant.

The widely known Tower of Hanoi problem-solving task has been used in studies on the learning of cognitive skills and habits. On this task, some researchers have found normal learning in amnesic patients under some circumstances (Cohen & Eichenbaum et al., 1993) but not others (Salmon & Butters, 1995). According to Viskontas and Knowlton (2003), it is likely that the tower task draws upon both procedural memory and declarative memory for the consequences of particular moves already tried. Viskontas and Knowlton (2003) report other tasks (artificial grammar tasks, and probabilistic classification, such as weather prediction), which indicate that amnesics perform equally as well as non-amnesics without conscious recollection of training episodes. For example, in a probabilistic weather prediction task, amnesics learnt the skill but showed no declarative memory of the learning episode whereas Parkinson's disease (PD) patients remembered the learning episode but did not learn the skill. According to Viskontas and Knowlton, since the brain regions damaged by PD include the neostriatum (caudate and putamen structures that are part of the basal ganglia) but not the hippocampal system, then the neostriatum is responsible for habit learning. Similarly, according to Packard (2003), the literature describes animal research on tasks where dissociation between the MTL and basal ganglia has been observed. These experiments include, for example, a conditioned eyeblink response task and procedural components of various water maze tasks. In such research, the neuroanatomical components of separable procedural memory systems in the mammalian brain have been shown to include the cerebellum, basal ganglia and amygdala (Packard, 2003). Furthermore, in a human brain neuroimaging study, Poldrack et al., (2001) found that during the probabilistic weather classification task

with two conditions – one emphasising the declarative aspects and the other the nondeclarative aspects – the declarative version elicited MTL activity, while the non declarative version elicited activity in the basal ganglia and other sub cortical structures. Furthermore, activity in the basal ganglia was negatively correlated with activity in the MTL. Conversely, however, other neuroimaging researchers maintain that a reason why it is difficult to find a task that addresses separate MTL and basal ganglia involvement in learning is that it is difficult to find a task in which the MTL is not activated (e.g., Myers et al., 2003). Taken together with Zola and Squire's (2003) view that the field's understanding of the MTL function in storage and mediation of event-representations is still evolving, Myers et al.'s interpretation that the MTL has ubiquitous involvement in memory processes highlights the need for caution in making absolute claims of dissociation in memory systems.

Memory consolidation. According to Squire and Alvarez (1995), the MTL and Diencephalic structures, but more specifically the hippocampal system, is essential for establishing information within long-term-memory (LTM), and is essential for a limited time after learning. Squire and Alvarez draw their conclusions from work on patients with temporally graded retrograde amnesia (TGRA) that involves damage to the MTL. TGRA refers to the ability of these amnesics to recall information from beyond some time in the past but not between that point in time and the present time. Unlike the temporally graded condition, ungraded retrograde amnesia (i.e., total inability to recall information from the past) also involves damage to neocortex and the anterior and lateral temporal lobe – all of which are also memory storage sites or knowledge systems. Squire and Alvarez hypothesise that there is a gradual reorganisation within LTM storage. That is, the hippocampal system manages the storage of memory until it is permanently consolidated into other storage areas that eventually become independent of the hippocampal formation – at which time the hippocampal

formation's role in storage is no longer needed. It is this intermediate functionality of the MTL that is of interest to the present study because it may allow an interpretation that a representation of a learning event can be held by the MTL so that sleep-consolidation effects, if present, would affect both the declarative and procedural components of the representation (see Zola & Squire, 2003).

Certain revisions of Squire and Alvarez' (1995) formulation of consolidation are detailed by Squire (2003) wherein he maintains that uncertainties remain concerning whether spatial memory operates by the same rules as non-spatial memory and whether memory for specific events that are unique to time and place consolidate in the same way as facts, which can be repeated in multiple contexts. Squire also reports recent animal studies that suggest that retrograde amnesia can become more extensive as damage extends beyond the hippocampus into adjacent MTL structures. The implications of these findings are, according to Squire, that the hippocampus itself is important for memory for a relatively short period after learning and that the adjacent perirhinal and parahippocampal cortices remain important for a longer time. Eventually however, neocortex serves as the final repository for LTM.

Squire and Alvarez (1995) claim that, in contemporary usage of the term, consolidation of memory can also mean the time-dependent process during which memory becomes fixed, irrespective of the storage site(s) involved. The term is also used to describe the molecular cascades and morphological changes through which synaptic modifications become stable after learning (Ribeiro, Goyal, Mello & Pavlides, 1999; Rose, 2003; Silva, 2003). Rose (2003), for example, describes a process of protein synthesis that extends for several hours following initial learning. Mediated by gene expression phases, this process of protein synthesis is hypothesised to strengthen synaptic connections associated with recently acquired knowledge. Furthermore, Stickgold (1998) argues that consolidation can refer to the simple strengthening of

memory, its movement from one memory system to another, or its functional linking to other, associated memories.

The key question from the perspective of the present study was whether the endogenous processes that occur to strengthen memory representations might preclude any strengthening of the declarative components of an acquired cognitive skill. It appears more plausible that the entire representation of a learning event might be held by the MTL for a period time – pending later incorporation into long-term storage (see Zola & Squire, 2003). This being the case, the consolidation activity could easily be interpreted as having an effect on all knowledge component representations of the acquired skill.

Sleep-Consolidation

Brain activity in sleep. According to Maquet (2000), there are two main types of sleep. Slow wave sleep (SWS) is mostly expressed early in the night and is characterised by large-amplitude, low frequency electroencephalographic (EEG) oscillations. In contrast, rapid eye movement (REM) sleep increasingly occurs late in the night and is identified by low-amplitude, relatively fast rhythms on EEG recordings, by ocular saccades, and by muscular atonia.

The key aspects of Squire's (2003) memory consolidation hypothesis are that consolidation occurs via the constant reactivation of representations within the MTL and that consolidation reflects long-term, gradual changes in connections within and between cortical areas. Squire and Alvarez (1995) propose that the constant reactivation of MTL representations may occur during SWS. According to Squire and Alvarez (1995), the properties of SWS that make it conducive to such a role are twofold. Firstly, the effectiveness of neural transmissions within the hippocampal circuitry is greater during SWS than during REM or waking states. Yet, plasticity within the same circuitry is reduced during SWS. The implication of these phenomena is that

reactivation is enabled in the absence of destabilising modification of representations within MTL. Secondly, during SWS, CA3 and CA1 cells discharge in synchronous, high frequency population bursts that lead to increased activity in the deep layer neurons of hippocampal target structures. Squire and Alvarez argue that such a mechanism represents a way in which synaptic change can occur within the hippocampal- entorhinal circuitry, ultimately influencing representations in neocortex. These consolidation hypotheses are supported in some degree by animal research. For example, in the rat hippocampus, neurons that tended to fire together during exploratory behaviour when the animal entered overlapping place fields had an increased probability of firing together during a subsequent episode of SWS (Squire & Alvarez, 1995). Squire and Alvarez take such findings as suggestive evidence for the reactivation of memory representations during sleep as part of an endogenous, gradual process by which memory is consolidated in neocortex.

Similarly, Steriade and Timofeev (2003) note that intracellular recordings from thalamic and related cortical neurons in vivo demonstrate that, during natural SWS oscillations, both thalamic and cortical neurons progressively enhance their responsiveness. According to Steriade and Timofeev, this potentiation lasts for several minutes after the end of oscillatory periods. Furthermore, cortical neurons display self-sustained activity, similar to responses evoked during previous epochs of stimulation. Steriade and Timofeev suggest that, far from being a quiescent state during which cortex and sub-cortical structures are globally inhibited, SWS may consolidate memories acquired during wakefulness in corticothalamic networks. Furthermore, Stickgold (2003) maintains that the shift from non-REM sleep (NREM) to REM sleep is accompanied by an increase in release of acetylcholine in the brain and a simultaneous near-cessation release of norepinephrine and seratonin. Brain imaging studies show that most brain regions become less active during NREM sleep; several

distinct regions, including the anterior cingulate and medial orbitofrontal cortices and the amygdala become more active in REM sleep (Stickgold, 2003). According to Stickgold, during SWS the hippocampus appears to be replaying specific episodic memories to neocortex. Conversely, in REM sleep, information appears to flow from neocortex to the hippocampus. Based on these observations, Stickgold speculates that once neocortex has adequately integrated a memory, it may send a message to the hippocampus to erase it. Stickgold's account appears to accommodate the idea that the MTL holds information for a period. This is also a view of others (e.g., Zola & Squire, 2003). Thus, if the information that the MTL holds is representative of the entire event-representation, then, once again, it appears plausible that consolidation activity will have an effect on procedural *and* declarative knowledge representations. Again, this interpretation was important to the present study because separate declarative and procedural components of the present task were to be parsed in order to determine whether there was any dissociation in memory consolidation activity.

Behavioural research and sleep consolidation. The idea that sleep participates in the consolidation of new memory traces has been investigated in a variety of behavioural, experimental designs. These include memory effects of post training sleep deprivation, effects of learning on post-training sleep, effects of within-sleep stimulation on the sleep pattern and on overnight memories, and examination of the re-expression of behaviour-specific neural patterns during post-training sleep. Research has also studied the respective contributions of REM and NREM sleep processes in relation to both declarative and non-declarative memory. Relevant studies are summarised below.

Research has been conducted in the visual domain (Karni et al., 1994), demonstrating that, following training, delayed learning of a texture discrimination task occurs during a night of sleep. Karni et al. demonstrated that selective disruption of

REM sleep prevents the overnight performance gain. Similarly, Stickgold, Whidbee, et al. (2000), using a visual discrimination task, found that training only leads to improved performance after a night's sleep compared to retesting on the same day. They found that overnight improvement correlates both with the amount of SWS early in the night and the amount of REM sleep late in the night. Stickgold et al. concluded that their findings suggest a two-stage process of sleep-dependent memory consolidation requiring SWS followed by REM sleep. Furthermore, according to Stickgold, LaTanya, et al. (2000), delayed performance benefits are absolutely dependent on the first night of sleep after acquisition.

Just as in the visual domain, research on motor skill training has shown that the majority of improvement occurs the first day following overnight sleep, and that improvement continues over additional nights of sleep. Using a finger tapping motor skill task, Walker, Brakefield, et al. (2002) trained participants with a 12-hour break between training and subsequent testing. One group was trained in the morning with a 12-hour period of wake before testing. The other group had overnight sleep in the period between training and testing. The awake group showed no improvement at testing whereas the sleep group showed a 20% improvement the next morning. In a further experiment, Walker, Brakefield, Seidman, et al. (2003), using a sequential finger-tapping task found that following initial training, small practice dependent improvements were possible before, but not following, the large sleep related improvements. They found that doubling the amount of training did not alter the amount of subsequent, sleep-dependent learning that develops overnight. Finally, they also found no correlation between sleep-dependent learning and practice dependent learning that is achieved during training. Walker et al. took this final finding as an indication of the existence of two discrete motor-learning processes – one developing

rapidly during task performance and one developing across a night of sleep without active task engagement.

Furthermore, in a sequential motor task (finger-to-thumb opposition task) Fischer et al. (2002) found that, irrespective of when sleep occurred following initial acquisition (i.e., whether sleep took place in the daytime or at night), sleep after practice enhanced speed of sequence performance by 33.5% and reduced error rate by 30.1% when compared to corresponding periods of wakefulness. Fischer et al. also found that the consolidating effect of sleep was specific for the motor sequence learned and did not generalise to a similar sequence that involved identical movement segments in a different order.

Other researchers have suggested a role for sleep in consolidating memory that is dependent on preserved sleep cycles rather than on the individual preservation of REM or NREM sleep. Ficca, Lombardo, Rossi, and Salzarulo (2000) found that recall of verbal information presented before sleep was impaired for participants with disturbed sleep patterns (i.e., the natural sequence of sleep phases), but not for participants with disrupted sleep but intact sleep pattern. Similarly, Gais, Plihal, Wagner, and Born (2000) selectively deprived participants of early night SWS and late night REM sleep, and concluded that, for enhanced memory on a visual discrimination skill, consolidation is triggered by SWS-related processes, whereas REM sleep promotes additional consolidation, but only after periods of SWS.

In the study of the apparent benefit of post training sleep on performance, researchers have also taken account of whether improved performance is simply a function of time-lapse, or circadian phases during which sleep occurs, or some interaction between these two effects. Laureys, Peigneux, Perrin, and Maquet (2002) and Walker, Brakefield, Seidman, et al. (2003) studied these issues and demonstrated

that, for motor skills at least, improved performance is mainly a function of overnight sleep.

Animal research has also been prominent in the sleep literature. For example, in a fear conditioning experiment with mice, Graves, Heller, Pack, and Abel (2003) demonstrated that spatial orientation and recognition of physical surroundings were impaired if sleep was deprived during the first five hours after learning a task. However, sleep deprivation five to ten hours after learning produced no learning impairment. They found that impairment was confined to contextual memory (the memory involved in associating particular surroundings with an electric shock). Cued memory (recollection of facts and events, or associating a tone with an electric shock) was not affected. According to Graves et al., because the brain's hippocampus is key to contextual memory but not cued memory, the findings provide evidence that sleep helps regulate neuronal function in the hippocampus. They took these findings to support the hypothesis that sleep regulates neuronal function during memory consolidation. The findings of Graves et al. support previous findings (e.g., Smith, 1985) with rats where, using a water maze task, evidence of a paradoxical (REM) sleep window for place, but not cue, learning was found.

Thus, whereas, a great deal of research supports sleep-consolidation effects on perceptual and motor skills (e.g., Gais et al., 2002; Karni et al., 1994; Stickgold, LaTanya, et al., 2000; Stickgold, Whidbee, et al., 2000; Walker et al., 2002), the research on declarative memory consolidation is mixed. Whether declarative memory is consolidated in sleep was a question that is central to the present study – the task used in the present study has distinct declarative and procedural components. The following section discusses some of the field's observations about declarative versus procedural memory consolidation in sleep.

Procedural versus declarative memory consolidation. According to Stickgold (2003), sleep deprivation has been shown to have little or no effect on the retention of simple declarative memories such as paired word associates. However, Stickgold maintains that sleep deprivation may interfere with the retention or consolidation of more complex declarative memories, such as, for example, recall of lists of words grouped into categories, or foreign languages. According to Stickgold, it is however unclear whether it is the specifically declarative portion of such learning or the more subtle, non-declarative components that are being affected. Stickgold maintains that some aspects of complex declarative memories *are* supported by sleep. For example, in rats, spatial learning tasks are largely hippocampally mediated, and it is possible to look at the role of sleep in consolidating hippocampally mediated memories in rats by comparing spatial and non-spatial tasks. According to Stickgold, both types of tasks are found to be sleep dependent; post training REM deprivation impaired performance on both the Morris water maze and the eight-arm radial arm maze. Thus, Stickgold concludes that these tasks may correspond to the complex declarative memory tasks in humans, which show a similar REM dependency.

In a study designed to test the effects of REM and NREM sleep deprivation in relation to both declarative and procedural tasks, Smith (1995) presented students with word recognition, word fragment completion, visual memory, Corsi block tapping and Tower of Hanoi tasks. Smith found that, upon testing one week later, the REM sleep deprived and total sleep deprived groups were not impaired on the declarative word recognition or the visual memorisation task – thus indicating the lack of an effect for sleep on these ostensibly straight-forward declarative tasks. In contrast, Smith found performance impairment in these groups on the procedural word fragment completion, Corsi block tapping, and Tower of Hanoi tasks compared to the NREM deprived group and the no-sleep-deprived control group. Thus, by this account, REM sleep, but not

NREM sleep, appears to influence procedural memory consolidation, which appears to be a composite of both declarative and procedural knowledge. However, simple declarative memory appears unaffected by any phase of sleep.

The investigation of sleep-effects on declarative versus procedural knowledge has involved tests of memory for already-consolidated declarative material without any special context to the learning conditions. Paired word associates are an example of this (e.g., Stickgold, 2003). However, tasks such as the Tower of Hanoi task, as used by Smith (1995), are more likely to involve both declarative and procedural knowledge components (Stickgold, 2003). Accordingly, whether sleep can be expected to influence declarative memory that is already consolidated in cortex and is not contextually bound to any procedure is a question of interest. Conversely, already consolidated declarative components of procedural tasks represent materials that may be contextually bound to the representation of that task (e.g. Stickgold, 2003). Research on sleep-effects on this *complex* declarative knowledge has met with mixed results (e.g., Smith, 1995). Thus, interpretations that leave no scope for sleep-effects on declarative knowledge may be premature. For example, the field is presently investigating the observation that reactivated memories are subject to reconsolidation, which involves synaptic modification of the existing memories (e.g., Debiec, LeDoux, & Nadar, 2002; Walker, Brakefield, Tiffany, et al., 2003). This line of research is suggestive of the possibility that reactivated declarative knowledge might become associatively bound to the context within which it was initially activated. This notion was of interest to the present task because the declarative material could be described as *complex*, in the sense that it is associated with other knowledge – that is, procedural components, which are embedded in the skill-acquisition task.

In summary, although findings from sleep research point toward an important and complex role for sleep in the off-line reprocessing of learning and memory, the

evidence appears clearest for the role of REM sleep in the consolidation of procedural learning for perceptuomotor skills. The possible roles for sleep consolidating and integrating declarative memories is less clear, but this may be a consequence of previous research having been unable to parse sleep effects on respective declarative and procedural knowledge components of experimental tasks. The following section provides an analysis of the current task - with particular reference to its declarative and procedural components – within the context of some well-known theories of skill acquisition.

Skill Acquisition and Transfer

Skill acquisition. The above review identifies various aspects of current theory regarding memory and learning. However, despite recent technological advances in the field of neuroscience and a consequent burgeoning contribution to the study of biological processes in the brain, much of the nature and function of memory, learning, and skill development remains unconfirmed (e.g., Myers et al., 2003). There exists, however, a number of well-known models of memory, learning, and skill acquisition that are grounded in behavioural research (e.g., Anderson, 1982; Fitts, 1964; Logan, 1988; Newell & Rosenbloom, 1981; Rickard, 1997). The present study does not ground itself in any of these theoretical positions, but adopts broad terms of reference for its design and analysis. As mentioned in the introduction, the present study employs a cognitive skill acquisition task that involves training and transfer phases - a paradigm used in many behavioural studies on cognitive skill acquisition. Various theoretical models and behavioural works relevant to the present study are summarised below.

Fitts (1964) distinguished three phases of motor skill acquisition. His *early*, *intermediate*, and *late* phases also aptly describe the course of cognitive skill acquisition. Fitts' early phase focuses on the learning of domain knowledge, for example by reading and discussion, without attempts to apply it. The intermediate

phase involves problem solving, by reference to worked examples. When learners enter the intermediate phase, they have some relevant knowledge for solving problems but not all of it, as they may have also acquired some misunderstandings. Thus, initially, learners attempt to correct the flaws in their understanding before acquiring heuristic, experiential knowledge that expedites problem solving. However, learners can still make unintended errors or slips (Norman, 1981). In Fitts' late phase, speed improves, as does accuracy as learners practice, even though their understanding of the domain and their basic approach to solving the problem does not change.

The present study focuses on the late phase in Fitts' (1964) model, where continued practice causes further improvements in speed and accuracy. Anderson and Fincham (1994) found that the speed of applying individual components of knowledge increased according to a power law. Thus, unless the skill is encapsulated in a single knowledge representation, practice benefits components of knowledge rather than the skill as a whole. Anderson (1993) has argued that this speedup with practice is due to two mechanisms: knowledge is converted from a slow format (declarative knowledge) into a fast format (procedural knowledge). However, Anderson proffers that the procedural knowledge is abstract in nature and is increasingly refined in practice, enabling speed-up of performance with practice. Anderson thus makes a clear distinction between separable declarative and procedural skill components. Others (e.g., Haider & Frensch, 2002) have described this declarative-to-procedural conversion process as one of information-reduction – that is, the learning of more efficient or heuristic procedures that require less manipulation of declarative material to suit a goal of faster problem solving.

Other eminent researchers in the field have presented alternative explanations of speedup with practice. For example, Newell and Rosenbloom (1981), and Newell (1990) argued that small, general pieces of knowledge are gradually composed together

(chunked) to form large, specific pieces of knowledge, thus allowing the same task to be accomplished by applying fewer pieces of knowledge. Newell's implication is that these pieces of knowledge are a composite of declarative and procedural components.

In contrast, if participants are given enough practice with a particular input, then they eventually just retrieve the output from memory rather than mentally calculate it (Anderson & Fincham, 1994; Healy & Bourne, 1995; Logan, 1988). Memory retrieval can also apply to sub-procedures of complex tasks (Carlson et al., 1990). Participants report this change in strategy from algorithm to memory retrieval, and they are much faster in responding to practiced task inputs than unpracticed ones (Haider & Frensch, 2002). Haider and Frensch (2002) have found that participants' reports of strategy shift from algorithm to memory retrieval are matched by discontinuity in learning curves. Similarly, Rickard (1995) found that latencies for each of the calculation and retrieval strategies fit power curves quite well but that the overall latencies do not fit a power curve. Rickard took this to mean that a power relationship speed-up is not necessarily related to a shift in strategy from calculation to retrieval, as believed by Logan (1988), but is related to continued practice using either a calculation *or* a retrieval strategy. Logan's model of speed up with practice is a stimulus-response conceptualisation, however, an open question with respect to the response (i.e., the retrieved solution) is whether it represents declarative or procedural material, or both. Irrespective of its classification, Logan does not allow an interpretation that the material is abstract by nature. Thus, this represents a key difference between the ideas of Logan and Anderson (1982). Anderson classifies his productions as abstract and such, capable of being invoked to provide performance benefits across tasks with equivalent structure but with variation to declarative task inputs. Logan's instances do not have this quality; they are specific to precise stimulus-response memory representations that are dependant upon constancy of task input.

Skill transfer. The above accounts describe how practice might cause improvement in performance on a skill acquisition task. One means by which the assumptions of the various models may be evaluated is by examining performance on skill transfer tasks. Carlson et al. (1990) demonstrated that practice could cause a decrease in performance in transfer under certain conditions. Where the training task is to master a mental algorithm with one set of inputs, and the transfer task is to master the same algorithm with a different set of inputs, as long as the individual continues to use the algorithm during training, the effects of that training should transfer. However, as the individual starts to use direct memory retrieval instead of executing the algorithm, increasing the time spent in training will not reduce the time to master the transfer task beyond a certain point. That is, despite achieving fast, solution retrieval processing in training, novel inputs at transfer will cause a reversion to an algorithmic, mental-calculation strategy. Thus, in these circumstances, practice decreases the amount of transfer. According to Carlson et al., where the training and transfer task contain the same instructional materials, even a little practice on the training task familiarises individuals with the shared instructional materials, and thus saves them time in learning the transfer task. However, with increasing practice on the training task, those individuals gain no further benefit on the transfer task. Thus, in such circumstances, more practice causes less transfer – where transfer is defined as the time saved at transfer divided by the time during training. This effect has been found on a variety of cognitive skills (e.g., Anderson & Fincham, 1994; Singley & Anderson, 1989). In summary, the degree of transfer observed, and how it varies with practice on the training task, depend on exactly what is shared between the tasks and on when practice causes changes in problem solving strategies (VanLehn, 1996).

Speelman and Kirsner (2001) have also demonstrated that old skills can be executed slower in the context of a new task than would be predicted based on training

performance. That is, improvement in old skills appeared to be disrupted by performance of the new task. Speelman and Kirsner argued that their results suggested that any change in task structure may cause some disruption, but this disruption was greatest with an increase, rather than a decrease, in task complexity. Similar to the observations of Carlson et al. (1990), Speelman and Kirsner observed that results indicated task complexity rather than amount of practice had any effect on transfer performance. These results were interpreted as indicating that old skills do continue to improve in new tasks as if conditions were not altered, but that disruptions caused by transfer are related to performance overheads associated with re-conceptualising the task. In general terms, Speelman and Kirsner's *reconceptualising* the task might be viewed as the endogenous process by which individuals determine whether the trained processing rules remain applicable to the transfer task. The Speelman and Kirsner study represents one of only a few attempts to address skill transfer effects in terms of a more fine-grained analysis, which goes beyond typical explanations that tend to focus simply on feature overlap between the training and transfer task. That is, their conceptualisation of the cause of a lack of savings at transfer under certain conditions is couched within terms of there being memory system variables – *overheads* – that cause differential transfer performance. These *overheads* are rarely discussed in the literature that directly addresses cognitive skill acquisition and transfer, but they are well known in terms of human cognition theory, and have implications for any skill theory.

Processing Phenomena at Transfer

The present study suggests that there are fundamental memory-processing mechanisms that influence performance at transfer. These mechanisms are discussed within the context of the present experiment, where novel task inputs are introduced at transfer but task structure and context remains unchanged. However, the explanatory value of these mechanisms could be extrapolated to other training and transfer task

conditions. The mechanisms encapsulate three well-known principles of cognitive psychology theory - *proactive interference, inhibition, and mental set.* These principles are briefly summarised below. The manner in which they are expected to influence transfer performance in the present experiment is explicated in the *research predictions* section of this introduction.

Proactive interference. Proactive interference represents the difficulty that individuals sometimes have when learning or remembering recently encountered material, because of related material previously learned (Goggin & Wickens, 1971; Wickens, 1972). The most widely cited example of this phenomenon is the difficulty experienced in recalling a person's new telephone number due to interference from the old, well known telephone number. This phenomenon is associated with the *fan effect* (Anderson, 2000), which is the increase in reaction time related to an increase in the number of facts associated with a concept. The fan effect results from the spread of activation (see Collins & Loftus, 1975) from the representation of one stimulus to all associated, or related, representations. Thus, when novel task inputs are experienced in a transfer task, and where similar task context is likely to act as a cue (stimulus) with respect to previously encountered material relevant to it, then the old task inputs are likely to become activated and *interfere* with the establishment of the novel inputs in working memory. Such interference could manifest as a processing *overhead* that constrains the strengthening of novel inputs that is required for speeded performance. Thus, slowdown at transfer was conceptualised as being due to a primary process of building activation strength of novel task inputs, and a secondary process where still-activated training task inputs slow the rate of strengthening of the novel material.

Inhibition and set-effects. Inhibition is the phenomenon that describes the prevention of processing a stimulus, due to another process being in operation (Pashler, 1994; Pashler, Johnson & Ruthruff, 2001). This phenomenon generally applies to the

processing of stimuli within the same sensory modality. These stimuli, which can be internally generated, need to be processed in a serial fashion and the processing of subsequent stimuli is subject to a *psychological refractory period* effect (Pashler et al., 2001; Van Selst, Ruthruff, & Johnston, 1999), which is the time needed to disengage from old processing and engage the new. Within the context of the present study, inhibition was thought likely to affect the processing of novel inputs at transfer because of the pre-existing processing of abstract productions learned in training. The initiation of abstract productions is an automatic and fast process (Anderson, 2000), and was thought to be responsible for consuming processing time at the expense of the strengthening of novel inputs.

Mental set describes the phenomenon of automatic initiation of a problem solving strategy if it has been successfully applied in the recent past (Anderson, 2000). Mental set effects (*set-effects*) were, in fact, considered responsible for the occurrence of inhibition within the context of a transfer task as described above. Within the context of the present experiment, mental-set that causes the automatic initiation of previously successful operations, was expected to give rise to the inhibition as described.

According to the above conceptualisation of typical transfer effects on performance, the negative influence of *interference* and *inhibition* would be additive and, along with the process of the building the activation-strength of novel inputs, would be complicit in causing a slowdown in performance at transfer. These effects would subsume the *performance-facilitating* influence of general skill knowledge to create an overall slow down in performance at transfer. The relative valence of these effects is not known precisely, except that negative influences are typically substantively greater than the positive influence (e.g., Anderson, 2000; Speelman & Kirsner, 2001). That is, the slowdown at transfer is typically large, and the benefit conferred by general task knowledge can be quite small. This interpretation of the

valence of the effects at transfer has implications for sleep-consolidation effects, which are discussed in the *research predictions* section of the introduction.

Rationale for the Present Study

The introduction has identified many studies that have demonstrated a sleep-consolidation effect with perceptual and motor learning tasks (e.g., Karni et al., 1994; Walker et al., 2002). Despite significant findings in perceptual and motor tasks, there has been a comparative paucity of research in the sleep-consolidation literature for cognitive learning. Among the few reported cognitive skill studies in the literature, mixed results are reported (e.g., Smith, 1995). Underlying the mixed reports concerning sleep effects on cognitive skill is a view that sleep strengthens procedural memory but not declarative memory. In turn, lack of adequate parsing of declarative and procedural components of cognitive skill tasks has been problematic for research in the cognitive domain (Stickgold, 2003). Moreover, the literature reports that memory for simple declarative knowledge, such as word associates that may not be contextually bound to a more complex knowledge representation, do not appear to be influenced by sleep (e.g., Smith, 1995). However, whether sleep can be expected to influence declarative knowledge representations that are integral to complex procedural skills is an open question in the field (Stickgold, 2003).

Other researchers speculate that dissociation in brain structure and function is a basis for differential consolidation of memory during sleep (e.g., Squire & Alvarez, 1995). The basal ganglia are firmly implicated in motor tasks for example, whereas the hippocampal formation is more clearly associated with declarative material (e.g., Ullman, 2001). These facts are demonstrated in studies on patients with Parkinson's disease and on those with lesions to the hippocampal formation respectively (e.g., Squire & Alvarez, 1995). Curiously, however, the hypothesised consolidating effect of the replay of waking experience through patterns of neuronal firing between the

hippocampus and cortex in sleep (e.g., Maquet, 2000), has not yet been linked to consolidation of declarative material. This apparent contradiction represents a further aspect of confusion in the literature.

The lack of appropriate task design in past research, and the as yet imprecise definition of brain structure functionality – in particular, the functionality of the basal ganglia and the hippocampal formation – taken together with the hypothesised yet ill-defined implicit versus explicit memory system dissociation, represents the context within which the present study is embedded. Parsing of the declarative and procedural components of the present task, in order to discern sleep effects on the respective components was seen as an important aspect of the present study.

The Skill Acquisition and Transfer Task

The present study seeks to explore the effects of sleep-consolidation using a cognitive-arithmetic skill training and transfer task that has recognised declarative and procedural memory components (Anderson, 2000). Thus, the present study is qualitatively distinct from many past sleep-consolidation studies that have focused either on perceptual and implicit motor learning tasks, or on cognitive tasks without parsing of knowledge components. The arithmetic task was designed to detect differences in skill transfer between a *sleep* condition and a *no-sleep* condition. In each condition, the temporal gap between skill training and transfer practice sessions was equal, except that intervening overnight sleep separated the practice sessions in the sleep condition, while the inter-session gap in the no-sleep condition occurred during the course of normal waking hours.

Previous cognitive skill transfer research has demonstrated successful transfer of general skill to the same task with novel inputs (e.g., Anderson, 2000). That is, acquired general problem-solving skill that continues into the transfer phase as if conditions were unchanged produced lower response latencies at the commencement of

transfer compared to those at the commencement of training. Moreover, latencies at the commencement of transfer were typically greater than those at the completion of training (Anderson, 2000). This latter effect has been conceptualised as a slowing in response time due to processing overheads (Speelman & Kirsner, 2001). In the present study, these overheads were conceptualised to comprise a number of variables, namely, proactive interference, and inhibition-mental set effects. In the present task, the same arithmetic equation was used in training and transfer, but the numbers used in the equation were changed at transfer. Thus, according to the present conceptualisation of the variables that would influence transfer performance, the following predictions were made.

Research Predictions

Research predictions draw upon the principles developed in earlier discussion on *processing phenomena at transfer*. The first prediction of the present study was that if sleep consolidates both declarative and procedural knowledge acquired in training, then the sleep group performance at transfer would be *slower* than that of the no-sleep group. That is, because of strengthening of declarative knowledge and mental-set, the respective negative influences of *interference* and *inhibition* would subsume the *performance-facilitating* influence of strengthened general task knowledge. These same variables would be in operation in the same manner for transfer without intervening sleep, and they are the same variables that give rise to typical transfer performance slow-down. However, their strengthening in sleep was expected to magnify their *net effect* on performance to produce a larger slowdown in the sleep group compared to the no-sleep group. The second prediction of the present study was that if sleep consolidates only procedural knowledge, the lack of augmented interference from sleep-strengthened representations of training task inputs would enable sleep-strengthened general task knowledge to produce faster performance in the sleep group

compared to the no-sleep group. This outcome was predicted despite the expected negative influence of inhibition from strengthened mental set, which was considered procedural. The relative valence of these factors was unknown, thus it would be possible that, where procedural knowledge only were consolidated, inhibition could subsume the performance-facilitating influence of consolidated general task knowledge to produce a deficit for the sleep group. The third prediction of the present study was that if sleep has no effect on memory, then performance between groups on the transfer task would be expected to be equivalent.

Sleep-consolidation effects, if present, were expected to manifest in differing group performance at the commencement of practice on the transfer task. Moreover, any initial performance difference was predicted to persist throughout transfer due to perseverance of the effects described above. No difference between groups was expected in training because both groups were treated the same at that point.

The present study sought to contribute to an understanding of the role of sleep in cognitive skill acquisition in general, but more specifically, to explicate the influence of sleep on declarative versus procedural components of memory as they relate to simple, cognitive-arithmetic skill acquisition. In so doing, the aim of the present study was to advance the field's understanding of how sleep might impact strategies for training cognitive skill, given certain expectations of the influence of sleep on the further refinement of, or the transfer of those skills within similar task structures.

<div align="center">Method</div>

Participants

Forty-two participants were recruited for the study. Approximately fifty percent of participants were volunteer undergraduate students from the Edith Cowan University. A convenience sample of non-university acquaintances of the experimenter represented the remaining fifty percent of participants. The demographic characteristics

of the sample were constrained only by a requirement that participants be familiar with basic algebra. Accordingly, eduction level ranged from final year of formal schooling to tertiary qualifications. Participants ranged in age between 17 and 54 years, with the mean age being 29 years. Males made up 49 percent of the sample, and females made up the remaining 51 percent. Where applicable, participants were offered a small monetary incentive to cover fuel expense. Upon recruitment, participants were randomly allocated to one of two experimental conditions – a *no-sleep* and a *sleep* condition. From the initial recruitment sample of 42, three participants were eliminated due to non-compliance with a requirement that those in the no-sleep condition abstain from sleeping in the period between practice sessions. After random assignment, there were 11 males and 6 females of mean age 39 years assigned to the no-sleep condition, and 8 males and 14 females of mean age 26 years assigned to the sleep condition.

Design

The study recorded response time in milliseconds (the dependent variable) to solve the algebraic equation $(x^2 - y)/2 = A$ in the training phase and in the transfer phase of the experiment. Values for x and y were paired – with eight pairings presented in random order within each of fifteen blocks throughout the training phase. The transfer phase used eight different x and y values, presented in the same manner as in training. Of the two groups comprising the independent variable (*condition*), the no-sleep control group undertook the training phase at 8.00am and the transfer phase at 8.00pm on the same day. The sleep group undertook the training phase at 8.00pm and the transfer phase at 8.00am the following morning.

Measures

Response time for correct responses and the overall accuracy of responses were the two measures of principal concern. Written self-reports were also obtained from participants for the requirement to abstain from between-phase sleep in the no-sleep

condition, and the requirement for at least six hours of between-phase overnight sleep in the sleep condition. Furthermore, verbal self-reports of level of alertness before the commencement of each phase of the experiment, together with reports of participant's preferred time of day for mental work were obtained.

Apparatus and Materials

Apple Macintosh computers were used to present the algebra task to participants, collect their responses, and record their response times. Task presentation and data recording were programmed using SuperlabPro software. Data captured by SuperlabPro were further summarised in Microsoft Excel worksheets. SPSS (version 11.5) was used for statistical analysis. Details of gender, educational level, age, and self-reports were manually recorded.

The algebra equation used in the present study was adapted from that used by Greig and Speelman (1999). Values for x and y in the equation $(x^2-y)/2=A$ for the training and transfer phases of the experiment, together with answers and correct responses to the goal of the task (i.e., to determine whether A is odd or even) are presented in Table 1.

Table 1

Experimental Items: Values for x and y, the Resulting Answer (A) and Correct

Response when Values are Substituted into the Equation $(x^2-y)/2=A$

Set 1 (Training Phase)				Set 2 (Transfer Phase)			
x	y	A	Response	x	y	A	Response
5	9	8	EVEN	6	10	13	ODD
5	11	7	ODD	6	12	12	EVEN
5	13	6	EVEN	6	14	11	ODD
5	15	5	ODD	6	16	10	EVEN
8	2	31	ODD	7	1	24	EVEN
8	4	30	EVEN	7	3	23	ODD
8	6	29	ODD	7	5	22	EVEN
8	8	28	EVEN	7	7	21	ODD

Procedure

Before testing, approval was sought from the Human Research Ethics

Committee, Faculty of Community Services, Education, and Social Science, Edith

Cowan University, Western Australia, for all aspects of the research. A statement of

disclosure and informed consent (see Appendix A) that briefly outlined the structure of

the experiment, possible risks, and discomforts, and stated that the right to withdraw

from the study would be respected, was to be read and signed by each participant. After

completion of an informed consent form, participants' details were recorded (see

Appendix B), following which participants were randomly assigned to a condition in

the experiment.

Upon allocation to experimental groups, participants were asked to sit at a

private computer station for the conduct of the experiment. A standard computer

keyboard was used for responses, with the Z key labeled *ODD* and the forward slash (/)

key labeled *EVEN* for trial responses. The task was presented in the centre of the screen until the participant entered a response. With the experimenter present to answer any questions, participants were asked to read instructions on the computer screen explaining the experiment (see Appendix C). Following the instructions, participants were presented with eight practice trials (see Appendix C) before commencement of the training phase.

Following completion of the eight practice trials, participants were instructed to commence the training phase of the experiment, which consisted of 120 trials. Participants were instructed to initiate the beginning of the first trial by pressing the space bar, and to work as quickly as was practicable without sacrificing accuracy. In each trial, participants were initially presented with an individual problem in the centre of the screen, and instructed to press either the key labeled *ODD* or the key labeled *EVEN* to nominate their response to the problem. After making their selection, accuracy feedback was provided by presentation of the words CORRECT or INCORRECT on the computer screen for 500ms. Following accuracy feedback, the participant was prompted to press the space bar to continue onto the next trial.

Upon completion of the training phase, participants in the no-sleep condition, whose training phase was conducted at 8.00am, were requested to return to the test venue at 8.00pm to complete the transfer phase. Participants in the sleep condition, who commenced the training phase at 8.00pm, were instructed to attempt to obtain a normal night's sleep and return to the test venue at 8.00am on the following morning to commence the transfer phase. The transfer phase consisted of a further 120 trials, structured in the same manner as in the training phase. For counterbalancing purposes, half of the participants were presented with Set 1 in the training phase and Set 2 in the transfer phase, and the remainder was presented with Set 2 in the training phase and Set 1 in the transfer phase.

Participants were not informed of the purpose of the experiment at any point before completion of all trials. Following completion of the transfer phase, participants were fully debriefed, had all questions regarding the study answered, and had the experiment's hypotheses explained to them. Participants were then thanked for their participation and were offered a copy of the research report upon request following its completion.

Results

Data collected for each participant were response time and accuracy rate for each trial. The mean participant accuracy rate in all trials (trial 1-240) was 90% (SD = 14.7). Further scrutiny of accuracy data revealed that six participants achieved an accuracy rate below a nominal, well-above-chance level of 70%. However, elimination of these participants from the analysis did not alter the interpretation, therefore their data were retained. All analyses were conducted with the SPSS general linear model procedure. Reporting of significant differences was based on 95% confidence intervals, as calculated by SPSS.

For the training phase, a mixed 2 (group) X 15 (block) ANOVA was applied to the data. ANOVA's assumption of sphericity was violated; therefore, new degrees of freedom were calculated using a Huynh-Feldt value of 0.263. Response times displayed the typical speed-up with practice in training, with a significant effect for block, $F(3.683,136.254) = 55.742$, $p < .001$, $\eta_p^2 = .601$. There was a significant, Huynh-Feldt adjusted group X block interaction, $F(3.683,136.254) = 3.210$, $p = .018$, $\eta_p^2 = .080$. Between-subjects (group) differences were not significant, $F(1,37) = .324$, $p = .572$, $\eta_p^2 = .009$. Descriptive statistics are shown in Appendix D.

As no conditions were varied for either group in the training phase, no between-groups differences were expected. While ANOVA confirmed that there was no significant between-subjects difference, inspection of the marginal means plot for the

group X block interaction revealed that the sleep group started the training phase faster than the no-sleep group, but became slower than the no-sleep group over the latter part of the training phase (see Figure 1).
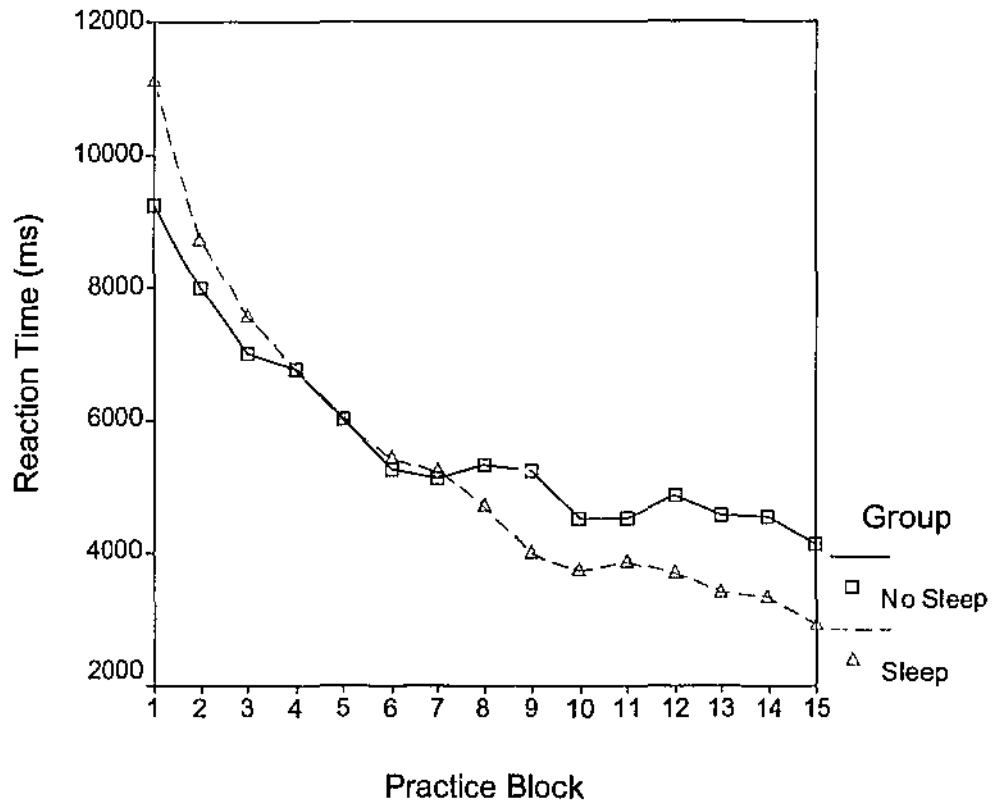
Figure 1. Mean training block response time for the sleep and no-sleep groups.

The principal comparison of concern in the present study was the between-groups difference at transfer. In order to account for intrinsic group-performance differences that may have influenced the interpretation of the principal comparison, a one-way ANOVA was used to investigate the group performance difference in the final block of training. ANOVA revealed a significant between-groups difference, $F(1,38) = 11.823, p = .001, \eta_p^2 = .242$.

Thus, the no-sleep group ended the training phase with slower performance than the sleep group. As a result, this difference between the groups could mask other differences that exist at the beginning of transfer that result from the sleep/no-sleep

manipulation. To control for this probability, the group performance difference in the final block of training was used as a covariate in a mixed 2 (group) X 15 (block) ANCOVA applied to transfer phase data. ANCOVA's sphericity assumption was violated; therefore, new degrees of freedom were calculated using a Huynh-Feldt value of 0.207. The effect of practice (block) was not significant, $F(2.896, 104.250) = 2.438$, $p < .071$, $\eta_p^2 = .063$. The block X group interaction was not significant, $F(2.896, 104.250) = .834$, $p = .475$, $\eta_p^2 = .023$. The between subjects difference was significant, $F(1,36) = 5.724$, $p = .022$, $\eta_p^2 = .137$. Descriptive statistics are shown in Appendix D.

The non-significant within-subjects block result occurred despite clear improvement in mean block response times from the beginning to the end of the transfer phase. Adjusted mean response times for the beginning and end of the transfer phase are shown in Table 2 (also see Figure 2).

Table 2

Mean Response Times and Standard Deviations in Milliseconds for the First Two Transfer Blocks and the Last Two Transfer Blocks, Adjusted by the Covariate of Mean RT in the Training Final Block

Transfer Block	Adjusted Mean	SE
Block 1	8811	861
Block 2	6676	531
Block 14	3097	211
Block 15	2984	181

Given a clear improvement in response time from the beginning to the end of transfer, and given also the near-significant Huynh-Feldt adjusted within-subjects F value of 2.438, block data appear to reflect the speed up with practice that is expected in studies of this kind (e.g., Speelman & Kirsner, 2001). However, within-subjects

block performance was not the comparison of principal concern for present analysis. Thus, the non-significant Huynh-Feldt adjusted result was not investigated further.

The absence of a significant group X block interaction in the transfer phase data suggests that the significant between-group difference in response time persevered throughout the transfer phase. Figure 2 supports this interpretation and shows that the sleep group performed slower than the no-sleep group at the commencement, as well as throughout the transfer phase, according to transfer block means adjusted by the covariate of mean RT in the training final block.
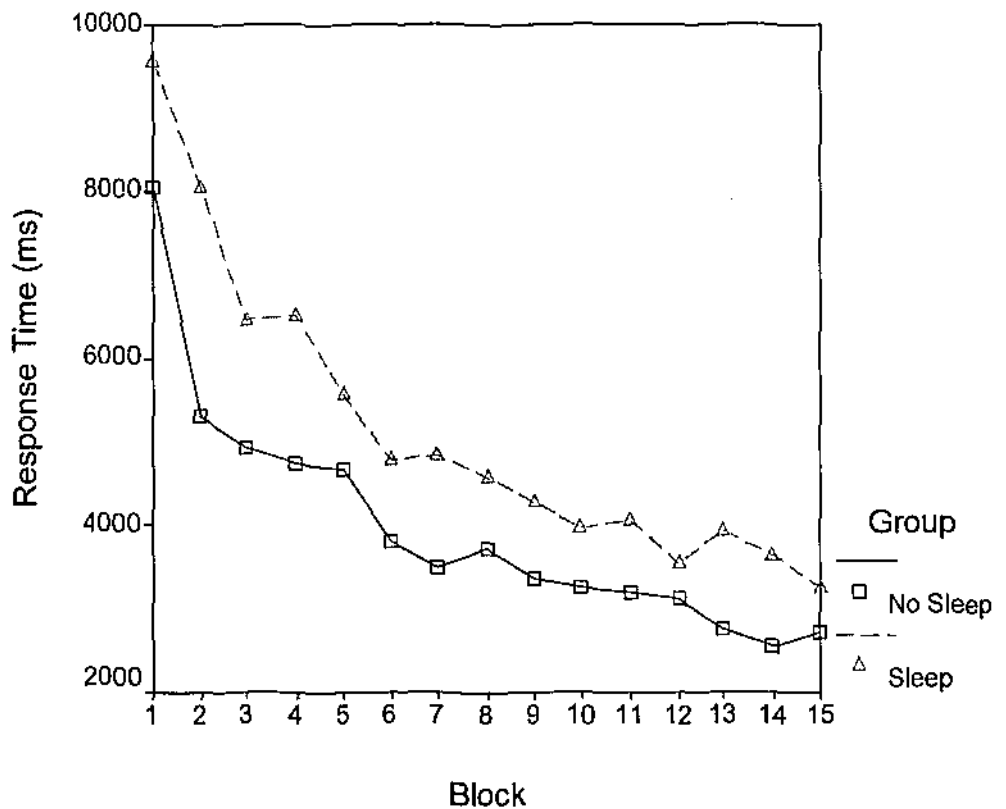
Figure 2. Mean transfer block response time for the sleep and no-sleep groups.

Data were also initially analysed for any influence of participant age and gender on results, however no effects were found. Thus, the reporting of age and gender differences was excluded from the above analyses. Similarly, the verbal self-reports obtained from participants concerning their perceived level of alertness before each

practice session and their preferred time of day for mental work, were inspected for potential to influence the interpretation of results. As there were only minor differences in the classification self-reported alertness between groups, none of these data were expected to change the interpretation, thus they were not analysed further.

Discussion

The results of the present study are consistent with the prediction that, where sleep consolidates both the declarative *and* procedural components of an acquired cognitive skill, then post-sleep performance on the same task with changed inputs would be disadvantaged when compared to performance on the changed task before overnight sleep. Thus, results support the idea that endogenous sleep processes consolidate procedural *as well as* declarative knowledge components of an acquired cognitive skill. It was predicted that sleep-strengthened declarative knowledge would proactively interfere with the process of building activation strength in the novel inputs that are encountered at transfer. The effect of proactive interference on the transfer task was predicted to result in a post-sleep performance deficit when compared to no-sleep controls. The transfer task performance deficit in the sleep group confirms this prediction.

The present study predicted that, if both declarative and procedural knowledge components of the training task were consolidated in sleep, a performance deficit would be observed in the sleep condition. Conversely, improved transfer performance in the sleep condition would be taken to represent sleep-consolidation of only the procedural memory component of the task, *not* the declarative component. More specifically, a sleep condition performance deficit at transfer was to be interpreted as the effects of both *interference* caused by the strengthening of training phase task inputs and *inhibition* caused by strengthening of a mental-set acquired in training. Furthermore, it was argued that the negative effects on performance of interference and

inhibition would subsume the performance *facilitating* effect of strengthened general skill, to produce an overall transfer performance deficit in the sleep condition. Memory representations of training task inputs were considered *declarative*, whereas general problem solving knowledge (familiarity with task structure and production rules) was considered *procedural*. Set-effect associated with the inhibiting influence of automatically initiated production rules was also considered *procedural*.

In the present study, the distinction between declarative and procedural knowledge components of the task was considered important because, as identified in the introduction, the literature conveys greatest support for sleep-consolidation of procedural knowledge whereas sleep-consolidation of declarative knowledge is less clear. As outlined in the introduction, most of the success in demonstrating a role for sleep in memory consolidation has been associated with perceptuomotor tasks where acquired knowledge is classified as implicit, or procedural. Furthermore, as discussed, in sleep-consolidation research that has employed cognitive tasks, few studies have attempted to parse separate declarative and procedural knowledge components in order to discern separable sleep-consolidation effects on these two knowledge categories. Accordingly, the field's understanding of the type of cognitive knowledge that is likely to be consolidated in sleep is unclear. Thus, the hypothesised implicit versus explicit dissociation in memory systems (e.g., Squire & Alvarez, 1995) was considered integral to the study of sleep-consolidation, as was the difference in functionality of relevant brain structures – namely, the basal ganglia for implicit knowledge, and the hippocampal formation for explicit knowledge (e.g., Myers et al., 2003). It is therefore necessary to discuss the present results within a framework of memory systems and architecture in an attempt to elucidate the influence of sleep on cognitive skill.

This discussion interprets the present findings with reference to the main computational models of skill acquisition, followed by a review of the results with

reference to recent research in brain-architecture and function, as well as memory system dissociation. Alternative explanations for the results are then examined.

The Present Results and Computational Skill Models

The introduction identified the key variables for interpreting the present results: *proactive interference* from strengthened declarative material, *inhibition* from strengthened mental-set, and *facilitation* from strengthened general task knowledge. Some of the more influential behavioural models to which the literature refers in the interpretation of research in skill acquisition and transfer have been described in the introduction. These models are discussed here, with emphasis on their relevance to the present results. That is, with particular reference to differentiation of declarative and procedural knowledge components, and to implications for the processing variables (i.e., *overheads*) identified in the present study.

Anderson's (1982) theory is premised on automatised mechanisms (known as productions), which are *abstract* representations of efficient problem solving procedures – they are a byproduct of initial detailed algorithmic processing and are continuously refined throughout practice on a task. According to Anderson, the act of consciously applying these abstract mechanisms during their development creates efficiency, but they eventually take on an automatic, pre-consciously initiated nature, that results in further performance speed. At transfer, these abstract representations persist, to create a performance benefit if the task structure and context is equivalent to that encountered in training. However, speed overall is slowed, because of novel task inputs encountered at transfer, until further practice in transfer returns speed to pre-transfer levels.

It is argued here that the typical slow down observed when novel inputs are encountered at transfer is related, in part, to the lack of activation-strength of the representations of the novel task inputs. That is, frequency of access to the new material

must accrue to enable the holding of the new information in working memory to create speeded processing. Anderson (1982) supports the concept of activation strength, and he relates it not only to declarative material (i.e., task inputs), but also to the abstract representations of problem solving procedures. A further premise of the present study was that the process of strengthening of novel inputs is likely to be handicapped by the still-activated old task inputs – that is, proactive interference of the old task inputs with the new task inputs. Thus, despite a benefit conveyed by established abstract operations at transfer, a net increase in latency was predicted in the event of all knowledge components (procedural *and* declarative) being consolidated in sleep. Thus, it is argued that a performance deficit at transfer would be related to a strong effect of working memory overheads associated with strengthening of new task inputs within an environment of proactive interference from the old task inputs. These negative effects were expected to subsume the facilitatory (i.e., positive) influence of transfer of general skill, to cause a marked deterioration in latencies at transfer.

It was also predicted that both groups would be subject to the effects of proactive interference at transfer. However, if sleep consolidated the old task inputs (i.e., the training task inputs), it is argued that interference effects at transfer would be strengthened relative to the no-sleep group. Furthermore, because processing new declarative material has greater influence on latency at transfer than does general skill (see Speelman & Kirsner, 2001) then, by implication, sleep-strengthened interference effects would arguably have greater influence on performance than sleep-strengthened general skill.

As argued in the introduction, performance deficits at transfer were predicted *not* to be related solely to strengthened proactive interference effects as described above. Speelman, Forbes, and Giesen (2003) describe the phenomenon known as mental-set, where individuals adhere to a particular problem solving strategy even

though it may be less effective than another strategy -- a concept also proposed by Woltz, Bell, Kyllonen, and Gardner (1996). Speelman et al. discuss the mental-set phenomenon in relation to changes in task structure, where, in such cases, attempts to apply outdated operations lead to disruption in performance. In the present study, there was no change in task structure; only the task inputs were changed at transfer. Thus, the present analysis argues that, due to the identical task structure in the present study, mental-set effects would have been invoked with high valence. This phenomenon, it is argued, would inhibit the processing of novel inputs encountered at transfer. By these accounts, processing and strengthening of novel inputs would be handicapped by two phenomena: proactive interference and inhibition.

As discussed in the introduction, inhibition is a process by which, when processing material within a single sensory modality (in this case, the cognitive modality), the processing of other material is inhibited because of the constraints of serial processing. Thus, processing of novel inputs is considered to be subject to the effects of a *psychological refractory period* (PRP), which the introduction described as the temporal, *task-switching*, delay caused by the necessary disengagement from a pre-existing process being in operation. *Processing*, within this context, means the loading of the novel declarative representations into working memory (see Speelman et al., 2003). Once again, in the present study, both experimental groups were expected to be subject to the effects of inhibition at transfer. However, strengthening of mental-set in sleep was expected to create an inhibition-PRP effect of greater valence for the sleep group.

In summary, it is argued that there would be three processing overhead phenomena typically in operation at transfer when inputs, but not structure, are changed in the transfer task: *proactive interference, inhibition*, and *facilitation*. It is further argued that strengthening of both the declarative and procedural components of the task

during sleep, has given rise to an *increase* in the effect of these three processing overhead phenomena at transfer in the sleep group. The relative valence of the phenomena is thought to be such that the deleterious effects of interference and inhibition would subsume the facilitatory effect of general skill. Accordingly, strengthening of the underlying knowledge representations in sleep would have the effect of proportionately increasing their impacts on transfer performance in the sleep group compared to the no-sleep group. Because the sleep group was slower at transfer than the no-sleep group, these arguments appear to be supported.

The present results can be interpreted within the terms of either Anderson's (1982) or Logan's (1988) models. In Anderson's model, operationalisation and proceduralisation do not preclude the need to perceive, and thus activate, declarative material (the task inputs). In Logan's model, early algorithmic processing is eventually replaced by stimulus-response mental behaviour. Both of Logan's processing stages require the perception of declarative material – that is, the activation of its representations. The conceptual difference in Logan's model compared to Anderson's, relates to the stimulus-response processing mechanism (known as instances) proffered by Logan. If sleep were to consolidate this type of learning, then clearly, the declarative information (stimuli) should also be consolidated through its bonds with relevant solutions (responses). Indeed, representations of *instances* are, in fact, pieces of declarative knowledge because no procedures per se are implicated.

According to the research mentioned in the introduction, sleep strengthening of general (procedural) task knowledge appears straightforward, in that many studies have shown that sleep improves procedural memory and its use. Furthermore, the consolidation in sleep of newly acquired knowledge appears plausible from an adaptive viewpoint. For example, Lovett (1998) found that individuals have a bias for recently

successful problem-solving operators. Sleep-consolidation of such recently acquired, and ostensibly useful, knowledge would therefore appear likely on adaptive grounds.

Conversely, sleep-consolidation of declarative material has been studied with mixed observations (e.g., Smith, 2001). However, the present study emphasises that a key to understanding whether declarative material is likely to be consolidated in sleep, concerns whether the declarative material is in some way bound to a representation of the task, which also includes the procedural components (operations and/or solutions) of the task. Moreover, if the declarative information were not task-bound, although in the case of Logan's (1988) instance retrieval idea it is difficult to imagine that it is not, then an open question is whether activated declarative material, which is independent of procedural representations, is strengthened in sleep.

A focus on whether or not declarative information is strengthened by sleep is crucial for the present interpretation, because the concept of strengthened proactive interference, as discussed above, is reliant upon the assumption that the training task inputs *were* consolidated in sleep. The present study emphasises the point that the literature reports mixed findings about whether declarative material is or is not affected by sleep. In particular, certain opinion (e.g., Smith, 1995; Siegel, 2001) holds that simple declarative memory is unaffected by sleep, whereas other studies (e.g., Plihal & Born, 1997) have found results to the contrary. Yet, other studies have shown sleep effects for complex declarative tasks, for example, the tower of Hanoi task (e.g., Smith, 1995). These complex-declarative-task studies have been unable to parse declarative and procedural components to describe differential sleep effects on each. The present study also emphasises the idea that an examination of the role of the hippocampal formation (e.g., Squire & Alvarez, 1995) may be key to a better understanding of the potential for declarative information to be bound to representations of a task and, therefore, to be better positioned for consolidation in sleep. It is necessary therefore, to

discuss relevant brain architecture and functioning in relation to the prospect of declarative material to be influenced by sleep.

Brain Architecture and Memory Consolidation

According to Squire and Alvarez (1995), the hippocampus is thought to serve as an organising mechanism, which stores newly acquired knowledge and binds cortical information to that knowledge to form a coherent set of interconnections that represents in full the piece of knowledge. Over the course of time, Squire and Alvarez hypothesise that, through a process of consolidation, knowledge representation is fully assimilated into cortical associative networks to a point where the hippocampus is absolved from any further involvement with the representation. Squire and Alvarez's hypotheses are grounded in studies involving temporally graded retrograde amnesia that have linked the severity of hippocampal damage to the temporal aspects of the condition. That is, the greater the damage to the hippocampal formation, the larger is the extent of the retrogradivity, thus indicating that the hippocampus stores knowledge independently of neocortex. According to Squire and Alvarez's conception, the activation of newly acquired knowledge relating to an event would appear to require hippocampal involvement. Moreover, pre-existing declarative knowledge that is integral to the event would, predictably, be bound to the representation of the event that is stored in the hippocampus. The present study argues that a binding of declarative material to the task representation may improve its candidature for consolidation. In this sense, consolidation of the declarative material means the strengthening of the hippocampally mediated bonds that this material has with the overall task representation.

In Squire's (1992) work on the declarative versus nondeclarative distinction, declarative memory is a single system that is supported by the hippocampal formation; however, nondeclarative memory is made up of a set of subsystems, all of which are largely intact in hippocampal amnesics (e.g., skill learning, priming, simple classical

conditioning, and non-associative priming). Furthermore, Schacter (1996) classifies motor skills and cognitive skills together as part of a *procedural* memory system, but they predict that a division may be drawn between motor skills and cognitive skills. They maintain that motor skills necessarily depend on premotor and motor cortices, whereas cognitive skills may not. However, research on skill learning by patients with basal ganglia damage suggests that basal ganglia *can* affect both the motoric and cognitive domains (e.g., Myers et al., 2003). Parkinson's Disease, which is rooted in the basal ganglia, leads to deficits in learning some motor skills (e.g., Gabrieli, 1995) and in learning some cognitive skills (e.g., Saint-Cyr, Taylor, & Lang, 1988). Gabrieli (1995) has proposed that the relevant contribution of the basal ganglia is in learning to quickly complete a sequence of steps, whether motor or cognitive, suggesting a common rule in both types of skill. An open question in relation to the respective roles of the basal ganglia and hippocampal formation is whether the hippocampal formation still mediates the activation of an event that may involve an acquired skill, despite the skilled knowledge being rooted in the basal ganglia.

The foregoing question is key to interpreting the present results because hippocampal involvement in the storage and activation of an event - including its procedural and declarative components - might allow an interpretation of joint sleep-consolidation of both knowledge components. Such an interpretation may help resolve the discrepant finding, that hippocampal replay of waking experience during sleep affects procedural knowledge only (see Stickgold, 2003). Hippocampal replay in sleep that consolidates procedural knowledge only, appears counter-logical, given that the hippocampus binds both forms of knowledge through reciprocal connections with cortex. A more plausible view would account for neuronal replay influencing the entire hippocampal event representation. The present findings support such a view in that the declarative components of the task appear to be sleep-strengthened, and declarative

material is typically associated with the hippocampal formation (e.g., Squire & Alvarez, 1995). By this account, consolidation may be construed as both a strengthening of procedural components, and a strengthening of declarative components, achieved by a strengthening of the reciprocal connections between the MTL and cortex where the declarative components may be temporarily (MTL) or permanently (neocortex) stored. Permanently stored declarative material in associative cortex is, by definition, already consolidated. Thus, it is plausible that the event-representation in the hippocampus, which is comprised of reciprocal connections with cortex, may be the target of observed neuronal replay activity in sleep. It is argued that such a view would accommodate the notion that sleep consolidates declarative material as well as procedural material, which is a position that is fundamental to interpreting the present results.

The foregoing discussion presents a model for accommodating sleep-consolidation activity that is inclusive of declarative material. It promotes one explanation of the results observed in the present study, and, in so doing it also addresses the field's discrepant observation of the occurrence of hippocampal replay in sleep to the exclusion of effects on declarative representations. The idea that declarative material might be consolidated in sleep because of binding into hippocampal event representations is informed by the work of Squire (1992) and others as discussed, and also by the views of several contemporary writers. For example, according to Brown and Aggleton (2001), recognition memory may be subdivided functionally and neuroanatomically within the temporal lobe into two main components: one component is a familiarity and recency discrimination system centred on perirhinal cortex (a component of the hippocampal formation in the MTL); the second component is a recollective system centred on the hippocampus. Brown and Aggleton maintain that the perirhinal system rapidly processes information about the novelty or prior occurrence

of individual stimulus items. In contrast, the hippocampal system is slower, associative, and processes information concerning the prior occurrence of individual stimuli or collections of stimuli in relation to other stimuli, including, more generally, information about the prior occurrence of episodes or events. Within the context of the present study, why this sort of hippocampal functionality might preclude any binding of the declarative information associated with an event, at least to some temporal extent, is a question of interest.

Furthermore, according to Simons and Spiers (2003), at encoding, information is processed by a hierarchy of unimodal and polymodal cortical areas, resulting in a bound representation of associated features in the MTL. Simons and Spiers maintain that, through interactions with different regions of prefrontal cortex, topdown control of the encoding process modifies, elaborates, and organises MTL representations in a goal dependent manner, ensuring that they are discrete enough for long-term storage. This account also places a focus on *bound representations* where the MTL holds representations subject to their integration into long-term store. According to this view, the holding for a time of the declarative information related to a practiced skill appears plausible. Moreover, Eichenbaum (2000) maintains that neocortex, the parahippocampal region (including the rhinal and perirhinal cortices), and the hippocampus make unique contributions to memory processing. In Eichenbaum's view, high-order neocortical areas provide dedicated processors for perceptual, motor or cognitive information that is influenced by other components of the system. The parahippocampal region mediates convergence of this information and extends the persistence of neocortical memory representations. The hippocampus encodes the sequences of places and events that compose episodic memories, and links them together through their common elements. Thus, Eichenbaum describes a role for the parahippocampal region in mediating convergence of episodic material extending the

persistence of associated cortical material. Why the declarative material involved in a learning event would not remain linked to the representation of that event for a period is also a question of interest to the present study.

It has been stressed that an elucidation of the MTL's role in memory encoding, storage, and retrieval appears key to a better understanding of the sleep-consolidation hypothesis. The above accounts of the function of the MTL, while informative, are not definitive in terms of allowing an interpretation that declarative information is maintained in linked fashion to representations of a learning event. This apparent lack of a definition of the role of the MTL is not surprising given the ongoing research in the field. This matter is confirmed by Zola and Squire (2003) who state the following in a very recent publication:

> Recently, there has been interest in the possibility that some aspect of memory function might be associated specifically and uniquely with the hippocampus itself and, correspondingly, that some aspect of declarative memory might be independent of the hippocampus (and be supported instead by adjacent medial temporal cortex). These ideas are currently active topics of experimental work. (p. 3).

Finally, according to Ullman (2001), in the declarative versus procedural memory model, lexicon associative-memory markers, and the knowledge about facts and events depends on declarative memory and is rooted in the temporal lobe, whereas the grammar, and procedural motor and cognitive skills, is rooted in the frontal cortex and basal ganglia. However, as is evident by the above accounts of the function of the MTL, few researchers address the question of whether there exists any reciprocal or other relationship between the MTL and the basal ganglia. Yet, as these are the two key pieces of brain architecture that appear implicated in skill acquisition, an explication of

their mutual contribution to memory processes may further assist a more complete appreciation of the interpretation of the present results.

Memory System Dissociation

An understanding of how the MTL and the basal ganglia are implicated in memory, learning, and skill acquisition may not be of great importance when examining the impact of sleep on skill acquisition. Findings from behavioural studies for various effects of sleep may be sufficient to inform stakeholders such as educators, trainers, students, athletes, and others. However, broader, and more fine-grained analysis i- warranted in order to account for diffe tial performance in memory and skill ac on for individuals with, for example, hippocampal atrophy or Parkinson's disease. For these patients, how the type and structural aspects of the task, the contextual and temporal aspects of training, and the influence of sleep affect their memory and their learning are questions that may be of greater salience.

Myers et al. (2003) have approached this question in a very recent study designed to investigate dissociation in hippocampal versus basal ganglia contributions to learning and transfer. Using an *acquired equivalence* (associative learning) task, Myers et al. found that basal ganglia dysfunction (BGD) resulted in slowed acquisition in training, while individuals with hippocampal atrophy (HA) learned at normal speed when compared to controls. However, in a transfer phase involving the same task structure with novel recombinations, HA impaired generalisation but BGD did not impair generalisation. That is, HA patients learned well, but did not generalise their learning, while BGD patients learned poorly but were able to generalise what they had learnt. According to Myers et al., the study was the first time that a single task was used to demonstrate a double dissociation between the associative learning impairments caused by hippocampal damage versus basal ganglia dysfunction. Myers et al.'s findings are consistent with previous studies on associative learning (e.g., Knowlton &

Squire, 1993; Mishkin et al., 1984; White, 1997) and probabilistic category learning (Shohamy, Myers, Onloar, & Gluck, 2002) which show that BGD patients are slower to learn initial discriminations than either controls or HA patients but that, once learned, BGD patients can perform subsequent generalisations as well as controls. Myers et al. suggest that their findings demonstrate that basal ganglia are important for incrementally acquired associative learning.

However, according to Myers et al. (2003), their data also suggest that a reliance on either the hippocampus or the basal ganglia will *not* produce normal performance on acquisition for PD patients. They note that their data do *not* distinguish the relationship between the hippocampus and the basal ganglia in acquisition by PD patients. However, they proffer that the obvious conclusion is that simply noting *how fast* a subject learns a task does not necessarily provide any information about *how* the subject is encoding the information, or which brain structures are being used. Myers et al. believe that this is one reason why transfer performance may be a more informative index than simply measuring trials to criterion. Thus, by its own account, the Myers et al. study may not have explicated much in relation to mutual functioning of the MTL and basal ganglia. However, their study demonstrates the challenges posed in interpreting brain functionality, particularly as it relates to the present study, which has sought to examine differential sleep-effects on declarative and procedural knowledge components of an acquired cognitive skill with reference to brain architecture and function. Accordingly, accounts that exclude the prospect of sleep-consolidation of declarative material may be invalid in doing so.

The Myers at al. (2003) study has striking similarities with the way in which the present study was conceptualised and designed. That is, the present study attempted to parse the differential effects of sleep on the procedural and non-procedural components of performance on a training-transfer task. In so doing, the present study attempted to

interpret differential transfer performance within a context of differential sleep-consolidation effects that are dependent on distinct brain regions in which the two types of knowledge may be encoded and stored – namely, the hippocampal formation for declarative knowledge, and the basal ganglia for non-declarative knowledge. While the present study supports the case for sleep consolidation of complex declarative memory, it does not preclude the idea that certain brain regions may be more directly related to the storage of certain types of knowledge. Rather, it suggests that sleep is not selective in its activity. That is, sleep may consolidate material associated with the basal ganglia, but it also may consolidate declarative material that is contextually bound by the MTL to a task representation. It appears that the key to a better understanding of this phenomenon is a better elucidation of the mediating role of the MTL through its reciprocal links with various regions of the brain. Similarly, Myers et al. reflect on the potential for brain imaging technology to address some of the unresolved issues in this area. Specifically, knowing whether brain regions activated for declarative information in training are further activated at transfer, might shed light on the question of whether declarative material. along with procedural material, is consolidated in sleep, and whether differences across task categories are evident. The present study has implications for further endeavour in this field because it promotes the idea that both the declarative and procedural components of a cognitive skill are indeed consolidated in sleep. Results of the present experiment confirm this view.

Alternative Explanations

Circadian effects. Analysis of variance on the final block of training data revealed that evening performance was significantly faster than morning performance. Similarly, analysis of variance for the transfer data revealed evening performance was significantly faster than morning performance. These observations might reflect circadian influences on performance. To evaluate possible circadian effects on

performance, participants were asked, at the data collection stage of the experiment, to provide verbal self-reports on their perceived level of alertness at the commencement of each of the training and transfer phases. Participants were also asked to report on their normal, preferred time of day for performing mental tasks – morning or evening. Self-reports revealed that 48% of participants thought the morning was better than the evening for mental work. Furthermore, when asked to classify their level of alertness before the morning trials, 55% of participants in the sleep condition classified their alertness as *good*, compared to 65% in the no-sleep condition. Whereas, before evening trials, 59% of participants in the sleep condition classified their level of alertness as good, while, in the no-sleep condition, 45% classified their alertness as good.

On balance, the above data do not favour an interpretation of circadian influence on morning versus evening performance. Moreover, other sleep-consolidation research has studied circadian effects and has found them not to be influential. For example, Walker, Brakefield, Seidman, et al. (2003) studied sleep effects on learning over several days and found that various performance data (e.g., error rate) for the same participants were reversed on different days, despite participants being tested at precisely the same time of day. They also found no indication of circadian influences in subjective reports obtained from participants at all testing points.

Therefore, taken together with other studies, the current data do not appear to support a case for circadian influence on the superior evening performance observed in training and transfer. Rather, the difference in performance between groups observed in the latter part of training was considered to relate to other individual differences – that is, the no-sleep group was intrinsically slower than the sleep group. Accordingly, this was a basis for adopting the difference between groups at the end of training as an *individual-differences* covariate in the principal analysis of between-groups transfer performance.

Other possible confounds. The introduction cited studies that report sleep consolidation effects that are dependent upon sleep cycle, sleep organisation, and amount of sleep (e.g., Stickgold et al., 2000). Stickgold, Whidbee, et al. (2000) found a requirement of at least six hours of sleep to improve performance on certain tasks. Furthermore, Mednick et al. (2002) and Tietzel and Lack (2002) found restorative daytime naps to improve post-nap performance on some tasks. These potential influences were controlled in the present study by requesting that participants in the sleep group attempt to achieve a normal night's sleep. A criterion of a minimum of six hours sleep was established for participation in transfer trials. Participants in the no-sleep condition were required to abstain from sleeping in the period between training and transfer trial sessions. Based on verbal self-reports obtained prior to commencement of the transfer phase for sleep-group participants, all participants reported having achieved a minimum of six hours sleep and all reported having achieved a fair to good night's sleep. Three participants were excluded from participation in the transfer session on the basis that they slept during the inter-session period. Therefore, sleep related performance confounds were effectively controlled in the present experiment.

Furthermore, alcohol intake before trials, and the amount of sleep that participants had on the night preceding trials, may have affected performance on the task. To some extent, these potential influences were controlled through the verbal reports on alertness obtained before each practice session. Similarly, caffeine intake may have influenced participant performance (see Lieberman, 2001), while age-differences in time-of-day performance may also have influenced performance (see Hashler, Chung, May, & Foong, 2002). In the present study these potential influences were not subject to particular control, rather, random allocation was expected to

provide an even distribution of effects between groups. As such, these potential confounds, if any, are considered not to have influenced the present interpretation.

The generalisability of the present results needs to be viewed in context with the sample that comprised individuals with at least final year high school education up to individuals with tertiary qualifications. Effects of education level were not tested in the present study, as the task required no special training beyond high school level. Thus performance was considered not to be education-dependent. Furthermore, as identified in the *method* section, there were slight variations between groups for gender and age. Gender and age differences have not been a feature of past sleep-consolidation studies, but were investigated in the present study. No effects of gender or age were found, thus findings should generalise well across age and gender.

Effect size. The central comparison in the present study was the between groups difference in transfer. In this comparison, the relatively modest partial eta squared measure (13.7% of the variability in response time scores was explained by the sleep manipulation) warrants that some caution be used in interpreting the effect. One implication of the observed effect size is the need for confirmatory research. However, interpretation should also be evaluated within the context of previous studies, which have demonstrated that consolidation occurring in sleep is incremental in nature (Walker, Brakefield, Seidman, et al. 2003). Walker, Brakefield, Seidman, et al. (2003) maintain that learning occurs in practice on a task, and practice is typically accompanied by large performance gains. Through consolidation during sleep, a second endogenous learning stage occurs that typically produces smaller gains than those experienced in practice. Thus, in the present study, the amount of training on the task was designed such that performance at the end of training would be well above asymptotic level to avoid ceiling effects. The present study used 120 trials in training whereas, in a study using the same task, asymptotic level was estimated to occur

beyond 240 trials (see Simpson, 2003). While it is possible that a greater number of trials in training would have produced larger effect sizes, the present results are similar to others reported in the literature. For example, in the present study, the difference in mean response times between groups across the transfer phase was 29%. This result appears to compare well with other studies, where: a 17% mean difference on a sleep-consolidation motor task was reported by Walker, Brakefield, Seidman et al.; a 30% difference was reported by Fischer et al. (2002); and a 20% difference was reported by Walker, Brakefield, Morgan, et al. (2002).

The final item of note in relation to effect size is that the present study is the first to use the training-transfer paradigm and the particular algebra task in sleep-consolidation research. Typically, sleep consolidation studies have used perceptual or motor tasks in training, with retesting on the same task with the same inputs following periods of sleep. Thus, benchmark effect sizes for the present study were not readily available. However, given the size of the transfer performance difference between groups, the present results appear consistent with those of other, related research.

Practical Implications of the Present Study

The present results demonstrate that the transfer of cognitive problem solving skill to an identical task structure with changed inputs following a period of overnight sleep will result in performance deficits when compared to skill transfer without intervening sleep. Conversely, according to the principles developed here, if task structure and inputs remain unaltered, sleep should improve performance on a previously acquired skill, when compared to reapplication of the skill without an intervening period of sleep. Thus, the present study has practical implications for learning or study situations where very *specific* skilled knowledge is acquired in training and is applied following a temporal delay, which may or may not include sleep. The case of an identical training-transfer task structure with changed inputs at transfer

has been considered in the present study. Implications for other training and transfer conditions, which may involve change in task structure and/or training context, are discussed below in *suggestions for future research*.

The present study also contributes to a clarification of the influence of sleep on cognitive skill, which, as discussed, remains a scantly investigated domain. While many studies have demonstrated a role for sleep in consolidating procedural knowledge using perceptuomotor skill tasks, sleep-effects on cognitive skill have been a less studied topic. Perhaps a reason for the lack of research in the cognitive domain relates to the field's tentative understanding of whether sleep influences the strength of declarative memory representations. By supporting a role for sleep in consolidating declarative knowledge components of an acquired cognitive skill, the present study partially resolves this issue, and provides a conceptual framework *and* an experimental paradigm for further research in the field.

It turns out that the present study also has implications for skill theories. The major skill theories that focus on computational modeling and/or stimulus-response behaviour may benefit from reformulation within the terms of the processing overhead phenomena that have been elucidated. Moreover, Newell and Rosenbloom's (1981) idea, that is briefly detailed in the present study, and which incorporates the concept of *knowledge chunking* as the basis for skill development and memory organisation, appears to have a striking resemblance to the integrative nature of the hippocampal formation, which has been a focus of the present study. Accordingly, the skill field may profit from a more eclectic perspective – a perspective that *integrates* relevant attributes from each theory, *accounts* for the processing overheads detailed herein, and *accepts* input from the burgeoning contribution that the neuroscientific field has to offer. The present study represents a step toward such an ideal.

Suggestions for Future Research

The present results might be tested conveniently by similar research that holds task inputs constant at *transfer*. In such a design, on the basis of the principles used in the present analysis, the strengthening of both mental-set and the declarative task inputs in sleep would be expected to create performance advantages for the sleep-group compared to the no-sleep group, that is, the reverse effects to those in the present task would be predicted. The present study was unable to specify the relative effect size of the three performance variables; *interference* created by strengthened declarative representations, *inhibition* created by strengthening of mental-set, and *facilitation* created by strengthening of general task knowledge. However, a basis for predicting that the interference effect may have greater valence than the facilitating effect of acquired general skill was promoted. Moreover, while emphasis was placed explicating a role for sleep in consolidating declarative components of the task, it is possible that set-effects (inhibition) alone created the observed performance deficit in the sleep-group.

Therefore, a parsing of the separate effects of these variables on performance may represent a further challenge for future research. By variation to changes in task inputs and/or structure in training and transfer, it may be possible for these effects to be observed. For example, if nothing were to be changed at transfer, all three hypothesised variables would be expected to influence transfer performance positively. That is, *proactive interference* would be absent because there would be no *competing* declarative material. *Inhibition* would be irrelevant because no change in task inputs would obviate the need to strengthen declarative material, as it would be already active in working memory. Finally, trained general skill would have a *facilitatory* effect because production rules would be appropriate to the unchanged task structure. Furthermore, the additive effect of these influences would be expected to produce a

positive effect (i.e., a performance benefit) of greater magnitude than that of the negative effect observed in the present study. By the same reasoning, if task inputs were to remain constant at transfer, but the operational aspects of the task (i.e., structure) were changed, then *interference* effects would be absent, *inhibition* effects would be absent, while general skill would *not* be *facilitatory*. In turn, this combination of variables would be expected to produce a further variation to the magnitude of the net effect on performance.

Conclusion

Some of the studies cited in the present report claim to have demonstrated an absence of sleep effects for certain categories of memory – that is, declarative memory, cued memory, episodic memory. However, these studies provide little rationale for the underlying causes of this purported lack of sleep-effect. It is also clear from the sources cited that, despite a growing contribution from modern neuroscience, human memory function and its interface with brain architecture, remains ill defined. Furthermore, why identified neural and molecular activity in sleep, that is thought to be associated with consolidation during sleep, should affect brain regions and memory categories differentially, remains an open question for the field. Accordingly, claims of a lack of sleep-effect on certain memory categories cannot be regarded as conclusive. Furthermore, it was proffered that certain discrete cognitive phenomena may exert influence on performance of an acquired skill at transfer. By testing the net effect of these phenomena following sleep, a state in which memory is thought to consolidate, the present study was able to claim some support for their prevalence. It was also suggested that it may be possible to parse discrete effects of these phenomena through manipulation of training and transfer conditions. In so doing the present study provides a viable basis for ongoing research in the fields of sleep-consolidation, memory, and learning. Finally, the sleep-consolidation effects demonstrated in the present study have

implications for training and skilled performance. It was demonstrated that changes to trained task inputs have a significant deleterious effect on post-sleep performance on the transfer task. Conversely, albeit by implication according to the principles developed here, sleep should confer a performance benefit of comparatively greater valence in situations where trained task inputs are not altered in post-sleep activity on the task. The findings have implications for those whose acquired cognitive skills are to be applied, under certain conditions, following a period of overnight sleep.

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APPENDIX A

PARTICIPANT INFORMATION SHEET

The experiment in which you are about to participate is designed to investigate some of the ways in which we acquire mental skills and is being conducted by Peter Croy as a requirement of his Honours Thesis project. This experiment conforms to guidelines produced by the Edith Cowan University Committee for the Conduct of Ethical Research. The approval of the Ethics Committee - Faculty of Community Services, Education, and Social Science has been provided for the conduct of this experiment.

In this experiment, you will be required to solve some simple problems. These will be presented to you on the computer screen, and you will be required to enter your responses into the computer via the mouse and keyboard. Do not worry if you have never done something like this before, as most participants are the same as you in this respect. The aim is to examine how performing this task is affected by practice. This research will hopefully lead to the development of more efficient training methods. Your participation in this experiment will be required for either one session of approximately two hours or two sessions of approximately one hour each.

Please be assured that any information that you provide will be held in strict confidence by the researcher. At no time will your name be reported along with your responses. All data will be reported in group form only. At the conclusion of this study, a report of the results will be available on request.

Please understand that your participation in this research is totally voluntary and you are free to withdraw at any time during this study without penalty, and to remove any data that you may have contributed.

Any questions concerning this project can be directed to Peter Croy (Principal Investigator) on 0417 917 573 or Dr. Moira O'Connor (Fourth Year Coordinator) on 6304 5593.

Investigator   (P. Croy)   Date

INFORMED CONSENT

I (the participant) have read the information on the research and the requirements of my participation and any questions I have asked have been answered to my satisfaction. I agree to participate in this activity, realizing that I may withdraw at any time. I agree that research data gathered for the study may be published, provided I am not identifiable.

_____   _____
Participant or Authorised Representative   Date

_____   _____
Investigator   Date

APPENDIX B

PARTICIPANT DETAILS SHEET

PLEASE NOTE: ALL INFORMATION PROVIDED WILL REMAIN CONFIDENTIAL.

Name:_____

Age:_____   Gender: M / F (Please circle)

Occupation (past and/or present): _____

Number of years of formal schooling: _____

Is English your native language?

☐   ☐

Yes   No

If no, please indicate your native language:_____

Are you taking any medication/remedies that might cause drowsiness or affect your performance today?

☐   ☐

Yes   No

If yes, please provide details of the medications below:

_____

_____

_____

_____

____

Do you have any health problems or injuries (e.g. head trauma) that might affect your performance toady?

☐   ☐

Yes   No

If yes, please provide details in the space below:

_____

_____

APPENDIX C

EXPERIMENTAL INSTRUCTIONS FOR COMPUTER GENERATED ALGEBRA SKILL TASK

In this experiment you will be presented with a small arithmetic problem such as the following:

$$\frac{x^2 - y}{2} = A$$

$$x = 3 \quad y = 5$$

A is ODD   A is EVEN

Your task is to substitute the values for **x** and **y** into the formula to determine a value for A.

Once you have calculated a value for A you then need to decide whether this value is an even or an odd number.

If A is an odd number, you should press the key marked 'ODD' on the keyboard. If A is an even number, you should press the key marked 'EVEN' on your keyboard. Please respond as quickly and as accurately as you can.

You will now have some practice trials to make sure that you understand the task.

Please press the Space Bar to Continue

PRACTICE ITEMS

VALUES FOR X AND Y, THE RESULTING ANSWER (A) AND CORRECT

RESPONSE WHEN VALUES ARE SUBSTITUTED INTO THE EQUATION

Practice Items			
x	y	A	Response
3	1	4	EVEN
3	3	3	ODD
3	5	2	EVEN
3	7	1	ODD
4	2	7	ODD
4	4	6	EVEN
4	6	5	ODD
4	8	4	EVEN

APPENDIX D

Training Phase Data

Block Mean Response Time and Standard Deviation in ms

	Group	Mean	Standard Deviation
Block1	No Sleep	9250	2653
	Sleep	11093	4994
Block 2	No Sleep	7998	2062
	Sleep	8713	3605
Block 3	No Sleep	7004	1547
	Sleep	7574	3847
Block 4	No Sleep	6787	2247
	Sleep	6753	3249
Block 5	No Sleep	6016	1677
	Sleep	5997	2884
Block 6	No Sleep	5265	1330
	Sleep	5419	2559
Block 7	No Sleep	5125	1417
	Sleep	5236	2360
Block 8	No Sleep	5327	1713
	Sleep	4720	1919
Block 9	No Sleep	5249	1754
	Sleep	3992	1852
Block 10	No Sleep	4520	1355
	Sleep	3736	1535
Block 11	No Sleep	4539	1651
	Sleep	3858	2034
Block 12	No Sleep	4883	1594
	Sleep	3700	1910
Block 13	No Sleep	4574	1044
	Sleep	3408	1663
Block 14	No Sleep	4548	1262
	Sleep	3342	1204
Block 15	No Sleep	4129	1310
	Sleep	2918	1021

Transfer Phase Data

Block Adjusted Mean Response Time and Standard Error in ms

	Group	Mean	Standard Error
Block1	No Sleep	8058	1390
	Sleep	9565	1203
Block 2	No Sleep	5310	857
	Sleep	8043	742
Block 3	No Sleep	4932	512
	Sleep	6451	443
Block 4	No Sleep	4734	566
	Sleep	6512	490
Block 5	No Sleep	4663	501
	Sleep	5564	434
Block 6	No Sleep	3807	319
	Sleep	4776	276
Block 7	No Sleep	3481	336
	Sleep	4832	290
Block 8	No Sleep	3728	395
	Sleep	4583	342
Block 9	No Sleep	3361	302
	Sleep	4274	261
Block 10	No Sleep	3248	325
	Sleep	3967	281
Block 11	No Sleep	3188	335
	Sleep	4061	290
Block 12	No Sleep	3118	327
	Sleep	3546	283
Block 13	No Sleep	2754	330
	Sleep	3932	286
Block 14	No Sleep	2557	340
	Sleep	3638	294
Block 15	No Sleep	2712	291
	Sleep	3258	252