The VAM Application: A New Test of Visual & Audio Working Memory

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Declaration

I, Colm Daniel Moore, declare, in relation to the thesis titled "The VAM Application: A New Test of Visual & Audio Working Memory" that:

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Summary

The VAM application (Visual & Audio Memory) is a new computer based tool for examining Working Memory. The VAM is a versatile, configurable application that produces detailed results on the nature of audio and visual Working Memory and can be completed independently, without the need for direct human administration.

A review of the current research surrounding the nature of Working Memory is presented in Chapter 2. In particular, the multicomponent model proposed by Baddeley and Hitch is examined. Baddeley's model is one of the most widely accepted theories of Working Memory, with a lot of evidence to support it. Baddeley's model is still evolving and there are still several issues regarding the exact structure and functionality of Working Memory that need to be resolved.

There are many different methods of examining Working Memory, and a review of some of the more popular ones is provided in Chapter 3. The differences between traditional testing methods and newer computer based methods are also explored, along with the advantages and disadvantages inherent in each.

The design and implementation of the VAM application is discussed in Chapter 4. The VAM application is composed of five separate sub-tests: two sub-tests focusing on visual stimuli, two sub-tests focusing on audio stimuli and one sub-test focusing on a mixture of both visual and audio stimuli.

The rigorous testing process used to examine the VAM application is discussed in Chapter 5. The test re-test reliability of the VAM was found to be **r** = 0.79. The VAM correlated with Riding's IPI, a known, independent

computer based test of Working Memory, at **r** = 0.33, although problems with the IPI may have impacted this result. The VAM correlated with Raven's Progressive Matrices at **r** = 0.36, a result consistent with similar studies in the area. These results indicate that the VAM provides a reliable, valid measure of Working Memory.

The role of Working Memory and the VAM application in associated fields of research is also explored. In Chapter 6, long-term Working Memory impairment is shown to be an important indicator of several medical conditions, including ADHD and Alzheimer's disease. Short-term Working Memory impairment can also indicate severe anxiety or dangerous levels of fatigue. The VAM application is discussed as a diagnostic aid in these areas.

In Chapter 7, the concept of cognitive training is introduced. Cognitive training aims to improve mental processing capacity by exercising cognitive systems like Working Memory. The cognitive training industry is growing fast, though concerns about its effectiveness have been raised. The VAM application is proposed as a benchmark research tool that investigates changes in Working Memory capacity related to cognitive training.

Another area where the study of Working Memory and the VAM application can be useful is that of e-learning. E-learning involves the use of computer based technologies to enhance traditional learning methods. E-learning is discussed in Chapter 8. Working Memory plays an important role in the learning process and is an important factor when designing e-learning courses. The VAM application can assist in this process and even help to design adaptable courses that take advantage of Working Memory capacity.

In Chapter 9, the contributions provided by this thesis are discussed, along with an examination of some of the problems and limitations that occurred and some suggestions for future research.

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Chapter 1: Introduction

1.1 Introduction

This thesis documents the development of the VAM (Visual & Audio Memory) application. The VAM is a new computer based testing application designed to examine audio and visual Working Memory. The VAM is based on the model of Working Memory proposed by Baddeley and Hitch in 1974. In this introductory chapter the reasons for and goals of this study will be discussed along with the design and implementation of the study. The chapter will end with a look forward at the contents of this thesis.

1.2 Background to the Study

Working Memory is the portion of the human mind concerned with the short-term storage of information, the manipulation of that information for further use, the retrieval of relevant information from other sources and several other functions besides. Working Memory controls the processing of both internal information retrieved from Long-Term Memory and external information gathered from our senses. In addition, Working Memory controls our attention span; helping to focus our attention, split it, or change its target as required. Both attention span and information processing play a large role in a person's ability to learn successfully [Baddeley & Hitch, 1974], [Baddeley, 1986].

By better understanding the nature of Working Memory and by being able to examine it quickly and efficiently, many possibilities are opened up. Problems with Working Memory will be able to be identified quickly, assisting in the diagnosis of dementia, a symptom of many terrible conditions including Alzheimer's disease [Baddeley, 1986]. In younger children, Working Memory impairments are often linked to conditions like ADHD [Barkley, 1997], [Klingberg, Forssberg, Westerberg, 2002] and reduced academic performance [Alloway & Alloway, 2010]. Temporary impairment of Working Memory can also indicate that a person is suffering from severe fatigue which can impair performance and lead to accidents, particularly in the motor industry [Nilsson, Nelson, Carlson, 1997], [Lal & Craig, 2001].

Working Memory can be used as more than a diagnostic tool though. There is a school of thought that believes that training Working Memory can help manage conditions like ADHD [Klingberg et al, 2005] and may even help delay the onset of Alzheimer's when accompanied by a social and active lifestyle [Stern, 2006]. The rise of cognitive training games like Brain Age for the Nintendo DS have also brought these techniques to a wider audience than ever before. The cognitive training industry is still in its early days, and not everyone is optimistic about the results so far [Owen et al, 2010], [Shipstead, Redick, Engle, 2010]. Nevertheless, it is still a fast growing industry [SharpBrains, 2010] with a lot of potential, and Working Memory lies at the heart of it.

Working Memory is also strongly connected to our ability to learn [Alloway, 2009b], [Alloway & Alloway, 2010]. By identifying a person's strengths and weaknesses in Working Memory, multimedia rich computer applications can be designed specifically to work with a person's ability to process information [Mayer & Moreno, 1998]. Such applications will help focus attention on the task in hand while minimising distractions. The applications would be easy to learn with and intuitive to use. In short, by learning how one's Working Memory system operates, new applications can be designed that live up to the term 'user friendly'.

1.3 Rationale of Study

The term Working Memory was first used by Miller, Galanter and Pribam in 1960 and research into its exact nature and functionality has been going on ever since. Every year there are approximately 800 papers published with Working Memory in their title and approximately 3,700 with it mentioned in their title, abstract or keywords [Baddeley, 2007]. There are many different tools and tests available to examine different aspects of Working Memory. Since most of these methods have likewise been around for decades, they are generally conducted on a one-to-one basis and use paper based media as part of the testing process. As a result of this, large scale research projects often spend exorbitant amounts of time and effort administering these tests and collating the results for analysis.

With this in mind, digitising the testing process seems to be an obvious solution. Computerised testing can allow multiple candidates to be tested at once, can gather accurate and detailed information for analysis and can store that information in a format that can be easily imported into common computer based statistical packages. Despite this, there appear to be very few computerised tests of Working Memory readily available.

By examining the available research in the literature it became clear that in order to qualify as a recognised, computer based test of Working Memory, an application must:

1. Stand on a solid theoretical basis.
2. Have been designed and built according to those theories with reference to previous efforts in the field.
3. Have been rigorously tested in order to determine their reliability and validity.

While the above requirements were derived from studying the current state of the art research into Working Memory, several further requirements were also decided upon. These requirements were chosen in order to expand current efforts in the field and build on the potential offered by computer based testing. With this in mind, it was decided that a new test of Working Memory should also:

4. Not be custom built for a single study, but instead be designed to be used in as wide a range of areas as possible.
5. Be fully automated and not rely on a human administrator to carry them out.
6. Be extensively configurable in order to suit a number of different ability levels and research goals.

As this thesis describes, the design and implementation of the VAM application fulfils all these requirements and more.

1.4 Research Question

Can a new computerised test of audio and visual Working Memory be specifically designed and implemented to become a new versatile research tool for multiple fields associated with Working Memory?

By building a series of tests designed to probe various audio and visual aspects of Working Memory, evidence of how each component works individually and as part of a larger system can be gathered. This evidence can then be used to investigate the nature of audio and visual Working Memory and can be applied to a number of different research areas.

1.5 Methodology

The main goal of this thesis is to design and implement a new computer based test of visual and audio Working Memory that is versatile, fully automated, configurable and based on a solid theoretical base. The development process for this approach is composed of four main stages:

1. The theory behind the Working Memory system and the current methods used to examine it will be discussed in order to form a solid scientific base for the new application.
2. An application to evaluate several aspects of the candidate's audio and visual Working Memory will be designed and built. This application will be composed of the following tests:
   - Two tests focusing primarily on visual Working Memory.
   - Two tests focusing primarily on audio Working Memory.
   - A final test that subjects the candidate to a mixture of both audio and visual stimuli with a view to determining how they interact or interfere with each other.
3. Once the application has been built, it will be put through an extensive testing regime in order to test the reliability and validity of the application and see if the results conform to the current theories of Working Memory.
4. To explore some of the main areas where the application can be of particular use in the future. Working Memory is an important aspect of many diverse research areas. Three important and growing areas were chosen where this application can be especially useful:
   - As a medical diagnostic and safety tool.
   - The popular but relatively unproven area of cognitive training.
   - E-learning, where information technology and educational theory combine to improve the learning experience.

1.6 Strengths and Limitations of the Study

Although every effort was made to enhance the quality of this study, as with any research project it has some strengths as well as some limitations.

Strengths of this study include:

1) The VAM application is a powerful research tool that was designed and built based on a solid theoretical model and by examining popular methods of testing Working Memory, both traditional and computer based. It is designed to be easy to use and to provide detailed results so as to be useful in a number of diverse research areas.

2) The VAM application is fully automated and can be completed without direct supervision from an administrator. It is extensively configurable so it can be varied in terms of both functionality and difficulty. It is designed to be homogeneous so that the results of the various tests can be directly compared and analysed.

3) The VAM was tested and proven to be a reliable, valid test of Working Memory using a large sample size.

The combination of all the above strengths makes the VAM application unique. With so few widely recognised computer based tests of Working Memory available, the VAM can play an important role in the future of Working Memory research and its associated areas.

Limitations of the study include:

1) Locating a benchmark test against which to validate the VAM application proved to be very difficult. To be appropriate, the benchmark test needed to be a well-recognised, already validated, computer based test of Working Memory. It also needed to be fully automated, not require individual administration and not be too expensive to procure. These conditions severely limited the options available for the validation process.

2) Similarly, the level of resources required to rigorously test the VAM application in terms of test subjects and funds available made follow-up studies difficult to organise.

3) Many of the alternative tests of Working Memory used as reference points in this study are available only to clinical psychologists or cost considerable amounts of money to obtain. As such, some of the details come from second hand sources such as academic papers or text books. All available effort was made to double-check and validate these sources.

The above weaknesses are largely a result of the small scale and limited resources of this project. Hopefully they can be rectified in future studies when the VAM application is more widespread and has more recognition behind it.

1.7 Chapter Summaries

Chapter 1 - Introduction: A brief overview of the reasoning behind this thesis and the goals to be achieved.

Chapter 2 - Working Memory: State of the art research into the human memory system focusing on the theory of Working Memory as proposed by Baddeley and Hitch [1974]. This is the theory on which the new application is based. This chapter also contains a discussion of some of the current issues surrounding the study of Working Memory.

Chapter 3 – Tests of Working Memory: An analysis of past and present methods used to examine Working Memory. This analysis focuses on both traditional and computer based testing methods and the advantages, disadvantages and availability of each.

Chapter 4 – Design and Implementation of the VAM: Detailed information on the purpose and layout of each test within the VAM application. This chapter also contains information on how each of the tests was implemented and the additional features that are available in the application.

Chapter 5 – Testing and Results: A detailed description of the testing procedures carried out on the VAM application along with analyses of the results that were generated.

Chapter 6 – Working Memory as a Diagnostic Aid: Examination of how Working Memory can be used in the diagnoses of a number of medical conditions including Alzheimer's and ADHD. This chapter also examines the concept of fatigue, the dangers associated with it and how the VAM application can help expose fatigue and limit those dangers.

Chapter 7 – Cognitive Training: Examination of the concept of cognitive training, what it does, what results it produces and how the study of Working Memory and the VAM application can help explore this area further.

Chapter 8 – E-learning: Examination of the concept of e-learning, its advantages and disadvantages and how the study of Working Memory and the VAM application can improve e-learning application design and implementation.

Chapter 9 - Discussion: A review of the thesis is presented here along with what the thesis has contributed to the body of knowledge. This chapter also contains a discussion of some of the problems encountered, suggestions for future research on the subject and some final conclusions about the VAM application.

Chapter 2: Working Memory

2.1 Introduction

In this chapter, the concept of human memory is explored; what it is, what it does and exactly how important memory is to one's concept of self. In particular, Working Memory, the memory of the 'here and now' is focused on. Working Memory is the cognitive system that allows the temporary storage of information received from one's environment or from one's own Long-Term Memory. Working Memory is also concerned with the manipulation of that information for use in other cognitive processes. Working Memory stores and processes different forms of information in different ways; of particular interest to this study is how it stores and processes audio and visual stimuli.

The following sections provide an overview of how human memory is thought to work. Here, some of the current theories regarding Working Memory are introduced, focusing on the multi-component system proposed by Baddeley and Hitch. But first, an overview of the human memory system will be provided.

2.2 An Overview of Memory

When commonly used, the term memory usually refers to one of two things. In many instances it is used to refer to Long-Term Memory - reminiscing over memories of events past and lessons learned. In others, it refers to Short-Term Memory - memories of the present such as memorising a phone number you just heard. While these are indeed aspects of our memory, in truth human memory encompasses a whole range of other important functions; far more than most people would suspect.

From the very beginning, our memory system was essential to our survival and growth as a species. Memory was the faculty that reminded us which foods were safe to eat and which were poisonous. Memory allowed us to interpret what our senses were telling us about our environment and helped us work out our options in any given situation.

As our memory systems grew in response to specific environmental threats, it is likely that these systems were adapted for new purposes which, in turn, allowed us to grow and evolve even further [Sherry & Schacter, 1987]. Memory allowed us to manipulate information in our heads. Memory allowed us to master useful skills such as reading and writing. Perhaps most importantly, memory allowed us to learn from our past and use this information to change our future.

2.3 The Memory System

The study of human memory goes back many centuries. Back in ancient Greece, philosophers recognised the important role memory had to play in growth and learning. Mnemosyne, the Titan goddess of memory, was worshipped as mother of the Muses of the arts and sciences. When the field of psychology began to grow in the nineteenth century, memory was one of the first areas it focused on. Despite this, it wasn't until the mid-twentieth century that researchers came to think of memory as a group of distinct processes rather than as a single unified system.

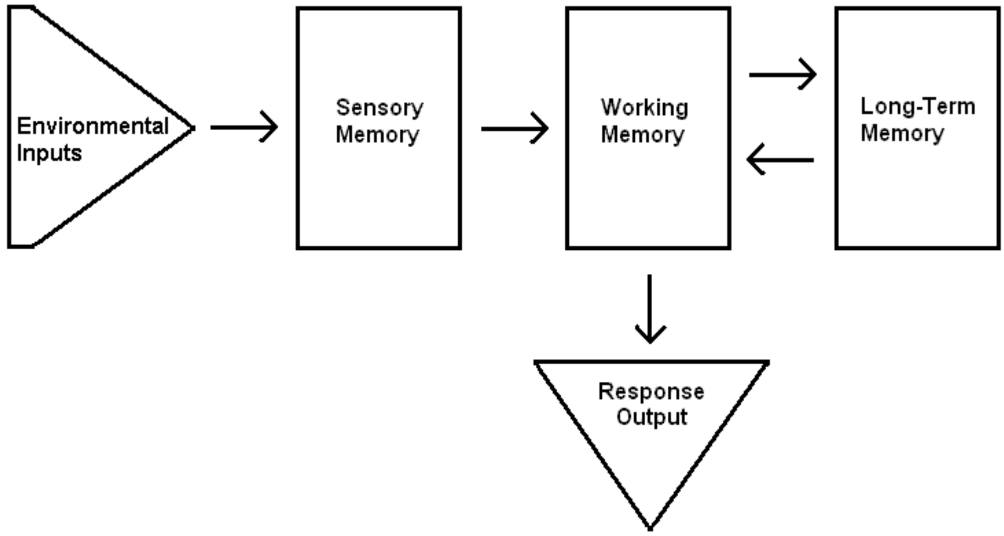

Figure 1: Overview of human memory system adapted from the Atkinson and Shiffrin Model [1968].

In 1968, Atkinson & Shiffrin proposed the multi component model of memory depicted above. They theorised that human memory could be broken down into three main components, each with its own set of important functions. These components are: Sensory Memory, Long-Term Memory and Short-Term Memory (which is often incorporated into Working Memory in modern theories).

While this study focuses on the important role played by Working Memory, it is still important to understand the main functions of the other two components and how they interact with Working Memory. As such, in the next section, a brief description of the composition and functions of Sensory Memory and Long-Term Memory is given, while Working Memory will be discussed separately and in more detail later on.

It is important to note that the study of memory has crossed over into many different scientific fields over the years, usually with little or no interaction between them. Only in the last few decades have neuroscientists studying the physical structure of memory joined forces with cognitive psychologists studying the traits and functions of memory to create the field of cognitive neuroscience [Brook & Mandik, 2004]. Because of this division, there are still very few certainties regarding human memory.

Therefore the sections below are composed of, for the most part, working theories based on the information currently available.

2.4 Sensory Memory

Sensory Memory is the name given to the very short-term storage system that allows us to retain impressions of sensory information after the stimuli themselves have ceased. In other words, it refers to the memory involved in allowing us to perceive the world around us.

Sensory Memory is thought to have many different components including 'echoic memory' for audio information, 'iconic memory' for visual information and 'haptic memory' for touch. Despite our presumably having a memory type for all five senses, few of the mechanisms involved are really understood. There are however several factors that all forms of sensory memory have in common [Cowan 1988], [Winkler & Cowan, 2005]:

1. Sensory Memory functions independently of a person's attention.
2. Each form of Sensory Memory (iconic, echoic etc.) stores a single type of information (visual, audio etc.).
3. Each form of Sensory Memory has an extremely high resolution, taking in an enormous amount of detail.
4. Information stored in Sensory Memory only lasts for a very brief period, although this period varies between different types.

Among other things, Sensory Memory is the memory that allows a person to hold an image in mind for the split-second needed to understand it. An example of this occurs in the cinema. The iconic memory facilitates the viewing of a continuous moving image even though, in reality, a series of still images is being viewed with a very brief period of darkness between each one. The iconic memory stores each image just long enough for the next one to arrive and replace it. Since there are usually twenty four images displayed per second in a cinema, this gives some idea of how fast the Sensory Memory can work. In fact, the maximum storage time for Sensory Memory is thought to be under a second and certainly less than two seconds [Sperling, 1960].

One of the earliest studies of Sensory Memory was attempted in the early eighteenth century by a German physicist - Johann Andreas Von Segner [Segner, 1740, (as described in Baddeley, 1999)]. Segner used a very simple technique to measure the length of the iconic memory store. He observed that by quickly moving a burning ember or sparkler around in a dark room, it was possible to see a trail left behind in the air. Segner experimented with this by tying an ember to a wheel in a darkened room and then spinning it at various speeds in order to create a circular trail in the air. When turning the wheel slowly only a partial circle was seen, but by turning at a fast enough speed, an entire circle was left. Segner then measured the speed needed to maintain a full circle and used this to deduce that the length of time the image was maintained in iconic memory was approximately one tenth of a second.

There are thought to be two main components to iconic memory, visible persistence and informational persistence. Visible persistence refers to the visual impression that briefly remains after the initial stimulus is removed. Informational persistence refers to the information that remains after the initial stimulus is removed. [Colthart, 1980]

A similar type of memory exists for perceiving audio stimuli. It is sometimes referred to as echoic memory due to the fact that it functions like an echo, temporarily living on after the sound that caused it has ceased. Like iconic memory, echoic memory has a brief lifespan, although research indicates that it is more durable than its visual counterpart [Crowder & Morton, 1969], [Darwin, 1972].

Echoic Memory is most commonly used when trying to pinpoint the location of a noise. When a noise is heard, one unconsciously uses the time difference between the sound hitting each ear to locate it [Darwin, 1972]. When a sound hits one ear it must be stored until it is heard by the other ear and the two versions can be compared. Naturally this is an extremely brief storage and retrieval period, but it still demonstrates the existence of some form of echoic memory.

Due to the brief storage period involved in Sensory Memory, care must be taken not to confuse it with Working Memory which is discussed later. The major difference between Sensory Memory and other types of memory is that storage and retrieval from Sensory Memory is entirely unconscious, whereas Working Memory and Long-Term Memory both allow a conscious exchange of information.

There are assumed to be many other types of Sensory Memory, but they fall outside the scope of this study. It is enough to be aware that some form of audio and visual Sensory Memory is involved – but only in a passive role - when analysing or testing Working Memory.

2.5 Long-Term Memory

Long-Term Memory is the system that allows memories to be stored for a prolonged if not indefinite period of time. Its primary function is the storage of large amounts of information, unlike Sensory Memory or Working Memory whose storage capacity and duration are both extremely limited. Long-Term Memory potentially contains the details of every single thing we have experienced in our lives; the way things smell, taste and sound, the way people look, each skill or ability we've acquired, each bit of information we've learned and so much more. Long-Term Memory contains the record of our lives and can be drawn upon as needed when dealing with the world around us.

As with the other types of memory, it is not yet fully established if Long-Term Memory is composed of a single system or is made up of several subsystems. There are, however, several distinct types of Long-Term Memory and each are briefly discussed below.

The first major division of Long-Term Memory can be made between 'procedural' (implicit) and ‘declarative’ (explicit) Long-Term Memory [Graf & Schacter, 1985]. Procedural memory usually refers to the learning of skills such as walking and talking. It also plays a role in cognitive tasks such as playing chess. These are the skills that can only be improved by practising. After the initial learning period, no new memories are created while practising these activities. Instead one unconsciously draws and builds on previous experiences [Roediger, 1990].

Implicit memory is particularly vulnerable to priming; an effect in which exposure to a particular stimulus can influence response to a later stimulus. This means that performance in a particular task can be improved by prior subconscious preparation for the task [Graf & Schacter, 1985]. Another aspect of priming is that people are also more likely to consider a plausible statement true if they have heard it before, regardless of its actual veracity [Hasher, Goldstein, Toppino, 1977]. This is referred to as the illusion-of-truth and is again largely unconscious.

In contrast, declarative memory is about the retention of facts. This form of memory requires conscious recall. In other words, some event must trigger the recall process. For this reason it is also known as explicit memory, since information is explicitly stored and recalled [Graf & Schacter, 1985].

Declarative memory itself can be further divided into episodic and semantic memory [Tulving, 1972]. Episodic memory refers to personal memories; remembering details about particular incidents such as going on a night out with friends. On the other hand, semantic memory is concerned with knowledge of the world around us, such as knowing the capital of Germany or the meaning of a road sign. It is still not certain if these are different parts of the same system or are two altogether separate systems. There is a clear difference in how these two types of memory are handled, but research suggests that the processes are linked and can affect and complement each other [Howard & Kahana, 2002].

One of the largest and most contentious questions regarding Long-Term Memory at the moment is how humans forget. Originally it was believed that the memories would begin to fade if not accessed for a long time and eventually may even disappear completely. This is referred to as decay theory and has largely fallen out of favour in terms of Long-Term Memory [Jenkins & Dallenbach, 1924]. There is evidence to suggest it plays a small role in forgetting in Working Memory though [Berman, Jonides, Lewis, 2009]. Instead, popular theory favours the interference theory where forgetting occurs because one memory interferes with the recall of another [Underwood, 1957].

Interference comes in two main varieties. Retroactive interference occurs when new information interferes with old information already stored in memory. Proactive interference is the reverse, where existing knowledge can interfere with the storage of new information [Underwood, 1957]. Exactly how interference works is still debateable, both on a psychological and neurological level [Wixted, 2004], but it is enough to know that the process exists and has a major impact on the way we store information.

In the case of forgetting skills, the situation is even more complex. Although it seems that procedural memory is more durable then declarative memory, apparently some skills can be lost. According to the popular phrase 'it's like riding a bike, you never forget', apparently there is some truth to this. Studies have shown that closed-loop skills such as riding a bicycle or flying a plane are virtually permanent, even if they haven't been practised in a long time [Fleischman & Parker, 1962]. On the other hand, open-loop skills such as typing or performing CPR (Cardiopulmonary Resuscitation) tend to degrade significantly in quality if left unattended [McKenna & Glendon, 1985]. The difference between closed-loop and open-loop skills is that closed-loop skills tend to be practised unconsciously with one action automatically following the other, whereas open-loop skills involve reacting to a stimulus and so can never really become a habit.

Long-Term Memory is still something of a mystery to scientists, with more questions than answers. However, it is an expanding area and currently it is the focus of considerable interest that will hopefully provide firm answers as to its exact nature.

For the moment it is enough to be aware that Long-Term Memory acts as an internal encyclopaedia that is consulted at need for both knowledge and skills. As such, it plays an important role when used in conjunction with Working Memory, allowing us to draw on past knowledge and experiences to help affect current situations.

2.6 Working Memory

"Working Memory allows us to know that the 'here and now' is 'here' and is happening 'now'" [LeDoux, 1998].

As has already been described, each sub-system of human memory has its own specific set of functions. Sensory Memory is primarily concerned with the perception of the immediate surroundings. Long-Term Memory is in charge of storing and retrieving knowledge and skills so that past experiences can be used as an aid in the present. The third and final system, known as Working Memory, is believed to function between these two systems. Working Memory is primarily concerned with the temporary storage and manipulation of information so that it can be used in complex cognitive tasks and processes [Baddeley & Hitch, 1974].

While Sensory Memory allows the perception of one's surroundings, it is Working Memory that allows one to think about and react to them. Working Memory is used every time one reads a book or performs mental arithmetic. It is the memory used when one 'works things out' e.g. comparing different faces and objects or mentally reorganising the furniture in a room. Working Memory is all about interacting with the environment and as such plays an important role in human consciousness and the learning process.

The term 'Working Memory' was first proposed by Miller, Galanter and Pribam [1960] in the book 'Plans and the Structure of Behavior' and soon spread across several areas of research until it was finally inducted into cognitive psychology by Atkinson and Shiffrin [1968]. Atkinson and Shiffrin defined Working Memory as a unitary short-term store for information. As further research in the area was carried out, the definition of Working Memory evolved to encompass not just short-term storage and retrieval, but the manipulation of information to be used in high level cognitive functions as well. The more information that is gathered on Working Memory, the clearer its importance becomes.

It should be noted that although Working Memory has largely subsumed the previously established system of Short-Term Memory, there is generally acknowledged to be a difference [Engle et al, 1999]. Short-Term Memory refers to the temporary storage and retrieval of information; Working Memory is concerned with the manipulation and organisation of that information for use in other cognitive processes. Therefore while the exact relationship between Working Memory and Short-Term Memory varies depending on the theory, Working Memory can be generally thought of as applied or focused Short-Term Memory [Cowan, 2008].

As with the other aspects of human memory, the study of Working Memory is still largely in the theoretical phase. In fact some researchers claim that it is not an actual independent system, but merely a sub-system of Long-Term Memory [Cowan, 1995]. Even amongst those who do believe Working Memory is a separate system, there is still disagreement about its composition and its function. One of the most popular and well supported theories is that Working Memory is composed of several subsystems all working in unison: the phonological loop, the visuospatial sketchpad, the central executive and the episodic buffer. It was proposed by Alan D. Baddeley and Graham J. Hitch [1974] and has been updated and revised by Baddeley many times since.

Baddeley's theory is both elegant and thematically fitting for a study focusing on the potential of interactive computer based testing. There are approximately 800 papers published every year with the term Working Memory in their title, and approximately 3,700 with it mentioned in their title, abstract or keywords [Baddeley, 2007]. The overwhelming majority of papers in the field of Working Memory recognise Baddeley's model as a leading theory, even if some do not fully agree with it. Baddeley's model has been used and referenced in many diverse fields of research. These include studies into education [Alloway & Alloway, 2010], medicine [Baddeley et al, 1986], linguistics [Baddeley, Gathercole & Papagno, 1998] and neuroscience [Dehaene & Naccache, 2000].

There have been many studies that provide evidence validating Baddeley's model and the model itself is still being refined as new information becomes available [Baddeley, 2003]. Baddeley's model is not without its critics and the main criticisms levelled at it will be discussed later, but it still provides a solid theoretical basis for a new test of Working Memory.

2.7 Baddeley's Model of Working Memory

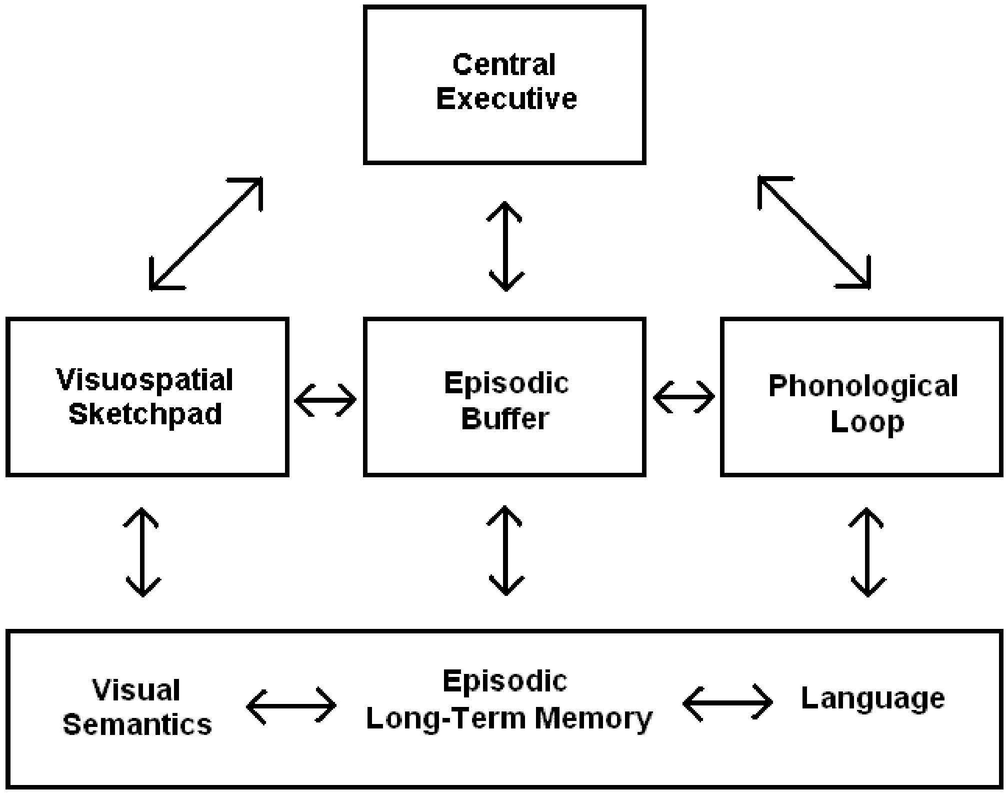

Figure 2: Baddeley's updated model of Working Memory [Baddeley, 2000]

The basis of Baddeley's theory is that Working Memory is not only a separate system from Long-Term and Sensory Memory, but is itself made up of several component systems. The first two components are known as the 'phonological loop' and the 'visuospatial sketchpad'. These two components act as Short-Term Memory stores for audio and visual stimuli respectively. The other two components are known as the 'central executive' and the 'episodic buffer'. The central executive acts as a control system for Working Memory, focusing primarily on attention span and information processing and manipulation. The episodic buffer acts as an additional information store and a link between the other components of Working Memory and Long-Term Memory [Baddeley, 2000, 2002].

The theory of a non-unitary Working Memory system originally developed as the result of an experiment to establish exactly which cognitive functions Working Memory controlled. The experiment was composed of a series of tests that Baddeley performed on deep-sea divers. The divers were asked to complete a series of verbal reasoning tasks while underwater. Previous experiments had shown that at about thirty metres below sea level, divers experience a kind of 'drunkenness' known as nitrogen narcosis which results from breathing air at high pressure. Baddeley felt that this might have an interesting effect on cognitive reasoning [Baddeley et al, 1968, (as described in Baddeley, 1999)].

In Baddeley's experiment he measured the number of quick verbal-reasoning questions that a group of divers could answer correctly in three minutes while they were submerged at a great enough depth for nitrogen narcosis to occur. Having achieved this, he had another set of divers perform the same task under the same conditions, but this time they had to remember and rehearse a six-digit number at the same time. Surprisingly, the divers found that they were still able to complete the verbal-reasoning task and repeat the six-digit number with few errors, but Baddeley noticed that the time taken by this group was significantly higher than the first. This indicated to Baddeley that the Short-Term Memory store was involved in the cognitive system that controlled reasoning, comprehension and learning. Baddeley deduced that the two systems must have some overlapping components and that the

Short-Term Memory system must play a far more important role than previously believed. Realising this, Short-Term Memory seemed an inadequate name for such a system and so his current theory of Working Memory was born.

The fact that the divers were able to complete both the verbal-reasoning and the digit store tasks simultaneously indicated that verbal reasoning and comprehension were not totally dependent on the same temporary store as the one used to keep the six-digit number in mind. This in turn led to his belief that there must be several components to Working Memory, that each component had its own individual role and that these components were slaved to a common control centre [Baddeley & Hitch, 1974].

2.7.1 The Phonological Loop

One of the two main short-term storage systems of Working Memory, the phonological loop, is responsible not only for the temporary storage of auditory stimuli but also for one of the main techniques used to aid memory, known as subvocalization [Baddeley & Hitch, 1974], [Baddeley, 1986]. Subvocalizing refers to the technique of repeating information under one's breath in order to mentally refresh it. In fact, as one reads this sentence one may become aware that the tendency is to 'hear' what is being read inside one's head. Some people even mutter what they read under their breath as they read it [Baddeley & Wilson, 1985].

Baddeley theorises that the phonological loop developed as a response to the essential task of learning a language, and therefore is very important for young children learning to speak and for anyone learning a second language [Baddeley, Gathercole & Papagno, 1998],[Baddeley, 2003a]. The capacity of the phonological loop is popularly thought to be about seven items long [Miller, 1956] as measured by the digit span test. The reality is far more complex than this though and is discussed in greater detail in Chapter 3.

Like Working Memory itself, the phonological loop can be further divided into separate components. These components are known as the passive 'phonological store' and the active 'rehearsal process' [Baddeley, 1986]. The phonological store represents the temporary memory store in which information is held in a phonological code. Unfortunately this information will fade quickly if not used. Information within the phonological loop tends to decay over a period of about two seconds unless reinforced. The job of the rehearsal process is therefore to refresh the decaying information held in the store [Baddeley, 1986].

There is significant evidence available to justify the existence of a separate phonological loop. The storage of words or noises whether presented visually or vocally has been found to be greatly dependent on the sound and complexity of the information being remembered. For instance, a sequence of letters such as 'V, C, D, E, G, P' is generally much more difficult to remember then a sequence like 'G, K, L, R, S, H' [Conrad & Hull, 1964]. This is because the first sequence of letters all sound the same; whereas the second sequence all sound different. This is referred to as the phonological similarity effect. Similarity of meaning appears to have little effect on short-term storage and retrieval [Baddeley, 1966a] but appears to play a larger role when subjects are presented with longer lists containing ten or more items. Baddeley attributes this to differentiation between Working Memory and Long-Term Memory (where semantic coding is more important than phonological coding) [Baddeley, 1966b].

Evidence for the rehearsal component of the phonological loop is seen when a person is asked to remember a sequence of words. The longer the words, the more difficult they are to remember. A much smaller word span is observed when storing and recalling from a list containing words like hippopotamus, university and refrigerator than from a list containing words like cat, ball and tree [Baddeley, Thomson & Buchanan, 1975]. This is known as the word length effect.

The retrieval of words has also been shown to be dependent on some form of phonological system. This is evidenced by the fact that hearing someone speak in the background can disrupt the recall of visually presented letters. It has been shown that this disruption takes place regardless of whether the speech is in the person's own native tongue or not. This is turn, indicates that the disruption occurs at the level of sound as opposed to the level of meaning [Salamé & Baddeley, 1982].

Even though the phonological loop is one of the elements most associated with Baddeley's model of Working Memory it is still far from universally accepted. There have been several challenges to its validity over the years, largely based on evidence that doesn't readily fit in with Baddeley's model [Nairne, 2002], [Jones, Macken, Nicholls, 2004].

Nairne's critiques of Baddeley's model focus on the 'activation' of memory or how memory is maintained over short periods. Nairne argues that there is evidence that short-term retention is cue driven much like long-term Memory and that Baddeley's Phonological loop relies too much on the rehearsal and decay of information as a method of remembering over the short term. Nairne also claims that Baddeley has an overly simplistic view of subvocal rehearsal which he refers to as central to 'the standard model' of remembering [Nairne, 2002]. To back these claims up, Nairne presents evidence that rehearsal is impacted by a host of external factors including list length, modality of presentation, presentation rate and similarity of sound.

Baddeley in turn believes that it is Nairne who has an overly simplistic view of Baddeley's model, treating the phonological loop as nothing more than a rehearsal process and not acknowledging that it has its own separate phonological store as well as the ability to interact both with other aspects of Working Memory and with Long-Term Memory too. Baddeley, however, also acknowledges that Nairne's criticism of the complexity of the rehearsal process does have merit and that it mostly identifies mechanisms of the phonological loop that need to be further developed rather than invalidating the entire model [see Baddeley, 2007, Chapter 3 for a detailed rebuttal].

2.7.2 The Visuospatial Sketchpad

The second main short-term storage system of Working Memory, the visuospatial sketchpad, handles the processing and interpretation of images and spatial information gathered either from Sensory or Long-Term Memory [Baddeley & Hitch, 1974], [Baddeley, 1986]. The visuospatial sketchpad grants the ability not only to visualise an image in the mind, but also to manipulate that image in terms of rotating, zooming etc. [Kosslyn & Shwartz, 1981]. It also allows a person to coalesce visual information together with similar information of a motor, tactile or kinaesthetic nature [Baddeley, 1999].

The capacity of the visuospatial sketchpad appears to be about 4 items [Sperling, 1960], [Cowan, 2001], [Vogel et al, 2001]. The problem occurs in trying to identify what exactly counts as an item when it comes to visual stimuli. Is capacity limited by the number of items or the amount of information stored in those items? A 1997 study by Luck and Vogel used a selection of different coloured bars displayed at different orientations as a source of stimulus. Bars were chosen in order to rule out verbal encoding as a method of storage and rehearsal. Luck and Vogel found that subjects were able to retain about four objects, regardless of whether they were asked about colour, orientation or both. They found similar results when the number of features associated with each bar was increased to four. This indicated that visual memory appeared to be based on objects rather than information. A later study using a wider array of visual stimuli however, indicated that even though the number of objects able to be stored does appear to be limited to about four or five, this figure is inversely proportional to the detail level of the objects being remembered. This indicates that the overall amount of visual information does have an impact [Alvarez & Cavanagh, 2004].

The spatial aspect of the visuospatial sketchpad is far less researched than its visual component, possibly due to the inherent difficulties in isolating it. There is evidence that it is a functionally separate subcomponent from visual Working Memory [Della Sala et al, 1999]. The exact distinction between visual and spatial Working Memory is still unclear. One theory proposes a distinction between two separate pathways. A visual one concerned with the 'what' of an object, and a spatial one concerned with the 'where' [Mishkin et al, 1983]. Another theory is that the distinction is between dynamic (spatial) and static (pattern) objects [Pickering, 2001]. The question of the relationship between spatial Working Memory and kinaesthetic or movement based coding complicated matters even further [Smyth & Pendleton, 1990].

Like the phonological loop, the visuospatial sketchpad can be further divided into separate components. In this instance it breaks down into the passive 'visual cache' and the active 'inner scribe' [Logie, 1995]. While the visual cache equates to the phonological store in terms of its function of temporarily retaining visual input, the rehearsal mechanism for the visuospatial sketchpad is less clear. The inner scribe may play some role in this, but is primarily concerned with recording sequential locations and spatial movement. Another feature of Logie’s model is that information enters the visuospatial sketchpad after being processed in Long-Term Memory as opposed to directly from sensory memory. This is consistent with his view that the visuospatial sketchpad should be primarily regarded as a mental workspace [Della Sala & Logie, 2002].

Baddeley now believes that the rehearsal system for the visuospatial sketchpad stems primarily from the central executive and episodic buffer and is somewhat analogous to attention span [Baddeley, 2002]. According to Baddeley, this is the typical mechanism of rehearsal. The phonological loop has its own self-contained rehearsal process mainly as a by-product of humans’ capacity to reproduce incoming verbal signals and, with familiar forms such as digits and words, to correct errors on the basis of prior knowledge [Baddeley, 2002, 2007].

Baddeley also regards the notion that the visuospatial sketchpad can only be accessed from Long-Term Memory as overly simplistic. While he agrees that the sketchpad is, or at least partly forms, a mental workspace, he sees no advantage in proposing that access must only come from Long-Term Memory [Baddeley, 2007]

As with the phonological loop, there is significant evidence that the visuospatial sketchpad is a separate system. A good example was shown in an experiment performed by psychologist Lee Brooks [1968]. Brooks showed subjects a two-dimensional block representation of the letter '**F**', and asked them to visualise it in their minds' eye. Then, starting at the bottom left corner, Brooks asked the subjects to move clockwise around the letter and at each corner answer 'yes' if that corner touched the top or bottom line of the letter and 'no' if it did not. The correct sequence here would be 'yes, yes, yes, no, no, no, no, no, no, yes'. The subjects in this test were first asked to answer verbally and then by pointing to the words 'yes' or 'no' printed on a page. Brooks discovered that his subjects found it much easier to vocalise their answers than to point to them, indicating that a visuospatial task, such as pointing, interfered with the imaging process.

Many other experiments have used similar approaches and these have shown that performing a visual or spatial task interferes with the visualisation process but not that with the vocalisation process [Logie, 1986], [Quinn & McConnell 1996]. Further evidence can be found in [Della Sala and Logie 2002] which detail a number of neuropsychological patients who have preserved verbal span but impaired visuospatial span or vice-versa. Developmental evidence for separate systems can also be found in [Alloway, Gathercole, Pickering, 2006] which details the use of a battery of audio and visuospatial tests to examine Working Memory in children. All these studies indicate that images are processed in a separate system to sound.

2.7.3 The Central Executive

The central executive is considered by many to be the core of Baddeley's model of Working Memory [Baddeley, 2007]. It is assumed to be an attention based system that acts as a control centre for both the phonological loop and the visuospatial sketchpad, in conjunction with the episodic buffer. The central executive is also thought to coordinate all of the cognitive processes associated with Working Memory performance. In other words, the central executive is the control system that allows individuals to store and manipulate information simultaneously [Baddeley & Della Sala, 1996], [Tronsky, 2005].

The problem with the theory of the central executive is the temptation to treat it as a dumping ground for any unexplained features of Working Memory. Because it is difficult to test the limits of the central executive, it has tended to be used to explain away any awkward questions about determining when the visuospatial sketchpad and phonological loop are used and how they are combined. Baddeley broadly admits to these charges, sometimes referring to the central executive as a homunculus, or 'the little man in the head who makes all the decisions' [Baddeley, 1996]. He claims the best way to handle this problem is by explicitly defining and analysing the functions of the homunculus until a clearer pattern for the individual sub-systems involved in the central executive emerges [Baddeley, 2007].

The main functions that [Baddeley 1986, 1996, 2002, 2007] has attributed to the central executive are as follows:

1. The ability to focus attention on a single task while actively ignoring irrelevant information.
2. The ability to process multiple cognitive tasks at once and switch between them as needed.
3. The ability to manage and allocate resources to other subsystems in Working Memory as needed.
4. The ability to control access to Long-Term Memory.
5. The ability to select and execute plans and strategies.

Humans are by nature creatures of routine. They navigate through their day-to-day lives using what are essentially an extensive series of schemata and habits that permit the use of external cues to perform daily tasks [Newell & Simon, 1972]. Researchers believe that the central executive comes into play when something is encountered which is not familiar - something new. The central executive then combines experience from Long-Term Memory (via the episodic buffer) with the existing stimuli to work out a new solution for the occasion; this is referred to as a

Supervisory Attentional System or a Supervisory Advisory System [Shallice, 1982], [Baddeley, 1996]. This infers the ability not only to focus attention on the external stimuli, but also to split attention between the external stimuli and the information from Long-Term Memory and to switch back and forth between them to compare past and present experiences and so make informed decisions [Baddeley, 1996].

The exact nature of the central executive is still under debate. Neuroimaging studies suggest that the structures behind the central executive all largely reside in the prefrontal cortex of the brain [Kane & Engle, 2002]. On the other hand, there is evidence to suggest that it is not a single centralised system at all, but instead a series of separate executive functions that vary between individuals [Miyake et al, 2000].

Miyake et al identify three main executive processes: 'shifting', 'updating' and 'inhibition'. Shifting refers to the ability to shift between tasks. Updating is the ability to monitor and update items in Working Memory and inhibition is the ability to override automatic responses to stimuli when necessary. While these tasks work together in the service of higher cognitive processes, they are nonetheless distinct systems in themselves, and are likely not the only ones.

2.7.4 The Episodic Buffer

The final component in Baddeley's model of Working Memory, the episodic buffer, is a late addition [Baddeley, 2000]. Initially, Baddeley believed the central executive was responsible for storing and manipulating information from multiple sources as well as connecting Working Memory to Long-Term Memory [Baddeley, 1996]. However, these tasks seemed at odds with the other processes attributed to the central executive which are all to do with attention [Baddeley & Logie, 1999]. Instead, Baddeley decided to disassociate all storage from the central executive and into a new component, the episodic buffer [Baddeley, 2000].

The role of the episodic buffer is to act as a communications and storage centre which integrates information from the phonological loop and visuospatial sketchpad as well as from Long-Term Memory and Sensory Memory so that they can be maintained and manipulated [Baddeley, 2000]. It is currently believed that the episodic buffer also acts as a temporary store for large amounts of information that exceed the capacity of the phonological loop and visuospatial sketchpad [Baddeley, 2002]. This allows information from multiple sources and senses to be merged together to act as an aid when making decisions or reacting to stimuli.

A central feature of the episodic buffer is its role in binding information from different sources into coherent chunks or episodes [Baddeley, 2003b, 2007]. These episodes are comprised of multiple different types of information: audio, visual, semantic etc. Several theorists have suggested that one of the primary functions of consciousness is to bind together information taken from different perceptual sources [Dehaene & Naccache, 2001], [Baars, 2002]. As such, it could be argued that the episodic buffer acts as a basis for conscious awareness itself.

Baddeley believes that much like the visuospatial sketchpad and the phonological loop can be broken down into active rehearsal and passive storage components, the episodic buffer could be viewed as the passive storage component of the active central executive [Baddeley, 2003b]. He is also quick to note that, at the moment, the episodic buffer is purely a conceptual tool and not a specified model [Baddeley, 2007]. Baddeley believes that extensive further research is needed to demonstrate how it actually functions.

Because Working Memory is theorised to control attention span, many researchers now believe that it can also provide a better way of measuring general intelligence [Kyllonen & Christal, 1990], [Engle et al, 1999], [Conway et al, 2002], [Ackerman, Beier, Boyle 2005] and learning ability [Alloway, 2009b], [Alloway & Alloway, 2010]. Standard intelligence tests tend to rely heavily on the subject's level of education. A person may have the potential to be an accounting genius, but if he/she never learned enough maths; it would never show on a standard numerical abilities test.

By testing a person's Working Memory capacity, many researchers believe that it will give a much more accurate representation of his/her true intellect. Improving a subject's Working Memory may also increase his/her measured IQ. These and other potential areas of Working Memory research will be discussed in greater detail in later chapters.

2.8 Alternate Theories of Working Memory

As previously stated, the design of Working Memory and its exact role in human cognition is far from being fully understood. In particular the nature of the central executive is still a matter of much debate and there are several theories available apart from Baddeley's that can contribute useful information to that debate. There are far too many theories to describe in detail here, but it may be useful to give a brief summary of the main issues surrounding the subject. The questions described in this section are based on those originally posed in the book 'Models of Working Memory' edited by Priti Shah and Akira Miyake [1999]. Miyake and Shah's book can also serve as a solid foundation for exploring alternative views of Working Memory.

The first issue raised is perhaps the most controversial one surrounding Working Memory. What is the nature of Working Memory? Is it a single system or does it have multiple components? If there are many components involved, what are they?

This issue is still fiercely debated on both sides. Many argue that Working Memory is a single system with many functions, others that it must be composed of a number of different subsystems. Among those in the non-unitary camp, there is also much debate about exactly how many subsystems there are.

Some researchers believe in a more hierarchical system than that offered by Baddeley's theory. While Baddeley accounts for only two slave systems dealing with phonological and visuospatial information, other theories such as the one put forward by Walter Schneider [1993, 1999] postulate multiple systems. Schneider's model is based on a more biological foundation than Baddeley's and takes a more connectionist approach, using neuronal growth to model Working Memory.

In Schneider's model the systems proposed include visual, auditory, speech, lexical, semantic, motor, mood and context. Beneath these lie an even vaster array of sub-modules, numbering in the hundreds or thousands. Despite these differences, Schneider argues that these subsystems have the same internal structure and are governed by the same processing principles as Baddeley's model.

An offshoot from the last issue concerns the relationship between Working Memory and Long-Term Memory. Are they related at all? Is Working Memory a separate entity or is it just a subsystem of Long-Term Memory? Also how does Working Memory affect components such as learned skills that reside in Long-Term Memory? Is it used to act upon those skills?

There are two main schools of thought on this issue. The school to which Baddeley belongs believes that Working Memory is a separate system that acts as a sort of gateway to and from Long-Term Memory with information passing through it at each end. Although there is evidence that suggests that long term knowledge contributes to Working Memory tests, it is assumed that the knowledge is brought from the 'slow' Long-Term Memory to be processed in the 'faster' Working Memory [Baddeley & Logie, 1999].

The other school of thought believe that Working Memory is merely a subsection of Long-Term Memory and should not be considered separately. In fact several researchers, including Nelson Cowan [1995], believe that Working Memory is largely composed of different sections of Long-Term Memory (which is itself distributed throughout the brain) that are 'activated' depending on the task at hand. These activated areas can then become the focus of attention which has a limited capacity of about four chunks [Cowan, 2001].

Getting away from the exact nature of Working Memory, there are still other issues to be clarified - in particular the issue of Working Memory and its limitations. There is much debate about just how much information it can store, how long it lasts and whether it can be interfered with. Also, given a multi-component memory system, are the limitations of each system the same or different? Are images easier to store than sounds and are they processed faster?

While it appears that many people do indeed have a digit span of about seven digits [Miller. 1956], it seems unlikely that this number holds true for everyone or for every form of information. Other factors such as age also need to be taken into account when studying the limits of Working Memory. Working Memory capacity and the Digit Span test are investigated in more detail in Chapter 3, but for the moment it is enough to know that the degree to which external factors affect one’s memory is highly controversial and there are many different theories as to which factors are the biggest causes of memory degradation.

The theory proposed by Ericsson and Kintsch [1995] notes that a limited capacity system (be it four or seven chunks) seems insignificant given our capacity to read large amounts of text and still understand and retain the complex connections within a novel or scientific paper. Similarly, chess players can maintain multiple moves in mind during a match and doctors can maintain detailed information about a patient’s status and prognosis during a consultation. All these activities require a Working Memory capacity much larger than four or seven chunks.

Instead Ericsson and Kintsch propose a model that primarily focuses on Long-Term Working Memory where the majority of information we take in goes straight to Long-Term Memory and is linked together via retrieval structures. The more skilled one becomes at a particular task, the stronger the retrieval structures linked to that task become and the faster and more efficiently storage and retrieval occurs. Ericsson and Kintsch propose that Short-Term Working Memory on the other hand is mostly used for holding cues which point to relevant areas of Long-Term Working Memory when needed.

As already noted, these are only a sample of the many issues and theories regarding Working Memory. While Baddeley's model is generally regarded as the most popular theory of Working Memory, it is well to be aware that it is not the only one. There are many other theories under debate and they can still pose viable questions regarding the exact nature of Working Memory.

2.9 Conclusions

Our Memory system is a vital part of what makes us human. As it evolved, it allowed us to evolve in turn and to thrive as a species. From the split second visual memory needed to identify an object in the way to the years old memories that still shape our views and beliefs, memory impacts almost every aspect of our lives.

Working Memory in particular underpins how we deal with the world around us and is a vital part of both cognition and consciousness. While we may not yet fully understand the Working Memory system, new research emerges every year showing its importance to diverse fields such as teaching (and learning), medicine, artificial intelligence and child development.

Baddeley's theory of Working Memory has a great deal of scientific evidence behind it and is widely accepted as one of today's leading theories. While the exact nature of each component in Baddeley's model is still under debate, Baddeley's theory provides a succinct framework which can serve as a solid base for exploring Working Memory.

The genesis of this study was to develop a new versatile computer application designed to test both audio and visual Working Memory. Using Baddeley's theory of Working Memory as a basis, suitable tests can be developed that will examine the abilities of the visuospatial sketchpad, the phonological loop, the central executive and the episodic buffer.

Due to the compartmentalised nature of Baddeley's theory, a single test would not be enough to explore Working Memory in sufficient detail. As such, an application design is needed that can contain multiple independent tests that explore different aspects of Working Memory. The design and implementation of this application is discussed in more detail in Chapter 4.

2.10 Review

In this chapter the concept of human memory was explored. Starting with the Atkinson – Shiffrin [1968] model, memory can be broken down into three main areas: Sensory Memory, Long-Term Memory and Working Memory. Sensory Memory refers to the very short term store that allows us to take in the information that is gathered by our senses [Cowan 1988], [Winkler & Cowan, 2005]. There are presumably five types of Sensory Memory to go along with our five senses, but the main ones of note to this study are iconic memory which gathers visual signals [Sperling, 1960], and echoic memory which gathers audio signals [Darwin, 1972].

Long-Term Memory refers to the long term store where all our detailed memories reside. Long-Term Memory can be broken down into two main areas, declarative (explicit) memory is about the retention facts, procedural (implicit) memory is about the retention of skills [Graf & Schacter, 1985]. Declarative memory can be further subdivided into episodic memory which deals with personal experiences and semantic memory which deals with knowledge of the world around us [Tulving, 1972].

Working Memory, the aspect of memory that is focused on by this study, is the memory of the here and now [LeDoux, 1998] and handles the short-term storage and processing of information that allows us to solve problems and work things out. It is also heavily involved in focusing attention and the learning process [Baddeley & Hitch, 1974].

There are many different theories of Working Memory, but one of the most recognised is the model proposed by Baddeley and Hitch [1974]. Baddeley's model of Working Memory involves four main components. The phonological loop is responsible for processing audio information. The visuospatial sketchpad is responsible for processing visual and spatial information. The central executive acts as a control system and helps manipulate our attention. Finally, the episodic buffer acts as an additional store that brings together information stored in the phonological loop and visuospatial sketchpad and combines it with information brought from Long-Term Memory in order to aid our ability to make decisions [Baddeley, 2000].

Baddeley's theory is extremely popular and well researched and although there are still numerous questions regarding the exact nature of Working Memory [Miyake & Shah, 1999], it provides a solid basis for a new application to explore Working Memory.

In the next chapter some of the more popular methods of testing Working Memory are discussed. Both traditional and computer based tests are examined in the hopes of discovering a satisfactory design for the VAM application.

Chapter 3: Testing Working Memory

3.1 Introduction

In Chapter 2, Baddeley's model of Working Memory was examined and discussed as a theoretical basis for the VAM application. In Baddeley's model, different forms of information are handled by different subsystems. Audio information is handled by the phonological loop. Visual information is handled by the visuospatial sketchpad. Both of these components are overseen by the central executive and have a backup storage facility in the form of the episodic buffer [Baddeley & Hitch, 1974], [Baddeley, 2000].

While Baddeley's model provides a solid basis for the VAM application, by itself it is not enough. In this chapter, some of the current methods used to explore the functionality of Working Memory are reviewed. To begin with, the concept of Working Memory capacity is discussed along with how it applies to different forms of information. The difference between testing the storage capacity and the processing capacity of Working Memory is also examined. Several popular tests of Working Memory are then reviewed, both traditional paper based tests and modern computer based tests. The advantages and disadvantages inherent in each testing format are also considered.

The goal of this thesis is to create a versatile, configurable computer application that investigates the interaction between audio and visual stimuli and can be used in a variety of different situations. But how should the VAM application be structured? The testing methods described in this chapter are used to provide some guidelines.

3.2 Digit Span and the Magical Number Seven

In 1956, psychologist George Miller published a paper called "The magical number seven, plus or minus two: some limits on our own capacity for processing information". Using several earlier studies into Short-Term Memory as a basis for his analysis, Miller noticed a common thread in the results of these studies. Miller claimed that in each study, what he termed the 'span of absolute judgement' of each subject seemed on average to be seven 'bits' long. The span of absolute judgement refers to the correlation between the number of 'bits' of information presented to a test subject and the number of 'bits' of information that the subject retained successfully. Miller further defined a 'bit' of information as the amount of information required to make a decision between equally likely alternatives.

Miller theorised that the more information a subject was presented with, the more he/she could absorb. At a certain point though, the amount of information he/she absorbed levelled off. If the subject was exposed to more information after this point, he/she would begin to make mistakes. The more information that was presented to the subject, the more likely he/she was to make mistakes. However, in the experiments that Miller analysed, he noticed that the span of absolute judgement remained relatively constant. On average, people could absorb up to seven 'bits' of information before errors began to creep in. Despite the very specific nature of his claims, Miller's theory has been twisted and generalised to a large degree in the years since. Because of this, it is sometimes viewed as the scientific basis of Working Memory capacity.

The theory of '7± 2' or "Miller's Magic Number" as it has become popularly known, claims that the average capacity of Working Memory is seven plus or minus two items long. That is, some people can only hold five or six items in memory while others can hold up to eight or nine items. Despite its rather vague definition, it quickly became very popular and is still used in a number of fields today. In fact Miller's paper is still one of the most oft cited papers in the field of psychology [Gorenflo & McConnell, 1991], [Kintsch & Cacioppo, 1994]. It is viewed by many people as a scientifically proven fact and is used as the basis for many studies relating to Working Memory. Unfortunately and contrary to popular belief, Miller's magic number is not a scientific fact, and in certain circles is regarded as little more than wishful thinking [Schweickert & Boruff, 1986].

Perhaps the reason the myth of Miller's magic number has persisted so long is due to it being confused with 'digit span', a rather simpler concept and merely one measure of Working Memory capacity. Digit span just refers to the length of a sequence of numbers that a person can store correctly in Working Memory. Digit span is measured by a simple test in which a random list of digits is presented to a candidate one at a time. The candidate must then store this list in memory and repeat it back to the examiner in the same order without external aid. If the candidate succeeds he/she is given another random list, one digit longer than the last attempt. This process repeats until eventually the candidate makes a mistake. When this occurs, he/she is given a new sequence of equal length to the last attempt. If the candidate gets two sequences wrong in a row, the test is over. The length of the last sequence successfully stored and repeated by the candidate is recorded as his/her digit span.

The problem with digit span is that although it is an accurate measurement tool in and of itself, using digit span to measure overall Working Memory capacity relies on two assumptions. Firstly the '7 ± 2' theory assumes that Working Memory stores different information in the same way and secondly, it assumes that individual concepts are the basic unit of storage [Jones, 2002]. Research has shown that these two assumptions do not hold true. In other words, digit span does only what it says it does, measure the numerical capacity of Working Memory.

Different types of information are processed and stored in different ways, hence Baddeley's theory of a multi-component Working Memory system. Audio and visual information are taken in and handled by different systems in Working Memory: the phonological loop and the visuospatial sketchpad respectively [Baddeley & Hitch, 1974].

Of course, the divide between different types of information breaks down far more than just into audio or visual categories. The complexity of the information being taken in has as much if not more effect on how much of it is stored as the method of transmission. Miller [1956] described a 'bit' of information as the amount of information required to make a decision between equally likely alternatives. But the amount of information needed to make a choice is not itself a set size. A single digit could be enough, or a complex idea might be needed.

Studies have shown that digit span can even change depending on the language of the candidate taking the test [Hoosain & Salili, 1998]. The Chinese spoken words for digits are shorter than their English equivalents and so require less space in Working Memory due to the word length effect [Baddeley, Thomson & Buchanan, 1975]. In their study, Hoosain and Salili reported that the average digit span when tested in Chinese turned out to be 9.9 digits long as opposed to the general theory of seven.

The ability to 'chunk' or bind information together in the episodic buffer [Baddeley, 2000] complicates matters even further. Grouping items together, for example when remembering a phone number, is a common technique and can turn a number of individual bits of information into a single chunk to aid processing.

With so many different factors involved, it is difficult to pin down Working Memory capacity to a definite number. If such is required though, a good starting point is Nelson Cowan's detailed review of the area of mental storage capacity [2001]. Cowan reviewed a number of different studies into Working Memory capacity and claims that when extraneous factors and rehearsal techniques are removed from consideration, the average capacity appears to be about four chunks.

While the digit span method by itself may be an inadequate tool for exploring Baddeley's model of Working Memory, it is a simple test and one that can be easily understood and completed by potential candidates. It could therefore prove useful as a baseline when developing the new application. In the next section, more complex notions of Working Memory capacity will be discussed to see what useful information they can provide.

3.3 Complex Working Memory Span

Another limitation of the digit span test described above is that it primarily measures storage and recall capacity. A key component of Working Memory is the ability to manipulate and process information [Baddeley, 1986]. As such, any well-developed test of Working Memory should include an additional processing element in order to fully explore Baddeley's model.

Daneman and Carpenter [1980] were among the first to examine the processing capacity of Working Memory. In their initial studies they focused specifically on reading comprehension. Test subjects were required to read a series of sentences out loud. The subjects were simultaneously required to remember the last word of each sentence. At the end of the test, the subject was required to repeat back a list made up of the final word in each of the sentences. The words also had to be recalled in the same order they were presented in. Daneman and Carpenter judged Working Memory capacity as the maximum number of sentences that could be processed and accurately recalled in this way. It was this combination of processing ability as well as storage and retrieval that has become synonymous with Working Memory capacity.

There have been many variations on Daneman and Carpenter's approach (which is often referred to as 'reading span') over the years [Conway et al, 2005]. One popular approach involves the test subject having to verify a semantic or grammatical component in the sentences they read, in order to more heavily load the processing element of the test [Turner & Engle, 1989]. Another popular approach is to make the last word in the sentences (the words that must be recalled at the end) completely unrelated to the preceding sentences [Engle et al, 1999]. Other variations involve focusing on solving arithmetic equations instead of reading comprehension [Turner & Engle, 1989]. This is often referred to as 'operation span'.

In his own studies into Working Memory, Baddeley tends to favour the 'concurrent task' or 'dual-task' paradigm [Sperling & Dosher, 1986]. The dual-task paradigm requires the test subject to perform two independent tasks simultaneously. The results of each are then contrasted with the results produced when the tasks are performed alone. If performance significantly suffers as a result of both tasks being undertaken at once, then it is assumed that they in some way interfere with each other or both make use of the same cognitive systems. If performance does not suffer much, then the two tasks are assumed to be cognitively independent.

An example of the dual-task paradigm is: a test subject is required to carry out an aurally presented digit span test. Upon completing the digit span task, the subject is then asked to use a stylus to follow a moving point of light projected onto a board. The test subject would then be asked to perform both tasks at the same time. The degree to which the two tasks are impaired by the dual-task paradigm is then used as a measure of how cognitively related they are. Baddeley makes good use of this approach in order to provide evidence for his multi-component model of Working Memory [Baddeley 1986, 1999, 2007 and many others].

One final measure of Working Memory capacity that has recently gained popularity is the dual n-back task. The n-back task was originally designed in 1958 by Wayne Kirchner. Kirchner's test involved a row of bulbs which lit up one at a time and in a random sequence. The candidates' task was to respond to this sequence by pressing a key. Each key was linked to a different bulb. As with previous tasks, the candidate had to store the sequence of lit bulbs in memory. The twist in this test though, was that he/she had to respond to the bulb that was lit '**n**' turns ago, where n increased over the course of the test. The test started with the zero-back where the candidate had to press the matching key as soon as a bulb lit up. In the one-back round, the candidate had to press the key linked to the bulb that had been lit one turn ago. In the two-back round, the correct answer was the key linked to the bulb that was lit two turns ago etc.

Kirchner's test has commonly been adapted for use in neuroimaging studies. One popular approach involves the examiner reading out a sequence of letters or numbers. The candidate is required to respond when a letter or number read out matches one that was read '**n**' turns ago. For example, in a three-back task using the sequence 6 8 3 **6** 9 1 3 4 **1** 2 **4**, the candidate should respond when the underlined numbers are read because they match the number given three turns previously. The dual n-back task [Jaeggi et al, 2003] involves the same process, except that two independent sequences are presented at once. These sequences usually involve two different stimulus types and presentation formats and place a very heavy load on the candidate's Working Memory.

In each of the above tasks, the purpose is much the same. The candidate is required to store and recall a number of bits of information, while simultaneously having an increasing load placed on the processing centre of their Working Memory. In each case, the difficulty level is steadily increased until recall breaks down. It should be noted though that serial recall is not the only method of measuring Working Memory. An equally valid measure can be obtained using recognition as a basis for testing.

3.4 Recognition Tests

The Recognition Memory Test (RMT) was devised by Elizabeth Warrington in 1984. While digit span tests measure the simple concept of numerical capacity, the RMT measures capacity using far more complex stimuli. Unlike digit span it also differentiates between visual and verbal information as in Baddeley's model of Working Memory. The test itself contains two different sections, one verbal and one visual. Of interest here is the visual portion of the test which relies on facial recognition to determine Working Memory capacity.

The methodology of the test is simple enough. In the visual portion of the test, fifty images of unfamiliar male faces are selected. The selection is specifically chosen to include as wide a variety of facial types as possible, although images with beards, glasses or other types of verbally mediated items are discarded. Twenty five of these images are then chosen as 'stimulus' items and twenty five are dubbed 'distraction' items. The twenty five stimulus images are then printed individually on separate but identical cards. Each stimulus image is also paired with one of the distraction images and then both are printed on another separate set of identical cards.

When the cards are ready, the candidate is presented with the twenty five stimulus cards one-by-one. As each of the stimulus cards is presented, candidates are asked to guess if they think the man on each card is "over forty" or "under forty". While the age of the man in question is not important to the test, this step forces the candidate to focus on the image in order to aid recognition later. Once the entire set of stimulus images have been displayed, the candidate is then immediately shown the paired stimulus/distraction cards. As each of the stimulus/distraction cards are displayed, the candidate is asked to point out which of the two faces they recognise from the stimulus cards. The candidate's results are then noted down and used as a basis for measuring his/her visual Working Memory.

Unlike the digit span test, the RMT facial recognition test focuses almost purely on visual Working Memory. Unfortunately, there are some questions regarding the initial validation studies and lack of test-retest reliability data of the RMT [Kapur, 1987] which must be considered. A later study validated Warrington's findings to some degree and showed the RMT to be reliable, at least when applied to neurologically impaired candidates [Soukup, Bimbela & Schiess, 1999]. Despite these criticisms, the RMT shows the potential of using images for focusing on different aspects of Working Memory compared to more traditional span based methods.

Unfortunately like most paper based tests of Working Memory, the RMT must be administered on a one-to-one basis making it very time-consuming to test a large sample size. The RMT also requires all results to be recorded by hand, leading to a much higher risk of mistakes when collating results.

The far bigger problem with the RMT test however, is that each set of images can only be used on the same candidate once. If the same set of cards are used again, candidates may recognise the faces from their previous attempt and so bias the results. Even if the faces are shuffled and remade into new card sets, familiarity with the images used could still seriously influence the results of any repeat candidates. If a Working Memory test that can be used by multiple candidates on multiple occasions is required, an element of randomness must be introduced into the system.

3.5 The Wechsler Scales

Of all the traditional paper based tests of cognitive ability, few are as well-known as the Wechsler Adult Intelligence Scale (WAIS). It was developed in 1955 by David Wechsler and is currently in its fourth generation. The WAIS is a battery of tests designed to assess Verbal Comprehension, Perceptual Reasoning, Working Memory, Processing Speed and overall IQ. It contains ten different sections including several variations on the digit span test and several recognition memory tests. It also contains five supplemental tests for use if further examination is required [Wechsler, 2008]. Of interest here are the sub-tests focusing on Working Memory.

The WAIS is well known in many circles as a reliable test of memory and it has done much to show the potential of psychometric testing as an assessment tool. Studies on previous versions of the WAIS have shown it to be extremely reliable even over long periods of time [Brown & May, 1979]. Unfortunately, the WMS is also a commercial product and only available to psychologists with relevant Ph.D. degrees. As such, gathering enough information for a detailed review of all the tests was not possible. However, following a discussion on the matter with an educational psychologist, some general information on the layout of the Working Memory tests was obtained.

The Wechsler Memory Scale lists three sub-tests under the heading of Working Memory; the 'letter-number sequencing' test, the 'digit span' test and an arithmetic test. The first two tests are basically extensions of the standard digit span test, but instead of measuring storage capacity they measure processing capacity.

In the letter-number sequencing test, the administrator reads out a sequence of alternating letters and numbers. After each sequence is read out, the goal of the candidate is to store this sequence in Working Memory and to rearrange it, without external aid, in ascending order of numbers followed by alphabetical order of letters. Sorting the letters first, followed by the numbers is also acceptable. This sequence is then spoken aloud to the administrator who checks to see if it's correct. For example, if the administrator reads out the sequence R, 7, K, 3, D; the candidate has to rearrange this mentally to form the ordered sequence of 3, 7, D, K, R and repeat this aloud to the administrator. The test begins with a sequence of two items and increases by alternately adding a letter or number each round until the sequence is eight items long. Each round contains three different sequences with the same number of items and if a candidate gets all three sequences ordered incorrectly he/she does not proceed to the next round. The purpose of this test is to measure both phonological Working Memory and executive Working Memory

The digit span test takes a similar approach, but has three separate parts. The forward digit span test is just as described earlier in the chapter. Candidates are presented with a sequence of digits which they must repeat back to the administrator in order. The backwards digit span test is slightly different. In this case the administrator reads out a sequence of digits. The candidate must then store this sequence in Working Memory and repeat it back in reverse order to the administrator. For example, if the administrator reads out the sequence 5, 9, 4, 2, 6, the candidate has to return the sequence 6, 2, 4, 9, 5 to the administrator. The sequential digit span test once again involves the administrator reading out a sequence of digits, only this time the candidate must mentally arrange them in ascending order and repeat this new sequence back to the examiner. For example, if the administrator reads out the sequence 5, 9, 4, 2, 6, the candidate has to return the sequence 2, 4, 5, 6, 9 to the administrator. All three tests start with a sequence of two digits and increase each round until the candidate must remember a sequence of eight digits. Each round contains two different sequences. If the candidate gives an incorrect response for both sequences, the test ends. As before, this test is primarily meant to measure phonological Working Memory and executive Working Memory.

The final test that comes under the banner of Working Memory is an arithmetic test where candidates are orally presented with arithmetic problems and must solve them from memory alone, without external aid and within a specified time. Unlike the other two sub-tests, there is some controversy over whether the arithmetic test should really be considered a measure of Working Memory. While there is no doubt that Working Memory is involved in the process, some argue that it is not the main process being measured and in fact has more to do with fluid reasoning than Working Memory [Keith et al, 2006]. The link between fluid reasoning and Working Memory is discussed in more detail in Chapter 7.

Leaving aside the arithmetic test, both the letter number sequencing test and the spatial span test are simple and elegant ways of testing processing capacity. The endurance of the digit span as a measure of Working Memory also speaks highly for it. However, both the tests here focus purely on the phonological aspects of Working Memory. In order to be an effective tool to explore Baddeley's model of Working Memory, the visuospatial sketchpad must be included to a larger degree.

Like the Recognition Memory Test and the various span tests, the Wechsler scales are popular, effective tests of Working Memory. Like the RMT and span tests they are also ordinarily carried out on a one-to-one basis using pencils and paper. In an age when computers are commonly available, why do these traditional methods still persist? In the next section some of the advantages of traditional testing methods are discussed in order to answer that question.

3.6 Advantages of Traditional Testing Methods

The main reason that traditional testing methods are still popular today is their ease of use. Anyone can complete the above tests without any special knowledge or skills. While some candidates might be uncomfortable or unfamiliar with using a computer, traditional testing methods often require nothing more than the ability to answer an administrator. While this is certainly a valid complaint, computers are becoming more commonplace every year. While there are still people who are uncomfortable with computers, they are becoming the exception rather than the rule. There will always be a need for paper and pencil tests of Working Memory to accommodate those who for one reason or another are unable or unwilling to use a computer. However, the vast majority of candidates completing Working Memory tests could benefit from computerised methods.

Traditional testing methods also allow administrators to monitor and interact with the candidate on a personal level. The clear advantage here is that administrators can pick up on certain details that a computerised test cannot. What techniques did candidates use to aid memory? When dictating a sequence of digits back to the administrator, did the candidate close his/her eyes or count off his/her fingers? While a computer application only records a candidate's response in terms of numbers, an administrator can record a candidate's behaviour which could prove equally as important.

An off-shoot of this level of interaction is that administrators can vary the approach and difficulty of traditional testing methods depending on who they are testing. While many traditional tests are accompanied by strict instructions on how the test is to be carried out, the administrator can still make changes if they feel the current approach is not working. If a test is too simple or too difficult for a candidate it can lead to boredom or frustration. The administrator can counter this by raising or lowering the challenge of the test as they feel appropriate. Computer applications on the other hand are more rigid in their structure. It is more difficult to accommodate a specific candidate's needs using a computer based testing application. There is potential in this area though. A configurable system is possible and it is something that should be considered when designing computer based tests.

The final reason why paper and pencil tests are still so popular today is sheer momentum. Some of the popular tests used have been around for years if not decades. They have been proven to be effective methods of testing Working Memory and so are still used today. Introducing new computer based tests of Working Memory means that these methods will have to be tested in turn for reliability and effectiveness before they become useful tools for administrators. This sort of testing takes time, and many administrators would rather stick with traditional methods than work with unproven ones.

But are these advantages large enough to deny that computer based testing is likely the future of Working Memory analysis? Traditional methods have several disadvantages too. In particular, the one-on-one testing format and the lack of accuracy in the results make traditional methods unsuitable for large scale research projects. The next section examines the disadvantages of traditional testing methods in detail and explains why computerised tests of Working Memory are a better choice.

3.7 Disadvantages of Traditional Testing Methods

One of the biggest disadvantages of traditional Working Memory Tests is that the vast majority are designed to be carried out on a one-to-one basis. Each administrator can only test one candidate at a time. As described in the previous section, sometimes this one-to-one testing is an important feature. When diagnosing a learning disability or other problems with a candidate, the administrator will need to look for signs outside of the candidate's results. An administrator can monitor candidates even while they use computer based tests but they might miss signs that would be apparent if they communicated with the candidate as part of the test.

Spotting problems with Working Memory is only part of a diagnosis though. Candidates would no doubt need to be interviewed separately to determine any problems anyway. If problems are picked up by a computer based assessment, they can in turn be followed up by the administrator in a more personal fashion. The computer based assessment can be used as a first line tool of diagnosis and one with the potential to reach many more people than an individual administrator can. This potential will be discussed in greater detail in Chapter 6.

Another advantage of computer based testing is its ability to quickly and efficiently gather data for research into Working Memory and related areas. Testing a hundred candidates using either the WMS or the RMT would take a single administrator a very long time. With the VAM application, several aspects of audio and visual Working Memory are examined. Consider how long it would take to administer four or five tests to each candidate on a one-to-one basis. If multiple sessions are required to examine changes in Working Memory over time, this period becomes even longer. This time can be cut down significantly if multiple candidates can use separate computers to be tested simultaneously.

Computerised testing also greatly assists the data collation and analysis process. With traditional testing methods, the administrator is required to record the answers and score of each candidate manually. These results must then be processed and collated to prepare them for analysis. Since most modern statistical analysis is done with the aid of computer software, the administrator must enter all the data in a standardised format into a computer.

With computerised testing, the data gathering process can be completely automated. Each candidate's results can be produced in the same format; one designed to work with common statistical packages. Upon completion of the tests, each candidate's results can be sent directly to a central database which allows for easy extraction and analysis later on. Automating the testing process therefore saves researchers both time and effort.

As well as saving researchers time, computer based testing also significantly reduces the risk of errors in the data. Administrators can be trained to conduct tests of Working Memory in a specific manner and to record results in a specific way, but there is no guarantee that the end result will be error free. Computers on the other hand will carry out their instructions exactly as given. Provided the software is rigorously tested to ensure there are no mistakes before it is circulated, each computer the application runs on will act like a perfect administrator and each candidate will be treated exactly the same.

Computers are not only more consistent than human administrators, but are more accurate too. When a computer measures a response time or calculates a candidate's final result, it can do so faster, and with a much higher degree of accuracy than any human. Using a computer, results can be compiled and sorted automatically and so reduce the risk of errors due to bad data entry.

A final point in favour of computerised testing is that of money. Because many traditional testing methods are carried out on a one-to-one basis, there are many extra costs associated with them. Not only is an administrator required for each testing session, but individual materials are required for each candidate tested. This is why many commercial testing packages charge on a per-candidate basis. Computer based testing can reduce these costs. The application can be purchased up front and can then be used as often as required for no additional cost.

Computerised testing saves time and money, reduces mistakes and increases the accuracy of results. As such, logically there should be many well respected computerised tests of Working Memory already available. Unfortunately this does not appear to be the case.

3.8 Computerised Tests of Working Memory

The use of computers as research tools in the field of cognitive science has grown steadily over the last few decades. Despite this fact, there are very few widely recognised computer based tests of Working Memory available. As previously explained, a lot of this is down to sheer momentum. The concept of computer based tests of Working Memory is still relatively new. As such, any tests produced would be untested and so rightly subject to scepticism. Because there are already proven methods to examine Working Memory available in the form of traditional paper based tests, there has yet to be a great push towards making computer based tests the standard, despite the many advantages listed in the previous section

While searching for computer based tests to serve as in inspiration for the VAM application, only two widely recognised and respected tests were located that fit the criteria: Riding's IPI [2000] and the Automated Working Memory Assessment [Alloway, 2007].

It should be noted that there may be other computerised tests of Working Memory out there, but largely these are either scientifically unproven, were built for a specific study and never distributed further or require specialised equipment and/or training to use. One of the goals of the VAM application is to be a simple and versatile research tool that can be used in many different areas and studies. As such, only applications with similar goals were considered in this section.

3.9 Riding’s IPI

Developed in 2000, The Information Processing Index (IPI) devised by Dr Richard Riding is a short application used to test the processing capacity of Working Memory. Riding recommends if for use on candidates aged nine and upwards. The concept of the test is simple yet effective. Its novel format also has the benefit of keeping the candidate interested and so focusing his/her attention. The test is easy to use and has no skill requirements beyond the ability to read the instructions and press a key on the keyboard.

The structure of the test is relatively straightforward. In each round of the test, the candidate is presented with a simple image of a railway train on the screen. Each train is composed of a certain number of carriages and each carriage is a different colour. The candidate must memorise the colour of each carriage of the train. When the candidate is ready, he/she must use the space key to move the train across the screen until the train is totally hidden from view inside a railway station. The train then reappears, one carriage at a time, on the other side of the station. On reappearance however, the colour of each carriage may be different from what it was prior to entering the station. The candidate is asked to examine each carriage in turn as it leaves the station. He/she must then indicate (by pressing one of two marked keys) whether or not the colour of each carriage has changed. Seven different colours are used in all.

Candidates can view each train for as long as they wish before moving it into the station. While in the station, the train cannot be seen by the candidate. The candidate can take as much time as he/she wishes before moving the train back out of the station. According to Riding, the IPI tests both retention and information processing skills. Candidates have to judge each carriage individually (information processing) while at the same time storing information on each of the carriages yet to reappear (retention). The candidate receives marks every time he/she responds correctly as to whether or not the carriage changed colour. Upon finishing, the percentage of total correct choices is taken as the candidate's Information Processing Index.

In the IPI application, train length begins with one carriage and increases to six carriages. Four different sequences of carriages are presented at each length. This gives a total assessment of eighty four carriages. In each sequence approximately half of the carriages do not change colours and Riding claims that the average IPI achieved by repeatedly making the same choice is 49.2% [Riding, 2000].

3.9.1 Advantages of Riding's IPI

The advantages that Riding's IPI has over traditional tests are clear. The software can be used by multiple people simultaneously (as long as there are enough computers available). An entire room of candidates can be monitored by a single administrator to ensure that everything goes well. Results are automatically recorded and stored in a data file on the computer or on a floppy disc to reduce data entry and aid analysis. All of these advantages make the IPI test a valuable tool for research into Working Memory, but they are not the only ones.

The pseudo-random nature of Riding's IPI is also a large advantage over traditional tests. Each sequence of carriages in the test is pseudo-randomly generated at run time by the computer. This means that each time the application is used the sequences will be different. This is an advantage as it allows candidates to use the test more than once without biasing their results due to familiarity.

The other advantage of Riding's IPI test is its interactive nature and interesting design. By allowing the candidate to control the movement of the train, he/she is helped to focus his/her attention on the task at hand. Rather than listening to an administrator read out the sequence or show them a series of pictures, the interactive nature of the application forces the candidate to keep his/her mind on the task at all times. This is a definite benefit where Working Memory is concerned.

Riding's application is an interesting and respected tool with many clear advantages over traditional paper and pencil memory tests, but it is not without its own problems. There are several disadvantages to Riding's IPI test which must also be examined in the interests of fairness.

3.9.2 Disadvantages of Riding's IPI

The main disadvantage of Riding's IPI test is that there is a bug still present in the application. This is always a risk in computer applications and it is why they need to be thoroughly tested before they are released for public use. The bug in this case occurs when the train is leaving the station. The candidate must judge each carriage in turn to see if any of them have changed colours. The bug only occurs after the candidate has judged the first carriage. Sometimes, and for no apparent reason, as one of the remaining carriages exits the station, the first carriage of the train will change colour. Although at this stage the candidate has already judged the first carriage and should be focusing on the latest carriage to emerge, the random change of colour can disrupt his/her concentration and cause confusion which in turn will affect his/her performance. Since the bug appears seemingly at random it is impossible to account for its effect on any results gathered [Redmond et al, 2007].

There is another disadvantage resulting from Riding's use of colour as a means of assessment, the condition known as colour blindness. Colour blindness is a genetic condition which leaves a person unable to distinguish between certain shades in the colour spectrum. The proportion of the population that suffer from colour blindness varies from country to country, but research suggests that in the United Kingdom, almost one in twelve males experience some form of impairment [Sharpe et al, 1999]. Because of this, there is a good chance that a candidate may fail to show his/her full potential on the test through no fault of his/her own.

Finally there is evidence that despite the pseudo-random generation of the sequences, Riding's test does not always provide candidates with consistent results. There is very little evidence in regards to its reliability. In a 2002 test re-test reliability study, a group of students (n= 51) completed Riding's test on two separate occasions, with a three week break between attempts. The results show a low level of correlation (r = 0.352) between the two sets of results, indicating a low test re-test reliability [Parkinson et al, 2002].

3.10 Automated Working Memory Assessment

The Automated Working Memory Assessment (AWMA) [Alloway, 2007] is an automated suite of computer based Working Memory tests developed by Dr Tracy Packiam Alloway. The AWMA is designed primarily to screen for Working Memory problems. It is recommended for use on children as young as four up to adults aged twenty-two. Like Riding's IPI, it takes minimal training to use the application and the gathering and collating of results are automated, though an administrator is still required to supervise the process. Unlike Riding's IPI however, it is specifically designed to examine several different areas of Working Memory and also uses Baddeley's model as a basis for its design. In particular, Alloway focuses on both verbal Working Memory and visuospatial Working Memory.

Another unique feature of the AWMA is that there are several levels of testing available depending on what the situation requires. There is a screening version of the test available containing only two sub-tests, a short version containing four sub-tests and finally a long version containing twelve different sub-tests. The long version takes up to forty minutes to complete. The AWMA is also available in over fifteen different languages, increasing its versatility and potential users [Alloway, 2009a].

The sub-tests in the AWMA break down into several categories. Additional details on each of these sub-tests were obtained from [Dehn, 2008]. Each sub-test begins with a set of instructions that are presented aurally by the application over a blank screen. The first group of tests are the phonological Short-Term Memory tests which consist of three simple tests. The first is a digit recall test which is a digit span test as described earlier. The second test is a word recall test which is again a span test, this time using words instead of numbers. Finally there is a non-word recall test. In this case, nonsense non-words are used as stimuli. In each case, the stimuli are presented aurally to the candidate who must then respond verbally. The administrator of the test then uses the keyboard to input whether the candidate was correct or incorrect.

The second group of tests are phonological Working Memory tests, which include an extra processing element. The first of these tests is a listening recall test based on Daneman & Carpenter's [1980] reading span test which was described earlier. The second test is a counting recall test wherein the candidate is presented with a series of images of groups of dots. The candidate must then count these dots and at the end recall the number of dots in each image in order of presentation. The final test in this category is a backwards digit recall test, which is the same as the digit span test except the candidate must reiterate the sequence in reverse order to the examiner.

While the first six sub-tests in the application deal with phonological Working Memory, the final six focus instead on visuospatial memory. The AWMA is one of the few computer based tests available that make this distinction and test both aspects of Working Memory.

The first group of tests here are visuospatial Short-Term Memory sub-tests. The first test is a block recall test. In this test, the application produces a grid of nine boxes on screen. The boxes then light up in a random sequence and the candidate must repeat that sequence by tapping the boxes in the same order. The test begins with a single block sequence and grows from there. The next visuospatial test is known as a maze memory test. In this test, an image of a maze is produced on screen. A path is then traced through the maze and the candidate must reproduce the same pathway himself/herself. As the test proceeds, the mazes become more complicated. The third test is referred to as the Dot Matrix test. Here a red dot in a four by four matrix appears on screen for two seconds. Once it has vanished, the candidate must tap the appropriate box on screen where the dots appeared.

Much like the audio Working Memory tests, the final group of visual Working Memory tests also include a processing element. The first of these is an odd-one-out test, in which the candidate is shown a sequence of screens, each of which contains three shapes. The candidate must identify the odd-shape-out in each case and then at the end of the test identify the location of the odd-shape-out from each sequence in order. The second test is called Mr X, which features two cartoon characters, one wearing a blue hat, one wearing a yellow hat. During the test, the characters hold a ball in various positions based on the directions of the compass. At the end of each round, the candidate must identify the different locations of the ball held by the character with the blue hat. The candidate does this by pointing at an eight point compass. The final test in this category is the spatial span test in which the candidate must recall the location of a red dot that appears on one of two objects, while also identifying whether the two objects are mirror images of each other. Again the candidate points out his/her answer on a compass like display.

Once the candidate has completed all twelve of the sub-tests, the application collates and processes their results automatically and provides details to the examiner. The AWMA clearly covers a much broader base of tests than those offered by Riding's IPI and in turn has many advantages.

3.10.1 Advantages of AWMA

Like Riding's IPI, the AWMA requires minimal training to use and so can be conveniently used by a wide variety of candidates. It also automatically collates and analyses the results of each test saving much time and effort on the administrator's behalf. These results can also be automatically exported to Microsoft Excel for further analysis.

Unlike Riding's IPI however, the AWMA covers an enormous range of tasks, providing far more useful information to researchers. The diversity and range of the tests will also likely keep candidate's focus on the task at hand. While the long version of the test may strain candidates' attention span, taking almost forty minutes to complete, the constant shift in tasks may help counter this effect. The screener version takes less than ten minutes to complete.

The main benefit of the AWMA application is that it seeks to clarify and explore many different aspects of Working Memory. There are two main divisions in the application, each with a selection of sub-tests that examine that particular portion of Working Memory. Firstly there is the clear division between audio and visual Working Memory and the acknowledgement that they handle information in different ways. Secondly there is the division between simple recall tasks and more complex processing tasks. These divisions also align closely with Baddeley's model of Working Memory whose multicomponent system includes the phonological loop for audio memory, the visuospatial sketchpad for visual memory and the central executive and episodic buffer for tasks that require further processing.

The AWMA represents a huge step forward in computer based Working Memory applications, and scores highly on test re-test reliability (**r** ranged from .69 to .90) [Alloway, Gathercole, Pickering, 2006]. However, there are still one or two areas that could be improved upon and in doing so take advantage of the automation that computers allow

3.10.2 Disadvantages of AWMA

One disadvantage of the AWMA system is that it still requires one-on-one interaction with the examiner. While all the test stimuli are automated, it still requires an administrator to manually input whether the candidate responded correctly or incorrectly to each stimulus. While this process has been pared down significantly in the AWMA (the examiner need only indicate the result by tapping one key for correct and another for incorrect), it still allows the opportunity for human error to creep in.

Similarly, the one-to-one method of assessment means that its use in large scale research projects is time consuming. As the AWMA was primarily designed to help diagnose Working Memory impairments, this personal approach is understandable. It does leave an opening in the field for a more independent application that tests different aspects of Working Memory though.

The other disadvantage of both the AWMA and of Riding’s IPI is that neither application is configurable. The AWMA includes several levels of difficulty in its tests, but apart from that the application cannot be altered by an administrator. Riding's IPI cannot be altered at all. Once again, there is a gap in the field for a configurable application that can be altered for use in different tasks as well as target different groups of people.

Despite these limitations, both the IPI and the AWMA applications represent a huge step forward in computer based testing. The AWMA in particular is gaining in popularity and being used in many diverse studies and is something that the VAM application can still learn a lot from.

3.11 Conclusions

While useful, Riding's test is limited by its use of a single stimulus type. In order to investigate both audio and visual aspects of Working Memory, the stimuli would have to be presented aurally as well as visually by the application. Unfortunately aural presentation does not work well with Riding's test design.

Riding's application does highlight the advantages of a computerised test of Working Memory though. The entire testing process is automated and the candidate is in control at all times. This reduces the risk of errors, allows for the gathering of more detailed results and also encourages candidates to become more invested in the process.

In contrast, the AWMA covers both audio and visual aspects of Working Memory and has a depth that matches, if not overshadows, most traditional testing methods. On the other hand it also falls between the gap of one-on-one traditional methods and fully automated computer based methods. The computer provides the stimulus for the test, but the candidate responds either verbally or by pointing to his/her answers while the results are judged by a separate examiner. This loses the independent aspects of Riding's IPI and makes large scale testing time consuming, though still much faster than traditional paper based methods.

A new test of Working Memory should learn from both the AWMA and Riding's IPI and build upon them by referencing the advantages of traditional tests of Working Memory as well. One of the benefits of traditional Working Memory tests is that they can be tailored to a specific person or study in a way the AWMA and IPI cannot. A new test of Working Memory should be able to set itself apart from these applications by providing this facility.

Looking back at all the tests reviewed in this chapter, the popularity of variations of the traditional digit span test is very noticeable. The digit span test is popular because it is simple to use. The digit span test can also be presented to the candidate in either audio or visual form. The administrator can either show the written sequence to the candidate, or simply read it aloud. This symmetry between the audio and visual formats is useful if the results of both tests are to be directly compared. The digit span can also be presented as is, to test storage and recall, or with additional elements that test processing capacity.

While the digit span test may not be enough by itself, it can serve as a good base for a new application for testing Working Memory. The VAM application will have the advantages of computerised testing, but endeavour to keep the simplicity and versatility of traditional testing methods. The design of the VAM application is discussed in greater detail in Chapter 4.

3.12 Review

In this chapter, several popular and well-respected tests of Working Memory were discussed and reviewed in order to build a solid foundation for the new VAM (Visual & Audio Memory) application. To begin with, the concept of memory span was introduced with reference to Miller's Magical Number of '7± 2' [Miller, 1956]. Some of the problems with this concept were discussed, in particular how memory span can vary depending on what is being stored.

In the next section, some of the more popular methods of examining Working Memory were discussed. The digit span was introduced along with more complex measures of Working Memory like the reading span [Daneman and Carpenter, 1980], operation span [Turner & Engle, 1989], dual-task approach [Sperling & Dosher, 1986] and the dual n-back approach [Kirchner, 1958], [Jaeggi et al, 2003].

Other popular paper and pencil or traditional tests of Working Memory were also discussed including the recognition test [Warrington, 1984] and the Wechsler Memory Scales [Wechsler, 2008]. The advantages and disadvantages of traditional testing styles were also explored.

Following this, the potential of computer based testing was discussed and two main computer based testing applications were reviewed, Riding's IPI [Riding, 2000] and Alloway's AWMA [Alloway, 2007]. The main benefits of both traditional and computer based Working Memory tests were then brought together as a basis for a new computer based test of Working Memory, the VAM (Visual & Audio Memory) application. In the next chapter, a detailed analysis of the realisation and implementation of the VAM is discussed.

Chapter 4: Design & Implementation of the VAM

4.1 Introduction

In Chapter 3, a number of respected methods for examining Working Memory were discussed and reviewed. In this chapter the VAM (Visual & Audio Memory) application is introduced, a new computerised system designed to function both as a test of audio and visual Working Memory and also as a research tool to further explore the area of Working Memory and its value in related fields.

Over the course of this chapter, the design decisions behind the VAM application will be explained along with how these decisions were implemented in the final application. The basic operation of the application is also discussed, using a section-by-section analysis of each individual test. The additional features that help make the VAM such a versatile tool will also be examined. Finally, a breakdown of how the application was implemented using the Authorware system will be provided.

4.2 Application Design Goals

There have been many methods for examining Working Memory in the past. Some of the more respected methods were examined in Chapter 3 in order to provide a basis for a new and improved suite of tests. Both traditional paper based tests and computerised tests were examined along with the advantages and disadvantages inherent in each. Through the study of these tests and using Baddeley's model of Working Memory [Baddeley & Hitch, 1974], [Baddeley, 2000] as a basis, the structure of the VAM application began to take shape.

In this section, the design goals of the VAM application will be discussed in detail. Before this discussion though, a summary is provided:

1. The VAM is designed to examine both audio and visual Working Memory.

2. The VAM is designed to have a homogeneous structure in order to make it easy to use and to assist in the analysis of results.

3. The VAM is extensively configurable so that it can be used in a variety of different research areas and by a variety of different people.

4. The VAM is designed to be carried out independently so that multiple candidates can be examined simultaneously without the need for one-to-one administration.

When deciding on the structure for the VAM application, one of the most important requirements was that it could be used to explore both audio and visual Working Memory. In order to achieve this, the application needed to be broken down into several subsections, each one focusing on a different aspect of Working Memory. Although the VAM application was to be composed of several different tests, it was decided that the application should still have a homogeneous feel so as not to confuse new candidates. It was also decided that the more closely linked the tests were, the easier it would be to look for connections within the results they generated. With this in mind, a format was required that could stimulate different aspects of the candidates audio and visual Working Memory but still have the candidate respond in a similar manner regardless of what form the stimulus takes.

As peer-reviewed, scientifically tested, computer based Working Memory tests are still comparatively scarce, it was decided that the application should not require much in the way of computer skills to complete. It should look simple and be intuitive to use. After examining several existing computer and paper based tests of Working Memory, it seemed beneficial to use a well-recognised form of test as a starting point for the application – the standard digit span test.

The digit span test was a solid starting point for the application. The stimuli could easily be presented in audio or visual format and the candidate only required the abilities to see, hear, read and use a computer mouse in order to complete the tests. However, while it was a good starting point, it was clear there were still many issues to overcome in order to set this application apart from other Working Memory tests. The first and most important of these was that the use of digits alone would focus too much on the phonological aspects of Working Memory only.

As described in Chapter 2, in Baddeley's model of Working Memory, audio information is handled by the phonological loop. As a result of developing in a verbal language driven society, Baddeley theorises that the phonological loop may play a more active role in the rehearsal of Working Memory than its visual counterpart, the visuospatial sketchpad [Baddeley, 2002]. Because of this, there is a tendency for people to 'hear' numbers in their head, regardless of whether they are presented in an audio or visual format.

In order to balance this effect, it was decided that a more visual form of stimulus should be used in conjunction with the digit span test. In this case, it was decided to use simple images as well as digits as stimuli. By creating an audio and visual image span test as well as an audio and visual digit span test, the focus on visual memory could be somewhat restored within the limits of the interface.

The basis for the image span test is exactly the same as the digit span test. The candidate is presented with a sequence of pictures or a sequence of words relating to the pictures which they must then store, process and re-enter into the system. While several types of images were tried out, in the end it was decided to use photographs of simple, recognisable objects. The reason for this is two-fold. Firstly, the objects must have simple and easily understood names or labels that can be used in the audio portion of the application and secondly, the objects need to be recognised and stored quickly by the candidate before the next item in the sequence appears. The more complicated the object in question, the less likely a candidate is to identify and store it in time. With the audio and visual image test used to balance out the audio and visual digit span test, there was a solid basis for an examination of the audio and visual components of Working Memory.

The interaction between the audio and visual components of Working Memory makes testing them separately difficult. Studies have shown that when possible people tend to phonologically recode or reinforce visually presented information, allowing subvocalization to aid in the rehearsal process. The reverse process also occurs with visual storage being used as a backup for audio information. Words that are easy to visualise are simpler to remember than abstract concepts. For instance a child might find it easier to remember a poem about a dog than one about happiness. This is known as the dual-coding hypothesis [Paivio, 1969, 1971]. In Baddeley's model of Working Memory, this blending and additional storage of information is thought to take place in the episodic buffer [Baddeley, 2000, 2007].

When considering methods of measuring visual Working Memory, it was decided against using methods to artificially inhibit the phonological and visual reinforcement of items. Although there has been success in the past with test items that cannot be readily verbalised such as wallpaper patterns [Broadbent & Broadbent, 1981] or unfamiliar Chinese ideograms [Wolford & Hollingsworth, 1974], it was felt that these measures would interfere with the real-world uses of the VAM application. It would also make the audio test of images extremely difficult since unrelated labels would have to be used for the images. By allowing the candidate to store information as they would in the everyday life, the VAM can be of more use to areas like e-learning which is discussed in Chapter 8.

If necessary, the process of dual-coding can be disrupted through the use of distractor techniques. While not directly built into the application, these simple techniques can be used if the VAM is included in studies that require isolating certain aspects of Working Memory. Phonological recoding and rehearsal can be prevented through the use of articulatory suppression during the stimulus phase of the visually presented tests. Articulatory suppression involves the subject having to repeat a word or words under their breath thus preventing them from subvocalizing elements in the test [Baddeley et al, 1984], [Alloway, Kerr, Langheinrich, 2010]. This allows a more independent measure of visual Working Memory capacity, though studies have shown that this capacity is very limited [Sperling, 1960], [Cowan, 2001], [Vogel et al, 2001]. Similarly, visual recoding can be prevented through distracting the candidate with a random varying image such as a moving computer screen saver during the stimulus phase of the audio presented tests [Quinn & McConnell, 1996]. This in turn would allow a more independent measure of audio Working Memory capacity.

In order to be a true measure of Working Memory, an additional processing element also needed to be included in the tests. This allows the application to examine not only the phonological loop and visuospatial sketchpad, but also the central executive and the episodic buffer, thus exploring all the components of Baddeley's model. As described in Chapter 2, the central executive is mainly responsible for focusing attention and manipulating information and the episodic buffer is responsible for storing and combining additional information [Baddeley, 2000].

In order to test these components, an extra function was built into the VAM application. When re-entering a sequence presented by the test, the candidate must re-enter it in reverse order. In other words, if presented with the sequence 8, 5, 2 he/she must re-enter 2, 5, 8. This additional element places a lot more strain on the candidate's Working Memory and by doing so, helps explore the abilities of the central executive and episodic buffer. In order to emphasise the configurable nature of the application, it was also decided that this option could be switched on or off by the administrator as desired.

The configurable nature of the VAM application was kept in mind throughout its development. Ideally the VAM should be usable in as many varied fields as possible. As discussed in Chapter 3, many current tests of Working Memory have set instructions for how they are to be administered. These instructions lay out everything from the exact stimulus sequences used and the difficulty level involved, to the presentation time of the stimulus and the number of attempts the candidate gets. While there may be some leeway in this process when it comes to traditional testing methods (depending on the administrator), many computer applications are, by nature, more fixed in their administration. The VAM application was designed to be more flexible in its design. An extra administrator's level was added to the VAM application to allow the settings used in each of the tests to be altered as needed. The options included in this level are discussed in more detail later on.

The need for multiple tests also brought up another issue of configurability, how would the VAM accommodate future modifications? To deal with this, it was decided to keep each aspect of the VAM self-contained. This approach allows future versions of the VAM to introduce new features and tests or alter old ones without disrupting the overall flow or requiring a major redesign of the application.

By designing and implementing each component test in the VAM to be fully self-contained and functionally separate from the others, it meant that individual tests could be switched on or off with little effort or overall effect on the application. This proved to be a great asset during the initial debugging and testing of the application. It will also prove to be beneficial to future iterations of the VAM application by allowing new tests to be easily added or removed. The flowchart based nature of Authorware, the design platform in which the VAM was implemented, helped a lot with this process. The nature of Authorware and the implementation of the VAM will be discussed in more detail later in this chapter.

A common element of many of the testing methods described in Chapter 3 is the requirement of an administrator to oversee the testing process. While there are some advantages to this approach, it does require an extra investment of time and resources when using them in large studies. The VAM application was designed to be used independently. Administrators can still monitor candidates on a one-to-one basis if required, but they are not forced to. A candidate can complete the VAM application without any external guidance. The VAM application provides the necessary instructions, monitors the responses and collates this data into a detailed results file automatically. A candidate can even use the VAM in his/her own home and simply send the results to the administrator when done. This saves both parties considerable time and effort and allows the VAM to be used in an even wider range of studies.

It is this combination of features that allows the VAM application to provide a unique contribution to the field of exploring Working Memory; one that will prove useful in a number of diverse fields. The next section discusses how this model was expanded and implemented to form the final application.

4.3 Layout of the VAM Application

The initial concept of this application was developed with input from Dr Tony Redmond and Dr Adrian Parkinson of Trinity College Dublin and has been expanded upon many times since. The format of each test in the application is simple. The candidate is presented with a pseudo-random sequence of either audio or visual stimuli; he/she must then store this sequence in Working Memory for a short time, reverse it, and re-enter it into the system, using the interface provided. The length of each sequence, and therefore the challenge, increases as each test proceeds.

As a test of Working Memory, the ultimate goal of the VAM application is two-fold. Firstly the VAM should provide a tool to measure the audio and visual capacity of a candidate's Working Memory and secondly it should be able to explore individual differences in that capacity. Does the candidate perform better or worse when presented with audio over visual stimuli? Does each candidate respond the same way or are some more inclined one way or the other? Investigating whether different candidates store more information when it is presented in different formats could play a key role in improving computer based learning technologies.

With a template for the application in place and the preceding goals in mind, the VAM application began to take form. In the following section, the structure of each component of the VAM application is discussed along with each component's role in the overall system.

4.3.1 Test 1: Visual Memory Test (Letters)

The first test within the application is a visual based Working Memory test using letters as stimuli. Originally, numbers were used instead of letters as in the traditional digit span tests. After further examination however, letters seem a better choice of stimulus. There are two main reasons for this:

Firstly, when generating a pseudo-random sequence of numbers, the potential pool from which these numbers can be drawn only ranges from 0-9. Letters, on the other hand carry a potential pool of up to twenty six items ranging from A-Z. Obviously, not all of these letters could be used in the final application as it would make the interface look far too crowded. However, by using letters as a basis instead of numbers, the number of different stimuli included in the test could be increased beyond ten.

Secondly, sequential runs of letters or numbers are easier to remember than random sequences. For example, the sequence 1, 2, 3, is simpler to remember then 5, 2, 9. This is simply because humans are used to hearing and seeing numbers and letters presented in order and so have those sequences chunked together in memory already. By using letters instead of digits, a majority of non-sequential letters can be chosen for the final stimulus pool to minimise the risk of lengthy sequential runs.

The letters chosen to be in the stimulus pool for generating sequences in this test are all consonants and were picked from throughout the alphabet. The letters were chosen carefully to minimise the chance of accidentally creating words or phonetic sequences and thus aiding recall. The lack of vowels and the distribution of the letters helped avoid this. Even with a pool of 21 items to choose from though, it was extremely difficult to eliminate every connection between the items chosen. In the end, a pool was chosen that helped minimise these connections. The final letters chosen were C, D, F, H, K, L, N, Q, R, T, V and X.

The purpose of this first test is to examine how a candidate's Working Memory responds when presented with a sequence of letters that he/she must store, process and reproduce. Before starting the test, there are two introductory screens containing instructions for the candidate. The first screen describes the layout of the test and explains what is required of the candidate. The second screen introduces the interface for re-entering the sequence and explains what each component does. When the candidate is satisfied that he/she understands the concept and functionality of the test, he/she presses the continue button and the test begins.

When the start button is clicked by the candidate, the first sequence of letters will be displayed on the screen in order (see Figure 3). Each letter will be displayed for a preordained length of time which can be controlled by the test administrator beforehand using the administration menus described below. The default display time is three quarters of a second.

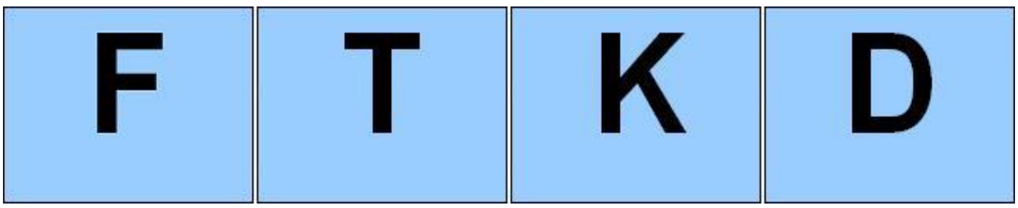

Figure 3: Example sequence of letters generated by the VAM application. Each box represents a single screenshot.

When the sequence is finished, the candidate is immediately returned to the application's interface screen and asked to re-enter the previously displayed sequence in either reverse or forward order depending on what mode the application is in. Once he/she has done this and is happy with the decision, he/she can click the continue button to move on to the next sequence. Meanwhile his/her performance is measured and stored by the application. If the candidate feels he/she has made a mistake while entering the sequence, he/she can reset the response field and try again; of course, doing so will add to his/her overall response time.

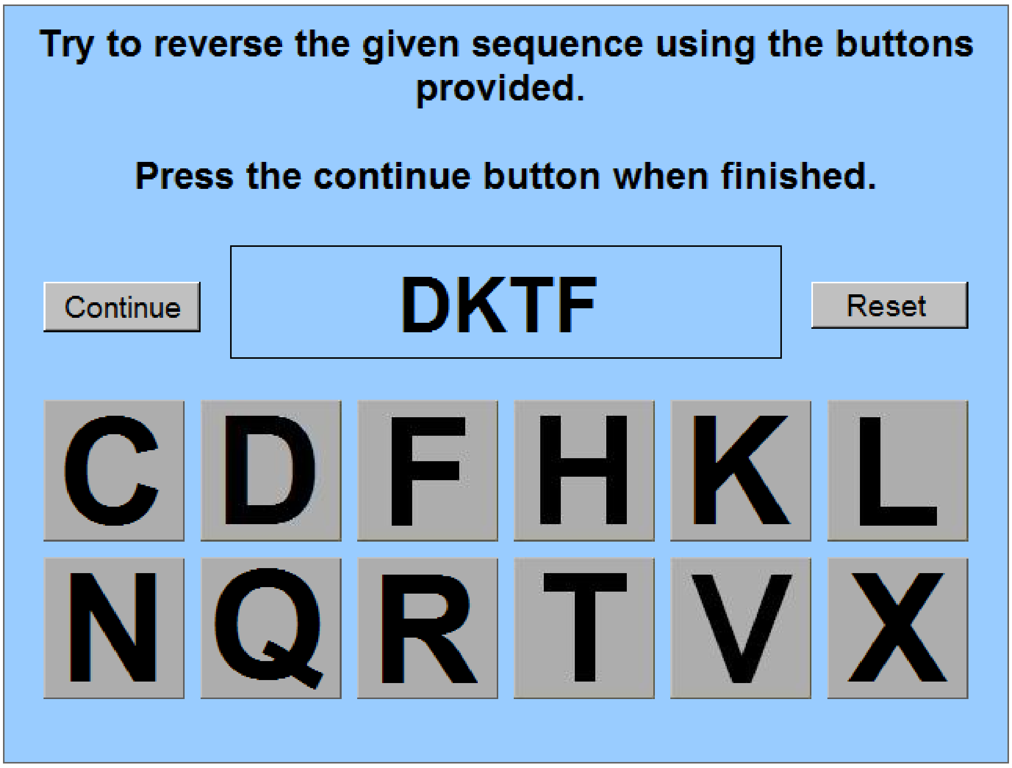

Figure 4: Screenshot of the test interface for the visual memory test with letters component of the application.

The candidate must use the letter marked buttons on the lower portion of the screen to re-enter, in reverse order, the sequence presented by the application. Once the candidate is finished, he/she clicks on the Continue button. If he/she makes a mistake, he/she clicks on the Reset button.

After each sequence, the application records the following information: The randomly generated sequence, the candidate entered sequence, the candidate's response time when entering the sequence and finally whether or not the candidate was correct. Although all this information is stored, no feedback is given to the candidate to avoid disrupting the flow of the test. Instead a brief summary is produced at the end of the last test.

The test proceeds in this fashion, generating a sequence of letters and asking the candidate to reverse it and re-enter it. The maximum sequence length, the number of trials per sequence length and the forward/reverse mode can all be altered by the test examiner beforehand using the administrator level in the application.

The functionality of this test is closest to how information is absorbed via reading, an extremely common learning tool and an almost universal practice in most cultures. As such, the visual memory test with letters can be viewed as representing one of the standard learning methods in the application.

4.3.2 Test 2: Visual Memory Test (Images)

The second memory test within the application is another visually based memory test. This time however, images are used as the stimulus instead of letters.

As previously explained, one of the design choices of this application was to ensure that each test had a homogeneous feel and could make use of the same format. With this in mind, the image based visual Working Memory test is functionally identical to the previous one except that it makes use of photos as the stimuli instead of letters.

As before, the candidate is presented with an introduction screen, this time showing the images that will be used during the test. The goal of this is to allow the candidate to familiarise themselves with the image based buttons beforehand so that they won't need to waste time searching for them during the test itself. When the candidate begins the test, a sequence of images will be displayed one by one and again the candidate must store this sequence in memory and re-enter it using the interface required (see Figure 5).

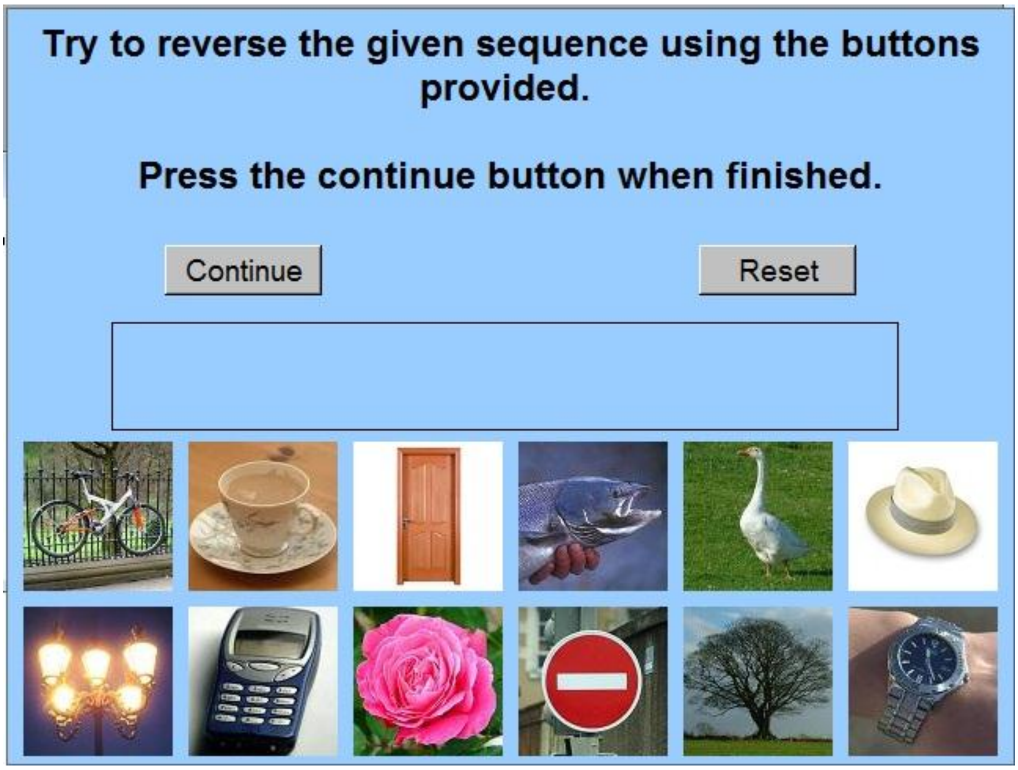

Figure 5: Screenshot of the test interface for the visual memory test with images component of the application.

The candidate must use the image marked buttons on the lower portion of the screen to re-enter, in reverse order, the sequence presented by the application. Once the candidate is finished, he/she clicks on the Continue button. If he/she makes a mistake, he/she clicks on the Reset button.

The decision on what images to use in this test was based on two main factors. Firstly, the images should be simple and universal. Objects were chosen that represented simple concepts that were easily recognisable such as fish, rather than more specific objects such as a bottle of brand X beer. Secondly, each object in turn was examined for any connections with the other objects in the pool. If any connections were found then that image had to be discarded. This is because a natural way to aid recall is to use the connection between objects to form partial sentences. For example, an early version of the test contained an image of a jacket and an image of a raindrop. It was not until later that the obvious connection of rain + jacket = raincoat was discovered. Because there was a connection there, candidates would find it easier to recall a sequence containing rain and coat than one that contained two unrelated objects such as rain and tree. In the end, the final images chosen for the test were as follows: A bike, a cup, a door, a fish, a goose, a hat, a light, a phone, a rose, a sign, a tree and a watch. As can be seen, an effort was also made to use objects from a variety of different settings, both living and non-living, indoors and outdoors, man-made and natural to further reduce the connection between them.

The goal of this test was to somewhat redress the balance between the visuospatial sketchpad and the phonological loop within the confines of the format. By using images, it forces the candidates to rely more on the visual aspect of their Working Memory. Obviously, the phonological loop will still come into play with any image that can be verbally identified and methods were considered to reduce this influence, but in the end it was decided that tampering with a candidate's natural methodology for learning in any way would be detrimental to the results obtained. This test also acts as a stand-in for image heavy methods of learning which are common in modern teaching, particularly in computer based systems.

4.3.3 Test 3: Audio Memory Test (Letters)

While the first two tests in the application focus mainly on visual based stimuli, the third test introduces audio stimuli into the mix. The purpose of this test is to see if there are any significant changes to a candidate’s results when forced to deal with a sequence of letters presented in audio form as opposed to visual form.

Because this test introduces a new element into the mix, further instruction screens are included to ensure the candidate is ready for the test. The first instruction screen asks the candidate to check that he/she has his/her speakers or earphones switched on and explains the concept of the test. In the second instruction screen, the candidate is once again presented with the interface buttons used to enter his/her responses, but in this case, the candidate can click on each button and hear that letter being spoken aloud. This allows the candidate to ensure that his/her earphones or speakers are working and at a comfortable volume before beginning the test.
When the candidate is ready, the test begins and proceeds in the same way as the

previous two. In this test, however, instead of a sequence of letters appearing on the screen, the screen remains blank to avoid distracting the candidate. While the screen remains blank, a voice calls out a sequence of letters that the candidate must then remember, reverse and input as in the previous tests. The sequence length and trials per sequence are the same as in the previous tests.

The theory behind this test is to shift the balance of the Working Memory load far away from the visual aspect and more in favour of the phonological loop. By removing the visual stimulus altogether, the only visual aspect of this test is the use of the input interface. Will candidates perform better relying solely on a single component or does visual stimulus provide a much needed boost to memory?

Similarly, just as the first test closely resembles reading as a method of absorbing information, the audio Working Memory test with letters most closely resembles actual speech. One of the most interesting possibilities of this application is to see whether candidates respond more favourably to speech or text as a method of absorbing information, and how much this varies from person to person. This is of particular interest to the area of computer based learning, where aural instruction is often quite limited. Many e-learning systems rely solely on text and images.

4.3.4 Test 4: Audio Memory Test (Images)

This test is the second of the audio based memory tests and instead of using spoken letters as the stimulus, it uses image describing words. In this test, the candidate is presented with vocalised words describing objects which he/she must then reverse and re-enter using the associated image based interface from the previous image based test.

The images used as the basis for this test are the same as those used in the previous image test. Although it was not mentioned before, another reason why those particular objects were chosen is that they each had names or labels that could be spoken as a single syllable. This was because, as previously mentioned in Chapter 2, the length of the words used could impact on the number that could be successfully stored. Multi syllable words are more difficult to store than single syllable words [Baddeley, Thomas & Buchanan, 1975]

As usual, before starting the test, the candidate is presented with an instruction screen. In this case, the purpose of the screen is to allow candidates to become familiar with the spoken label for each object by clicking on an image of that object. The ability to familiarise themselves with the stimuli content is particularly important in this case. Unlike the spoken letters where there is no confusion as to which letter is associated with the sound of 'R', some candidates might refer to an object by a different name than that used in the test. For example, an image of a wrist watch used in the test is referred to as 'watch', however it could just as easily be referred to as 'clock' or perhaps even 'time'. By allowing the candidate to see which specific word is linked with each image in advance of the test, it will hopefully minimise confusion and mistakes.

Once the candidate has signalled his/her readiness by clicking the start button, the test will proceed as normal. The screen will go blank and a voice will dictate a sequence of words relating to the images. After each sequence is completed, the candidate is returned to the image based interface and must reverse and re-enter the sequence as usual.

While the letter based tests of Working Memory explore how candidates respond to traditional methods of presenting information in the form of text and speech, the image based tests are more experimental. In each of the image based tests, the candidate is forced to rely on the visuospatial sketchpad as well as the phonological loop. This allows the tests to explore how these two components interact with each other and also whether the candidate's Working Memory capacity is impacted in any way when information is presented in a non-traditional or 'off-type' way. Again, this can play an important role in the way we view computer based learning and particularly the role of aural presentation within them.

4.3.5 Test 5: Audio-Visual Memory Test (Letters)

In the further spirit of experimentation a fifth and final test was added to the VAM application. In this case, the audio and visual memory tests with letters were combined into a single audio-visual test. Using the letter interface from the first test, the candidate must try and store, reverse and recall a sequence of letters presented in a pseudo-random mixture of both audio and visual form.

This test begins and proceeds exactly like the ones before it. The same interface is used as in both the previous letter based tests. The only difference is that, in this case, the stimuli that make up each sequence are presented either by flashing an image of the letter up on the screen or by having the letter be spoken aloud while the screen remains blank. This mixture of audio and visual stimuli requires that the candidate pay close attention.

There is approximately a fifty percent chance whether each individual letter is presented in an audio or visual fashion. While this approach means that any given sequence will possibly be presented in either a completely visual or aural fashion, as the sequences get longer it is expected that a good mix between the two will be attained. Because of this effect though, the application also records whether each letter in the sequence is presented in audio or visual form. This way, outliers can be spotted more easily.

The goal of this test is to examine how the candidate copes when presented with mixed input sequences. In each of the four previous tests only a single type of stimulus was presented at one time. The candidate took in information in a single format and processed it in their preferred way. This meant that the phonological loop and the visuospatial sketchpad were focused on the same task. In this test however, rather than working together, the phonological loop and the visuospatial sketchpad will be competing to absorb similar forms of information that are presented in a rapid fashion. By forcing these two components of Working Memory to compete rather than co-operate, candidate performance is expected to suffer. The results of this test may therefore show the risks of overloading the candidate and providing them with information presented in a non-harmonious fashion and may provide further insight to the design of useful computer based learning systems.

4.3.6 Finishing the Tests

Once the candidate has finished the final test, a brief summary of his/her results is displayed. The summary simply informs the candidate of his/her score in each of the five tests, what proportion of sequences they answered correctly. The candidate is also encouraged to check that his/her detailed results file has been correctly saved to the preferred location and he/she can view this file if they wish. Finally, the candidate is brought back to the start screen of the application which can then be closed down or left ready for the next candidate.

4.4 Extra Features

As well as the five Working Memory tests themselves, several other features were included in the application in order to improve its versatility. This section examines these extra features and what each one adds to the application.

As has been previously mentioned, one of the details recorded by the VAM application during the Working Memory tests was the candidate’s response time. Initially the purpose of this was to separate the time the candidate spent processing the information from the time they spent re-entering the sequences in each test. As an offshoot of this, several reaction time tests were included as part of the VAM. These included a simple stimulus/respond reaction test, a ‘do’ or ‘do not’ respond reaction test and a respond differently to different stimuli reaction test. Although detailed information was gathered on each candidate's reaction times, early testing showed there were too many variables involved to apply this data directly to a candidate's response time in the Working Memory tests. As such, the usefulness of the reaction tests has somewhat fallen by the wayside. They are still included as part of the VAM application though in case they can prove useful in some other role. The design and layout of the reaction tests themselves are discussed in more detail in Appendix A.

One of the primary goals of the VAM application is to explore and record data on various different aspects of Working Memory. A large amount of data is gathered over the course of the VAM. All five tests record the stimulus sequence, the candidate response sequence, whether the candidate is correct and the time it takes for him/her to respond to each individual sequence in each test. At the end of each test the VAM application uses these results to calculate further information including the average time taken per sequence and the percentage of sequences answered correctly by the candidate. This information is then formatted into readable result files and stored safely for further analysis.

As well as the data described above, the candidate is also required to enter other relevant information before beginning the tests. When the candidate first logs in to the system, he/she is asked to input his/her name, age, gender, occupation and whether he/she has previously used the application. This information is recorded so that future studies can explore the differences in Working Memory capacity with reference to factors such as gender or age.

The application stores three separate copies of the results file that are created for each candidate. One set of results is stored in a location preselected by the administrator so that all of the records can be kept together or at least in a common location on each machine. Another copy is stored in a more public location, the same folder the application is stored in. This is so that each candidate can have access to his/her results and can see how he/she fared in the tests without risking damaging the backup copies. Finally, as well as two text based versions of the results file, a more spreadsheet friendly summary of the results is saved as a .csv or comma spaced values file. When opened in Microsoft Excel or similar spreadsheet packages, the candidate's results are laid out in a format easily imported into many computer-based statistics packages. This saves much time and effort during the analysis phase and is one of the many benefits that computerised tests of Working Memory have over using traditional paper based methods.

Another benefit of computer based tests of Working Memory is the flexibility and level of configurability they allow. In this case, an administration level was built into the application to allow administrators to configure various aspects of the application.

The administration level of the application has four main set-up options. The first option allows the administrator to specify the storage location of the backup copy of the candidate's results. This was included so that the candidate can view his/her results without risking him/her altering or damaging the originals. If the administrator does not wish an additional copy of the results to be stored, this option can be turned off. When initially activated, the default storage location of "C:\" is used.

The second menu option contains the settings for the Working Memory tests and allows the administrator to change both the number of rounds used in each test as well as the number of trials given per round. The number of rounds refers to the maximum sequence length; each new round increases the maximum length by one. The number of trials refers to the number of sequences presented at each sequence length.

The trials menu also allows the option of staggering the round structure so that there are fewer trials in the early rounds and more in the later rounds. When the administrator opts for this staggered round option, the candidate is only presented with two sequences if the length of the sequence is fewer than four, but is presented with five sequences to re-enter if the length of the sequence is four or over. By default, this option is turned off.

Another important option here is the ability to alter the structure of the tests to change whether the candidate needs to re-enter the sequence in forward or reverse order. The reverse order option is the default setting. This option can be useful in studies that differentiate between the storage aspect of audio and visual Working Memory and the information processing aspect. It should be noted that since the reverse option loads more heavily on a candidate's Working Memory, it is advisable to set the maximum sequence length used in each test accordingly.

The memory test options also allow the administrator to change the display time of the visual stimuli used in the memory tests. Some people may find a quicker presentation easier to remember, while others may prefer more time to digest the information they are seeing or hearing. By allowing the administrator to alter the display time, the test could be used to investigate not only the capacity of Working Memory but the storage length as well.

The third option on the main menu allows the administrator to alter the settings of the reaction tests that are not used in this study.

The final option on the main menu allows the administrator to change the password needed to enter the set-up menu. The default password of 'ADMIN' is already in place, but by using this option, the administrator can alter it to something they can remember more easily. When the administrators menu is exited, all of these settings are saved to a set-up file in the same folder as the program and so only need to be set-up once before using the VAM application in a particular study.

The default values for the configurable variables in the VAM application are as follows: The default number of rounds (which is also the maximum sequence length) is set to six. The number of trials per round is set to four. The display time for the visual stimuli is set to three quarters of a second.

These default values were chosen through a combination of examining current testing methods and conducting some initial pre-tests on the VAM. The maximum sequence length was set at six based on previous studies into digit span. As described in Chapter 3, the average digit span of native English speakers tends to be about seven digits long. In this case, digit span refers to the number of digits that can be presented as a sequence and correctly recalled by a test subject. Many Working Memory test batteries that make use of digit span tests, such as Wechsler's Memory Scales, set the maximum number of rounds at eight. This means the longest digit sequence will be eight items long. Because the stimuli types used in the VAM are more complicated than simple digits and because in the case of the VAM, the sequence needs to be reversed by the test subject before they re-enter it, it was felt a sequence of eight items might be too complicated for test subjects to reverse and recall. Initial pre-testing showed this deduction to be accurate and that a sequence of six items provided a challenge without being too difficult and disheartening to the average candidate tested.

Similarly initial testing showed that four trials per sequence length, as used in Riding's IPI, allowed detailed data to be gathered on candidate performance while still allowing the tests to be completed in a relatively short amount of time. Using the above settings, candidates took, on average, twenty-five minutes to complete the VAM application. The more trials that were included per round, the longer the VAM took and the more subjects were likely to complain of test fatigue.

The visual stimulus display time of three-quarters of a second was chosen because initial tests showed that subjects felt most comfortable with this presentation time, with stimulus not being presented too fast, or too slowly. It should be noted however, that although these values are used as the default settings by the VAM, it is recommended that administrators use their own judgement and if possible, some form of preliminary testing before choosing what values will be applied to the VAM in their own particular studies.

A complete, usable version of the VAM application can be found on the CD attached to the back cover of this thesis. This version contains a copy of the VAM application containing all five tests; the visual memory test with letters, the visual memory test with images, the audio memory test with letters, the audio memory test with images and the audio/visual memory test with letters. This version of the VAM also contains all the extra features that have been discussed in the preceding sections including the reaction time tests. For further information on how to setup and run the VAM application contained on the CD, please refer to Appendix B.

4.5 Implementation of the VAM Application

The VAM application was developed and implemented using the Authorware system [Authorware, 2002]. Macromedia Authorware is a graphical programming language initially developed in 1987 by Dr Michael Allen as a tool for developing interactive learning systems. Authorware quickly became an extremely popular development tool, particularly in the growing e-learning sector and went through many versions and updates. Development on the Authorware system was eventually discontinued in late 2007 following a merger between Macromedia and Adobe.

Authorware was designed specifically to help develop interactive, multimedia enriched programs and employs a flowchart based design process. With conventional programming languages, a flowchart is simply a method of describing the flow and functionality of an application; in Authorware it is used to create the structure of the application itself.

In Authorware, much of the complex syntax of a text-based language is replaced by a series of easily manipulated icons. These icons are placed by the developer on the flowchart structure and controlled via easy-to-use dialogue boxes. The developer can use these icons to add and manipulate many different forms of media in their applications. There are also icons that can be used to monitor different forms of user input and use it to control the flow of the application through various interactive and navigational tools.

It is still necessary for the developer to visualise what each aspect of his/her application is required to do and how these requirements can be achieved, but unlike traditional text-based languages, the structure and functionality of each segment of an Authorware application can be easily compartmentalised throughout the design process. Each segment of the application can be designed and tested separately before including it in the core program.

Complementing its icon based design system; Authorware also uses a complete text-based scripting language with its own extensive set of built-in functions. While the icon system allows developers to focus on the appearance and flow of the application, the scripting language provides the developer with a greater level of control over the functionality of the application. With the scripting language, the developer has the ability to design and build complex new functions that the icon system does not already have, thus broadening the scope of an already impressive toolkit.

Because of its focus on multimedia and interactive applications, Authorware was a natural choice for implementing the VAM Application. As the development process continued several other extremely important benefits also became apparent.

Authorware proved extremely useful when it came to expanding and modifying the VAM application. Over the course of the development of the VAM several different approaches to testing Working Memory were considered as well as numerous different stimulus types and interface designs. While these approaches may have varied greatly in approach and appearance, the data gathering and analysis portions of the tests remained largely the same. By using Authorware, the core measurement components could be placed in a self-contained sub-tree of the application and remain untouched while the interface was radically redesigned. Authorware provided the opportunity to try out new approaches without having to start each new application from the beginning. This mechanism will also be beneficial to future versions of the VAM application, allowing new tests to be added, modified or removed as the VAM changes and grows, without disrupting the flow of the existing application.

The ability to easily separate components within the application was also extremely useful during the debugging process. The nature of the Authorware system allowed each segment of the application to be run and tested separately. The scripting language made it simple to pass variables through different components to look for errors. Temporary functions could be quickly created to test different aspects of the application and then removed just as quickly, without upsetting the overall structure of the application. The fluid nature of the Authorware design structure allowed modifying, debugging and testing the VAM application to be carried out methodically but efficiently.

4.6 The VAM Application Development Cycle

The development of the VAM application largely followed a simplified version of the waterfall model of software design. The waterfall model is so called because progress flows downwards through several distinct stages of development. It consists of five main stages, each of which must each be fully completed before moving on to the next one. The five stages, in order of completion are: Requirements, Design, Implementation, Validation and Deployment/Maintenance.

When developing the VAM application, a more iterative version of the waterfall model was used. This approach was greatly assisted by using Authorware as a development platform, as changes could be made to individual sections without affecting the overall application. In this case, the iterative approach meant establishing a development loop between the design, implementation and validation stages that allowed the VAM to be altered based on feedback from the implementation and pre-testing processes.

According to the waterfall model, the first stage of software design is the requirements analysis. This involves describing in detail the purpose and goals of an application; in other words, what the application is required to do. The design goals for the VAM application were decided upon after analysing many different methods of examining Working Memory. These goals were based on current research into the field of Working Memory and how that research could be pushed farther and be of use to a wider audience. These goals were also discussed in detail in section 4.2.

The second stage of the waterfall model is the design stage. In this stage, the requirements of the application are used as a basis for creating a detailed design model of the application itself. In other words, the requirements stage specifies what has to be achieved; the design stage focuses on how these goals are achieved. In the case of the VAM application this involved designing the structure and layout of the tests of Working Memory and was discussed in more detail in section 4.3.

As described in section 4.5, the design for the VAM application was implemented using Authorware as a development platform. As with the overall development cycle for the VAM, this stage was largely an iterative process. The different tests and aspects of the VAM were implemented one by one in Authorware and older sections were revised or improved as the application evolved. Around these tests a support structure was built that increased the versatility of the VAM and focused on interpreting and recording the data gathered from the tests. These extra features were discussed in detail in section 4.4.

Once a prototype version of the VAM application was completed it was time to begin testing it. The testing that occurred at this stage of the development cycle should not be confused with the testing carried out for the reliability and validity studies discussed in Chapter 5. Instead, these pre-tests largely involved looking for bugs and errors in the VAM application as well as gathering feedback on the tests themselves. Several friends and colleagues participated in this stage and their feedback was invaluable to the development of the VAM. This feedback was used to alter the design and layout of the VAM application which in turn caused the implementation process to change accordingly. This iterative approach to the design of the VAM application was crucial to its development and is hoped to continue once the VAM becomes a more widespread tool.

The final stage in the waterfall model of software design is the deployment and maintenance of the application. One of the goals of the VAM application is that it will be a useful tool for a wide range of researchers in a number of diverse fields. To achieve this, the VAM application must first be made available to other researchers as well as have its merits promoted through conferences and journal articles. This in turn will hopefully lead to future versions of the VAM itself as well as maintaining and improving the version that accompanies this thesis.

The VAM application is a work in progress. Although a complete version of the VAM was developed for this thesis, there is still much room for growth and expansion. The future of the VAM application is discussed in more detail in Chapter 9, along with how this future may be realised.

4.7 Review

In this chapter, the design and implementation of the VAM (Visual & Audio Memory) application were discussed. Originally based on the popular digit span test, the VAM application has grown to focus on visuospatial and phonological Working Memory and the similarities and differences between them.

The application consists of five separate tests: the 'visual test with letters' and the 'visual test with images' focus on the visual portion of Working Memory; the 'audio test with letters' and the 'audio test with images' focus on the phonological portion. Finally the audio-visual test with letters explores how these areas interact when both portions of Working Memory are in demand simultaneously.

The results of these tests are gathered into highly detailed results files covering each individual sequence in each test, whether the candidate answered correctly and how long it took them. The VAM application is also highly configurable, allowing the administrator to control everything from the display time of the stimuli, the length and the difficulty of the sequences presented and whether the stimulus sequence needs to be re-entered as given, or reversed.

As can be seen, the VAM application provides a versatile tool for exploring audio and visual Working Memory. It can be used as a tool to study capacity, response times, manipulation of information and the different ways that information is stored in Working Memory. More than this though, the VAM application's versatility opens it up for use in a variety of fields associated with Working Memory.

Before any of this occurs though, the VAM needs to prove itself a viable application. In the next chapter, the testing of the VAM application will be discussed. How it was tested, what was tested and the results of the testing will all be described along with some interesting exploratory analysis on the nature of audio and visual Working Memory.

Chapter 5: Testing and Results

5.1 Introduction

After the VAM application was implemented, a large-scale testing process was carried out. There were several goals for this testing process: first, to prove that the VAM application provided a reliable test of audio and visual Working Memory. Second, to validate the VAM application against another popular test of Working Memory, Riding's IPI. Third, to validate the VAM application against Raven's Progressive Matrices a popular test of fluid intelligence that has been linked to Working Memory in previous studies. Fourth, to explore the potential of the VAM application by further analysing the results generated.

Before providing the results of these testing sessions however, the structure and methodology of the testing process will be discussed.

5.2 Testing the Application

Once the VAM application was designed and built, the next stage of the development process was to examine its reliability, validity and functionality. To prove itself a reliable test, the application must provide consistent results for each candidate every time he/she undertakes the tests. In other words, the application must provide statistically similar results for each candidate across more than one testing session.

In order to prove itself a valid test of Working Memory, it is advisable to compare the results of the VAM application against another already recognised test of Working Memory. In this case Riding's IPI (Information Processing Index) [Riding, 2000] was chosen, mainly due to the lack of availability of other suitable tests. The problem of locating a suitable benchmark test for the VAM is discussed in more detail in Chapter 9. Riding's IPI was discussed in greater detail back in Chapter 3.

The results of the VAM were also compared with those of Raven's Progressive Matrices [Raven, Raven & Court, 1998], a test of fluid intelligence that has been shown in previous studies to correlate well with the results of various measures of Working Memory. Raven's Matrices and the link between fluid intelligence and Working Memory are discussed in greater detail in Chapter 7.

A large group of candidates was required to gain sufficient data for this analysis. It was therefore decided to organise multiple testing sessions over the course of several weeks. In this way a large enough sample size could be ensured.

5.2.1 Methodology

To prove that the VAM application provides a reliable test of Working Memory, it is necessary for a group of candidates to successfully complete the VAM on two separate occasions and for each candidate's results in the initial testing session to be compared with his/her results from the later re-testing session.

In Chapter 3, it was noted that using a test of Working Memory more than once within a short span of time can bias a candidate's results due to his/her familiarity with the test. This can be an issue particularly with traditional testing methods which often use pre-set sequences to test Working Memory capacity. If the candidate had already been tested with these sequences, it is possible that he/she would still retain some knowledge of them the second time around. This would give the candidate an unfair advantage in the test and could allow him/her to achieve artificially high results.

On the other hand, leaving too large a gap between the initial test and the later re-test sessions allow time for external changes in the candidate to occur which could also impact his/her results. For example, if a candidate was suffering from a medical condition that causes mental deterioration, a six month gap between the initial testing session and the later re-testing session could cause the candidate to produce significantly different results that are not due to a fault in the application itself.

There are no set guidelines for choosing a waiting period between the initial test and later re-test sessions. Different studies often leave different intervals between testing sessions that range from as little as ten minutes to more than a month [Marx et al, 2003]. In this instance, a gap of four weeks between the initial testing session and the later re-testing session was decided on. This was chosen because it gave a long enough gap to limit the effects of familiarity and practice on candidate performance, while also limiting the risk of changes in the Working Memory capacity of the candidate themselves. This gap also allowed enough time to re-evaluate the testing process itself so that any problems that occurred during the initial testing session could be rectified or guarded against in the re-testing session.

When testing for validity, the goal is to compare the results obtained by the VAM application against those obtained by a more recognised test of Working Memory. In order to keep external factors to a minimum, ideally both tests should be completed by candidates in the same session. Similarly, when comparing the VAM to other non-Working Memory tests, these tests should also be completed in the same session as the VAM. Of course, completing a number of tests in one sitting can cause problems itself, and this is dealt with in more detail in the section on bias below.

Because the VAM application and Riding's IPI are both independent computer based tests, the only limiting factor on the number of candidates tested at once was the number of computers available. Thankfully, because the research was carried out in a University, there was an abundance of computer laboratories available for the testing process.

In the initial testing session a group of candidates were asked to complete the VAM application, Raven's Progressive Matrices and Riding's IPI one after the other. Then a gap of four weeks was left as required by the reliability analysis. After the four week gap, the candidates returned to complete the same set of tests again. While some of these tests were not required the second time around as part of the analysis itself, every effort was made to ensure that the testing conditions in the re-testing session were exactly the same as in the initial testing session in order to limit external factors affecting results.

In order to accommodate a large number of candidates being tested at once while still allowing them to be closely monitored, both the initial testing session and the later re-testing session were further broken down into separate nightly sessions. This divide was also required because the available computer labs had a limited number of working computers in each room. Each lab could hold approximately twenty candidates. The initial testing session took place over three evenings, with a different group of candidates being tested each evening. Similarly, after the four week gap, the re-testing session was also split up to take place over three nights.

Three separate computer labs were used each night during the test and re-test sessions. The test candidates on each night were divided into sub-groups and assigned a lab to work in. Each lab had a separate administrator observing the candidates. This accommodated a relatively large sample size while ensuring that each candidate could be watched closely and no cheating occurred. Once again this organised approach was employed in order to limit the effect of external factors on the results of the tests. Further details on the structure of each session are included in section 5.3 below.

5.2.2 Sample Selection

The sample chosen for the testing sessions came from the student body of the Computer Science faculty at Trinity College Dublin. This population was chosen because it provided a mix of healthy, intelligent males and females aged between eighteen and twenty four years. The students also have a working knowledge of computer use, so no time would be wasted training them in the basic skills required to start up and use the computers and to open the test applications.

The testing sessions were advertised by sending e-mails to all the undergraduate class lists in the faculty. Students were offered a reasonable amount of money to participate in two testing sessions each. Only the basic nature of the research was explained to the students so as not to taint his/her view of the tests. Candidates were then selected on a first come, first served basis until there were enough people to make up a sample group.

5.2.3 Data Collection and Collation

Because the main applications being tested were computer based, for the most part data collection was a simple matter. Upon completing the application, each candidate's results were written to an external disc which was then collected at the end of the session. Each candidate's results were stored as a text file and as a spreadsheet. The text file contained a detailed description of his/her results. It also provided a summary of the overall results at the end of each test. The spreadsheet provided less detailed information but in a format easier to import into a statistical package.

Collating the data was also done via computer. Each candidate's results were uploaded, one at a time, to a computer where another specially created application added the details to an overall spreadsheet which contained the relevant information for each candidate in each section. This reduced the risk of errors due to incorrect data entry. It also allowed each set of results to be processed and standardised into an overall spreadsheet in a relatively fast time. There was however a slight downside to the automation process.

The reliance on computers in the testing process, along with the inexperience of the researcher in conducting large scale tests, caused several sets of results to be lost due to malfunctioning discs or other computer errors. Although there were few result sheets lost in each session, if a candidate was missing results for either of his/her two sessions they were useless to the reliability study. This problem is discussed in more detail in Chapter 9.

Apart from these few invalid records, the testing sessions were successful. Candidate results were gathered, collated and processed automatically and analysed using the computer-based statistical package Data Desk version 6. The results, analysis and conclusions drawn will be discussed later in this chapter.

Due to the paper and pencil based nature of Raven's Progressive Matrices, the results of these tests had to be scored and collated by hand. This was a very time consuming process. This set of results was processed by Dr Adrian Parkinson who also wished to use some of the data gathered in his own research. The results from this test were collated in a spreadsheet format, similar to the computer based tests, in order to provide a consistent repository when analysing results. The upside of this process is that no results were lost due to malfunction, however, the process was extremely slow and as always with manual data gathering, the chance for human error crept in.

5.2.4 Bias and considerations

There are several issues to note regarding the testing process which may have influenced candidates' results. Before the results of the testing sessions are presented, these issues should be discussed.

One of the main considerations in the analysis of this application was the length of time it took to complete the VAM application. The VAM application is a very complex measure of Working Memory. It contains five separate tests that need to be completed and early pre-testing sessions showed that it took candidates an average of twenty five minutes to complete while on the default settings. During this time constant focus and concentration is required by the candidate. While completing the VAM application, candidates may have grown weary and by the end may not have been performing at their best. This may have caused a slight decrease in performance by the last test in the VAM.

Similarly, candidates had to complete other tests in the same session as the VAM application. These included Riding's IPI and Raven's Progressive Matrices. Every effort was made to ensure the candidates were not overwhelmed by having to complete all these tests in one sitting. This included taking regular breaks and advising the candidates to complete each test in their own time. Nevertheless the concentration required for this level of testing may have had a slight impact on the overall results.

Another issue to recognise are the differences between the VAM application and Riding's IPI itself. While both are measures of Working Memory, the VAM provides a much more detailed analysis than the IPI. Because the results of these tests are directly compared as part of the validation process for the VAM, it is best to be aware that the VAM requires significantly more time and focus than Riding's IPI. As explained above, on the default settings, the VAM application takes approximately twenty-five minutes to complete, whereas the IPI takes approximately five minutes.

Another source of possible bias may have arisen during the phonological tests of Working Memory. Each candidate was provided with a set of head-phones for use in the audio tests and asked to use a low volume setting so as not to disturb others. Nonetheless, it is possible that even though every precaution was taken to ensure minimal noise levels, some candidates may have been distracted.

The above considerations are worth mentioning. Even though it is likely the impact they had on results was minimal, it is best to be aware of its existence before the results are analysed and presented.

5.3 Results

The initial testing session took place over three nights from the 5th of February 2007 to 7th of February 2007. Over the three nights, 110 candidates were tested with 36 on the first two nights and 37 on the third. On each night, the candidates were further divided into three separate groups and each group was assigned to a separate computer lab and overseen by a separate administrator. Each candidate was required to complete the VAM application, Riding's IPI and Raven's Progressive Matrices. During this session they also had to complete several other tests not related to this research. Candidates were allowed several breaks during this time so as not to tire them out too much. The results of each candidate in each test were collected, although several sets of results were lost due to unforeseen problems. This is discussed in more detail in Chapter 9.

After a gap of four weeks, the re-test sessions occurred on the nights of the 5th to the 7th of March 2007. Once again, there were supposed to be 110 candidates tested in total, but unfortunately, not every candidate returned for the follow-up testing session. Each candidate that did return had to once again complete the VAM application, Riding's IPI and Raven's Progressive Matrices as well as several other tests not relevant to this research. Every effort was made to ensure conditions in the re-test session were as close as possible to the initial testing session. Once again, several sets of results were lost due to unforeseen problems.

After both the test and re-test sessions were complete, the results were collated and analysed for use in the studies below. Out of the initial 110 candidates selected; 99 complete sets of results were available for analysis into the reliability of the VAM application, 77 complete sets of results were available for validating the VAM against

Riding's IPI and 92 complete sets of results were available for validating the VAM against Raven's Progressive Matrices.

All the statistical analysis carried out in the following sections was completed using Data Desk version 6 [Data Desk, 2001]. Spreadsheets containing the data that were used in the statistical analyses are also included on the CD attached to the back cover of this thesis.

5.3.1 Study 1: Reliability of the VAM Application

Showing that the VAM application provides a reliable test of Working Memory is an essential aspect of this study. As discussed back in Chapter 3, there are few widely recognised computerised tests of Working Memory currently available. Therefore, if proven reliable, this application could fill a much needed role in the study of Working Memory and act as a benchmark for future computerised tests in the area.

There is another reason why this application must be proved reliable. During the testing sessions a lot of data was gathered on Working Memory. As an addendum to this study, this data will be used do draw some initial conclusions on the nature of audio and visual Working Memory. The application must be proved reliable in order for these conclusions to have merit.

In order to show that the VAM application provides a reliable test of Working Memory, statistical analysis was carried out on the results of the testing sessions. The overall result of each candidate from testing session one was compared with the result he/she achieved in testing session two. The overall result refers to the percentage of correct answers the candidate obtained in each of the five tests combined. This can be considered to be a rough measure of their overall Working Memory capacity taking both audio and visual stimuli into account. An analysis of the results of each individual test will be discussed later.

5.3.1.1 Analysis of Results

As can be seen in Table 1 below, the mean percentage correct result achieved in session one is very similar to that achieved in session two. However, in order to determine if the test is truly reliable, the difference in each candidate's results from the initial test and the later retest must be examined. This is done by analysing the correlation between the two sets of results.

Variable	n	Mean	Median	StDev
VAM Test	99	0.694	0.6923	0.104
VAM Retest	99	0.688	0.69998	0.109

Table 1: Summary of candidates' overall results in the VAM test and retest

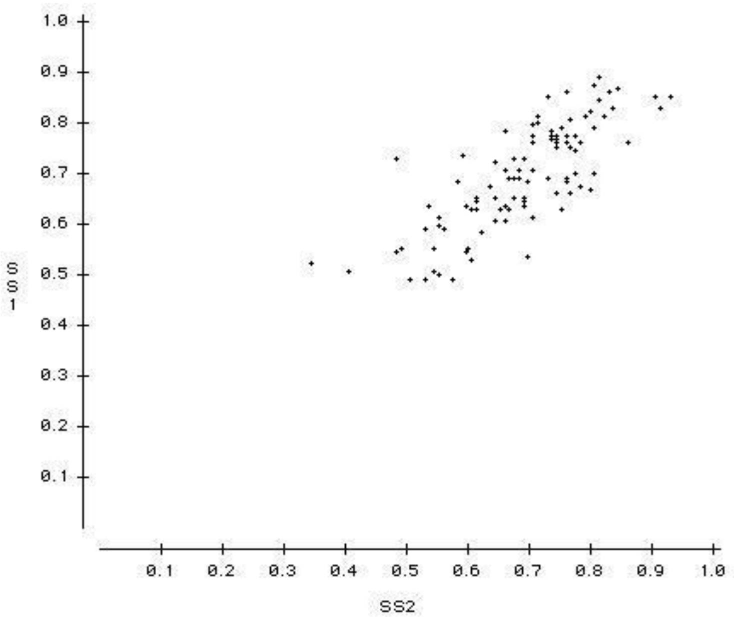

Figure 6: Scatterplot of candidates' overall results in the VAM test and the VAM retest

Correlation produces a single result which describes the strength of the relationship between two variables. The value of the correlation (commonly referred to as **r**) will be between -1 and +1. The further away the value is from zero (whether positive or negative) the stronger the relationship between the two variables [Altman, 1991]. In this case, the higher the value of **r**, the more reliable the application is. Calculating the correlation between the two sets of results yields a value of **r** = 0.789 (a 78.9% correlation).

The reliability of the VAM application can also be measured using a 99% confidence interval. A 99% confidence interval means that there is a 99% chance that the difference between two variables is within the bounds given [Altman, 1991]. In this case, if the VAM produces statistically similar results in both sessions, the mean difference between the results of the two sessions should be ranged closely around zero. A 99% confidence interval of the results of session one minus the results of session two yields (-0.0128, 0.0239) indicating that the mean difference is very close to zero.

Variable	**Mean Diff**	**r**	**99% C.I.**	**n**
Test - Retest	0.0055	0.789	(-0.0128, 0.0239)	99

Table 2: Correlation between candidates' overall results in the VAM test and VAM retest, backed up by a 99% confidence interval

The evidence provided by the test-retest reliability of the VAM is extremely encouraging. Kline suggests a test-retest correlation of 0.8 [Kline, 2000] with a minimum of 0.70 in order to prove a test reliable. A very high level of correlation **r** = 0.789, indicates that the VAM provides consistent results across multiple testing sessions, even with four week gap between sessions. Similarly, the 99% confidence interval with bounds of (-0.0128, 0.0239) demonstrates that in 99% of cases any difference in results is extremely minor and can be safely attributed to one of the many other factors involved that may affect results. Because of this, it is concluded that the VAM is a reliable application.

5.3.2 Study 2: Validity of the VAM Application

In order validate the VAM as a test of Working Memory it needed to be compared to an already established test. In this case Richard Riding's Information Processing

Index was chosen as one of the few available computer based tests of Working Memory that was scientifically tested [Riding, 2000] and that could be used in a large scale testing operation without the need for one-to-one supervision.

Riding's IPI is described in more detail in Chapter 3, but for convenience, here is a short review. The IPI consists of a number of rounds. Each round begins with a train consisting of a number of different coloured carriages. The number of carriages increases as the test progresses. The candidate is asked to move the train into a station using the space bar on the computer keyboard. Once the train is hidden in the station, it reappears on the other side, one carriage at a time. The candidate must then decide if each carriage in turn is the same colour as it was when it entered the station or if it has changed colour. There are a number of advantages as well as disadvantages to Riding's IPI, also discussed in Chapter 3, but it was one of the few tests available that matched up well with the VAM in terms of functionality and independence of use. The problem of locating a benchmark test for the validation process in discussed in more detail in Chapter 9.

5.3.2.1 Analysis of Results

In order to show that the VAM application provides a valid test of Working Memory using the IPI as a benchmark, statistical analysis was carried out on the results of the testing sessions. The overall results of each candidate in the VAM application were compared with their overall results in the IPI.

Variable	n	Mean	Median	StDev
VAM	77	0.708	0.7033	0.088
IPI	77	0.970	0.9762	0.0254

Table 3: Summary of candidates' overall results in the VAM and the IPI

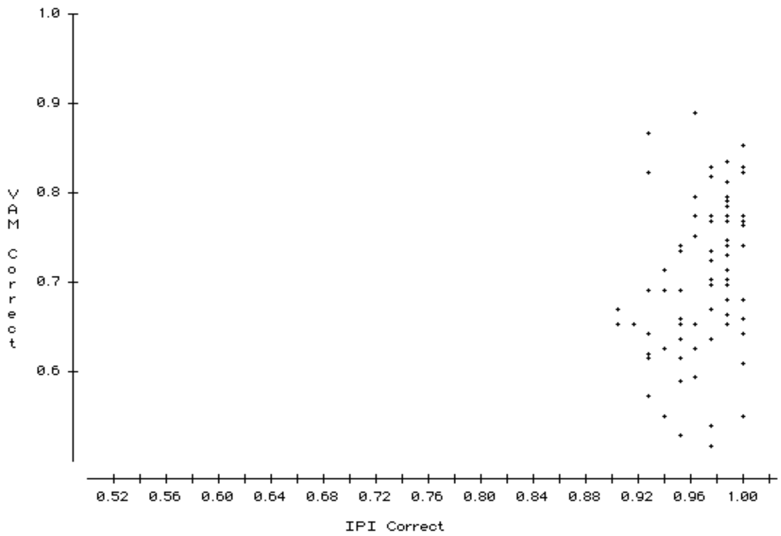

Figure 7: Scatterplot of candidates' overall result in the VAM and the IPI

Calculating the correlation between the results of the two tests yields a value of **r** = 0.327. As with the reliability studies, a 99% confidence interval was also carried out to see if there was a statistical difference in results between the VAM and the IPI. The bounds of the 99% were (0.2339, 0.2886)

Variable	**Mean Diff**	**r**	**99% C.I.**	**n**
IPI - VAM	0.262	0.327	(0.2339, 0.2886)	77

Table 4: Correlation between candidates' overall results in the VAM and the IPI, backed up by a 99% confidence interval

The first thing to notice here is that there is a definite correlation between the results of the VAM and the IPI. The correlation level is smaller than could be hoped for though. A higher correlation value would be better for validating the VAM application, but further examination of the results can provide more insight into the matter.

The main thing to notice is the large ceiling effect on the results of the IPI. While the mean result of the VAM is approximately 70% correct, the mean result of the IPI is

97%. A frequency breakdown of the different results achieved shows that over 16.88% (or one in every six) candidates scored the maximum possible score on the IPI, compared with 0% on the VAM. This limiting effect can have a significant impact on the results. This suggests that the IPI may have been too simple a test to use a validation tool and unfortunately, unlike the VAM, the difficulty levels on the IPI are not configurable.

It should be noted that the default settings of the VAM application are similar to those of the IPI. Both tests consist of a maximum sequence length of six objects with four sequences presented in each round. The difference between the IPI and the VAM is that the stimuli used in the VAM application (sequences of letters, images and sounds) are much more varied and complicated than those used in the IPI (sequences of different coloured carriages).

The structure of the VAM is also more complicated than the IPI. The VAM requires the manipulation of several objects on screen using a mouse and results are judged based on sequences of objects recalled and re-entered correctly. The IPI, on the other hand, only requires the user to make yes or no choices by pressing one of two buttons on the keyboard and results are judged based on individual objects rather than sequences. This means that even if a candidate does not recall an answer, he/she has a fifty percent chance of guessing it correctly anyway. Because of this it is difficult to equate the IPI to the VAM in terms of challenge. Pre-testing of the VAM application indicated that the default settings chosen presented a suitable level of difficulty for young adults similar to those that made up the testing sample. Riding claims the IPI is similarly suitable for anyone aged nine and up. While it is possible that altering the settings of the VAM application to make it easier would bring it better in line with the IPI in terms of challenge, the result would just create a similar ceiling effect on the VAM as already occurred on the IPI.

Another factor to consider, as noted back in Chapter 3, is the relatively small amount of data regarding the reliability of the IPI. One study, (**n** = 51) produced a test re-test reliability of r = 0.352 [Parkinson et al, 2002]. If the IPI does not produce reliable results it could easily impact the validation process here. With this in mind, it was decided to examine the reliability of the IPI on a larger scale. The results of this study are discussed later.

Thirdly, when Riding was validating the IPI himself [Riding, 2000], he reported a correlation between IPI and the reading span Working Memory test proposed by Daneman & Carpenter [1980] of **r** = 0.37. Riding's validation result was not much higher than the result achieved here. Presumably Riding used the Daneman & Carpenter span test because of the lack of other computer based tests of Working Memory available to use as a benchmark. The design of Daneman & Carpenter’s reading span test was discussed in greater detail in Chapter 3.

While the results of the validation testing are lower than hoped for, there is still a demonstrable correlation between the results of the IPI and the results of the VAM. Hopefully further studies and further improvements to the VAM can provide more definitive results in the future.

5.3.3 Study 3: The VAM and Raven’s Progressive Matrices

In addition to comparing the VAM to the IPI test, the VAM was also compared to Raven’s Progressive Matrices for validation purposes. The connection between Working Memory and Raven’s Progressive Matrices will be discussed in more detail in Chapter 7, but in summary:

Raven’s Matrices [Raven, Raven & Court, 1989] are widely regarding as an accurate measurement of Spearman’s '***g***’ [1904]. Spearman’s '***g***’ initially referred to a measure of the 'g factor', an attempt to link the underlying elements in the results of different tests of cognitive ability. Spearman referred to '**g**' as a 'general fund of mental energy' [Spearman, 1914] and it is often wrongly equated with general intelligence. Instead some researchers assert that '**g**' is an abstract concept implied by the common variance among cognitive ability tests [Jensen 1998], [Ackerman, Beier, Boyle, 2005].

Many studies in the past have demonstrated a correlation between tests of Working Memory and Raven's Matrices [Engle et al., 1999], [Conway et al., 2002], [Kane et al., 2004], [Unsworth & Engle, 2005] and so it was felt that they would be a suitable addition to the VAM's validation process.

Raven's Matrices consists of thirty-six 3x3 grids containing geometric patterns. Each grid has one pattern missing. Below each grid is a set of eight patterns, one which is the missing piece from the grid above it. Candidates are allowed thirty minutes to complete as many of these grids as possible and their score is the total number completed successfully.

5.3.3.1 Analysis of Results

In order to see if there is a connection between the VAM application and Raven's Matrices, statistical analysis was carried out on the results of both tests. The overall results of each candidate in the VAM application were compared with his/her overall results in Raven's Matrices.

Variable	n	Mean	Median	StDev
VAM	92	0.6976	0.7033	0.102
RPM	92	29.326	0.9762	4.2713

Table 5: Summary of candidates' overall results in the VAM and RPM

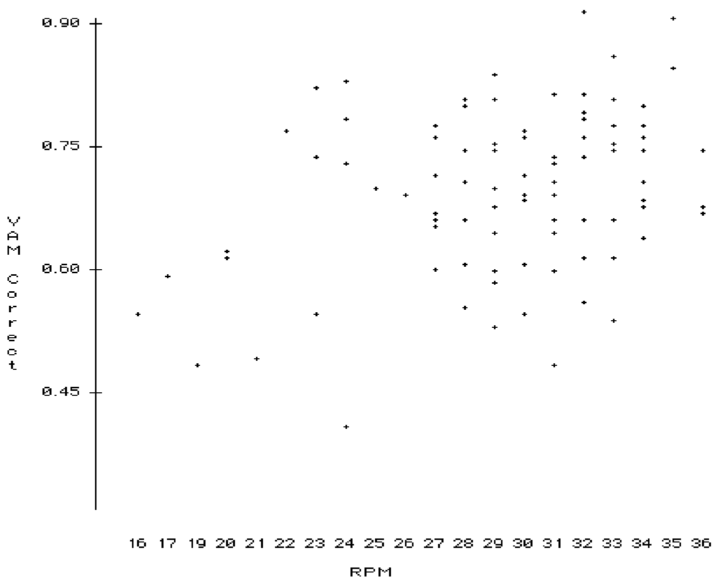

Figure 8: Scatterplot of candidates' overall result in the VAM and RPM

Calculating the correlation between the two sets of results yields a value of **r** = 0.358 with **n** = 92. In this instance a 99% confidence interval was not carried out since the two tests, the VAM application and Raven's matrices, are marked on different scales so a difference in the mean result values of each is not significant.

Variable	**r**	**n**
RPM - VAM	0.358	92

Table 6: Correlation between candidates' overall results in the VAM and RPM

Once again there is a correlation between the two results indicating a link between the VAM application and Raven's Matrices and hence linking the VAM application to fluid intelligence. In this instance the value for **r** is to be expected since neither '*g*' nor fluid intelligence can be easily attributed to a single factor.

This **r** value also lines up extremely well with similar studies in the area of Working Memory and fluid intelligence using Raven's matrices [Engle et al., 1999], [Conway et al., 2002], [Kane et al., 2004], [Unsworth & Engle, 2005] where an average correlation of **r** = 0.30 was found between measures of Working Memory and Raven's Matrices. Again, this is a very positive result and indicates that the VAM application fits in well with other tests of Working Memory when it comes to predicting Spearman's '***g***' and hence when it comes to examining intelligence.

The above sections outline the main points of the VAM's testing process and so far have produced very encouraging results. However, there is still more information that can be gleaned from these studies. Later in the chapter, some of the other relevant information produced by the VAM testing sessions will be analysed. These results will hopefully allow us learn more about the VAM application itself and provide some additional information on the nature of audio and visual Working Memory. Before this though, the results of the study into the reliability of Riding's IPI are presented.

5.3.4 Study 4: Reliability of Riding's IPI Application

In order to check the reliability of Riding's IPI, a test re-test approach was taken, just as was done for the VAM application. Candidates were required to complete the IPI on two separate occasions, with a four week gap in between attempts. A summary of the results of two testing sessions is given below.

It should be noted that because of the extremely short time needed to complete Riding's IPI (approximately 5 minutes) it was easy to solicit extra candidates for this reliability analysis. On top of the candidates who completed the IPI during the initial testing sessions, several other candidates were asked to complete this test during an unrelated study focusing on reliability in tests of cognitive styles.

These additional testing sessions were carried out under the direct supervision of the researcher and conformed to the standards set for the initial testing sessions. As such, including approximately 90 candidates from the initial testing sessions, a total of 163 people participated in this reliability study.

5.3.4.1 Analysis of Results

As can be seen in Table 7 below, the mean percentage correct result achieved in session one is very similar to that achieved in session two, however, the standard deviation in both cases is extremely high.

Variable	n	Mean	Median	StDev
IPI Test	163	86.4755	89.3	11.8901
IPI Retest	163	87.0706	91.7	16.0786

Table 7: Summary of candidates' overall results in the IPI test and retest

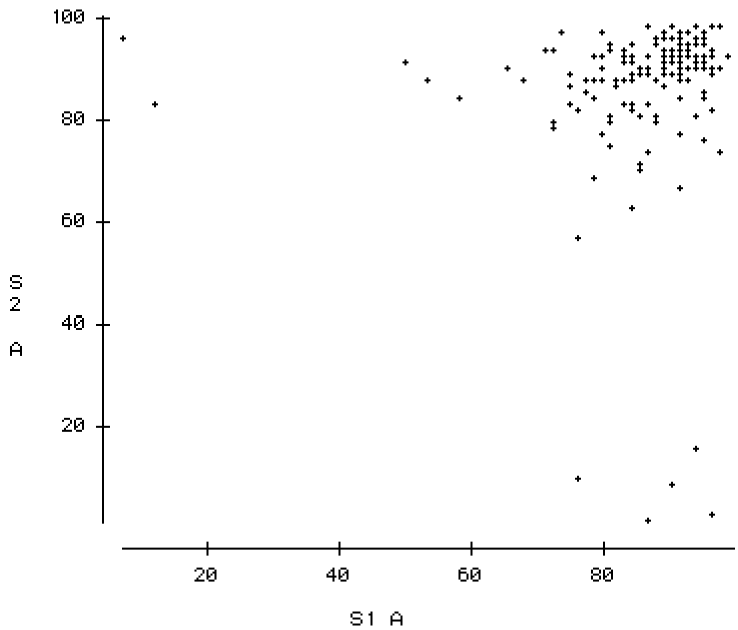

Figure 9: Scatterplot of candidates' overall results in the IPI test and the IPI retest

Calculating the correlation between the two sets of results yields a value of **r** = 0.044 (a 4.4% correlation). This is an extremely low correlation between the two sets of results. As can be seen from the diagram above though, there are several obvious outliers that could be influencing this result.

In the interest of fairness, the correlations were therefore recalculated with these outliers removed to see if it would improve the situation. The only outliers removed, were ones where the difference between the results of the two sessions was over 60% and one session had a result of under 20% correct. It was felt that these values were unusual enough to indicate that some other problem may have interfered during the testing process.

Variable	n	Mean	Median	StDev
IPI Test	156	87.3878	89.3	8.28
IPI Retest	156	89.5891	91.7	7.58

Table 8: Summary of candidates' overall results in the IPI test and retest with outliers removed

Recalculating the correlation with these updated results led to a new test re-test reliability of **r** = 0.246 or 24.6%. As with the VAM application, a 99% confidence interval was also calculated in order to see if there was a statistical difference between the mean results of the two sessions. The bounds of the 99% confidence interval were (0.1649, 4.2376). Though a better result than before, this reliability value is still far lower than is recommended for a cognitive test. Similarly the mean difference between the two sets of results and the 99% confidence interval indicates that candidates tended to perform better the second time they used the application, suggesting a learning effect inherent in the test.

Variable	Mean Diff	r	99% C.I.	n
IPI S1 – IPI S2	-2.2013	0.246	(0.1649, 4.2376)	156

Table 9: Correlation between candidates' overall results in the IPI test and retest, backed up by a 99% confidence interval

Once again, the ceiling effect of the test likely impacted the results obtained. This indicates that the test itself might be too simple for the candidates using it, though Riding claims the IPI is suitable for everyone from the ages of nine upwards [Riding, 2000]. The results of this reliability study also broadly agree with the results found in a smaller reliability study carried out in 2002 by Parkinson et al which established a rest re-test reliability of **r** = 0.352 with n = 51.

These results indicate that Riding's IPI does not produce a reliable estimate of Working Memory and as such may explain the level of correlation between the results of the VAM and the results of the IPI. In future validity studies involving the VAM application, perhaps a different computer based test of Working Memory can be substituted instead.

5.3.5 Further Studies with the VAM

5.3.5.1 Reliability Results of the Individual Tests

While the overall results of the VAM application have proven it to be a reliable measure of Working Memory, it may be of interest to examine the differences in results in each of the five component tests of the VAM. Each test is designed to pose a separate challenge to audio and/or visual Working Memory and so examining how they perform alone might be of use. To save space, a summary table of the results for each test are given.

Test 1: Visual memory with Letters

Analysis of the reliability results of Test 1 yields a 66.5% correlation and a 99% Confidence Interval of (-0.0214, 0.0260). There is a noticeable drop in the correlation value between the overall results compared to the results of each individual test. Despite this, a correlation of 66.5% is still very respectable and the 99% confidence interval is still tightly based around zero indicating a very small mean difference in any results.

Variable	Mean Diff	r	99% C.I.	n
T1: Test - Retest	0.002	0.665	(-0.0214, 0.0260)	99

Table 10: Correlation between candidates' overall results in Test 1 test and retest

Test 2: Visual memory with Images

Analysis of the results of Test 2 yields a 53% correlation and a 99% Confidence Interval of (-0.0275, 0.047). Again there is a drop in the correlation value but the confidence interval is still based closely around zero.

Variable	Mean Diff	r	99% C.I.	n
T2: Test - Retest	0.0097	0.530	(-0.0275, 0.047)	99

Table 11: Correlation between candidates' overall results in Test 2 test and retest

Test 3: Audio memory with Letters

Analysis of the results of Test 3 yields a 49% correlation and a 99% Confidence Interval of (-0.0119, 0.0608). Test 3 has the worst correlation value and the highest range of any of the confidence intervals.

Variable	Mean Diff	r	99% C.I.	n
T3: Test - Retest	0.009	0.490	(-0.0119, 0.0608)	99

Table 12: Correlation between candidates' overall results in Test 3 test and retest

While the results here are somewhat disappointing, there were several problems with the audio segments (as mentioned earlier in this chapter and discussed in more detail in Chapter 9) which may have had a greater impact on the results than previously thought.

Test 4: Audio memory with Images

Analysis of the results of Test 4 yields a 64.3% correlation and a 99% Confidence Interval of (-0.0484, 0.0236). By the time the candidates had started this test, they had likely settled into the audio aspect of the application and the higher correlation may reflect this.

Variable	Mean Diff	r	99% C.I.	n
T4: Test - Retest	-0.007	0.643	(-0.0484, 0.0236)	99

Table 13: Correlation between candidates' overall results in Test 4 test and retest

Test 5: Audio & Visual memory with Letters

Analysis of the results of Test 5 yields a 53.8% correlation and a 99% Confidence Interval of (-0.0306, 0.0376). Again, this is an acceptable result, if lower than hoped for.

Variable	Mean Diff	r	99% C.I.	n
T5: Test - Retest	0.0035	0.538	(-0.0306, 0.0376)	99

Table 14: Correlation between candidates' overall results in Test 5 test and retest

Immediately noticeable about the results, in terms of **r**, is that the correlation between the overall results from Session One and Session Two is much higher than the correlation between the results of any of the individual tests. While this may seem surprising, there is an explanation. The overall result for each candidate is the percentage of correct answers they achieved in all five of the tests combined. This means it is a more general measure of ability than the results from any one test.

Variable	r	99% C.I.	n
Overall Results	0.789	(-0.0128, 0.0239)	99
Visual Letters Test	0.665	(-0.0214, 0.0260)	99
Visual Images Test	0.530	(-0.0275, 0.047)	99
Audio Letters Test	0.490	(-0.0119, 0.0608)	99
Audio Images Test	0.643	(-0.0484, 0.0236)	99
Audio/Visual Letters Test	0.538	(-0.0306, 0.0376)	99

Table 15: Overall summary of reliability analyses of the five tests in the VAM application along with the overall reliability of the VAM.

Small differences in results have a much bigger impact on the correlation values for each test than they do for the overall results. When calculating the overall results, slight differences in the results of the different tests work to cancel each other out. This indicates that although some candidates may have got slightly different results between one session and the next, there was no definite improvement one way or the other in all five tests. Instead, while a candidate may have performed slightly better in one test during the first session, they conversely may have performed slightly worse in another of the tests which balanced out the difference in results.

The lack of consistent bias between one testing session and the other demonstrates that there is no clear learning effect in any of the sub-tests involved in the VAM application. This is important if the VAM is to be used in repeated studies and multiple fields. In summary, these results are extremely encouraging and further points towards VAM being a useful application.

5.3.5.2 Analysis of Audio and Visual Working Memory

The preceding sections of the chapter have primarily focused on proving that the VAM application provides a reliable and valid test of Working Memory. While this was the primary goal of the testing sessions, it was not the only one. Another goal of the testing sessions was to gather some initial data on the nature of audio and visual Working Memory. By analysing how well candidates' Working Memory copes with different forms of audio and visual stimuli, some initial conclusions can be drawn on the use of audio and visual media in computer applications. In this section, the results of the different tests in the application will be compared and contrasted in order to examine the properties of audio and visual Working Memory.

Table 16 below displays the average results recorded in each of the five sub-tests within the VAM application. Here, the average result of each test is taken as the average result over both testing sessions. The mean values can be considered as the percentage of sequences correctly processed in each test. In other words, the mean result of Test 1 is that on average 78.24% of sequences were processed correctly.

Test	Mean	SD	n
Test 1: Visual memory with letters	0.7824	0.0967	99
Test 2: Visual memory with images	0.6502	0.1259	99
Test 3: Audio memory with letters	0.7353	0.1158	99
Test 4: Audio memory with images	0.6629	0.1427	99
Test 5: Audio / Visual memory with letters	0.6280	0.1178	99

Table 16: The mean results achieved in each of the five tests in the VAM application.

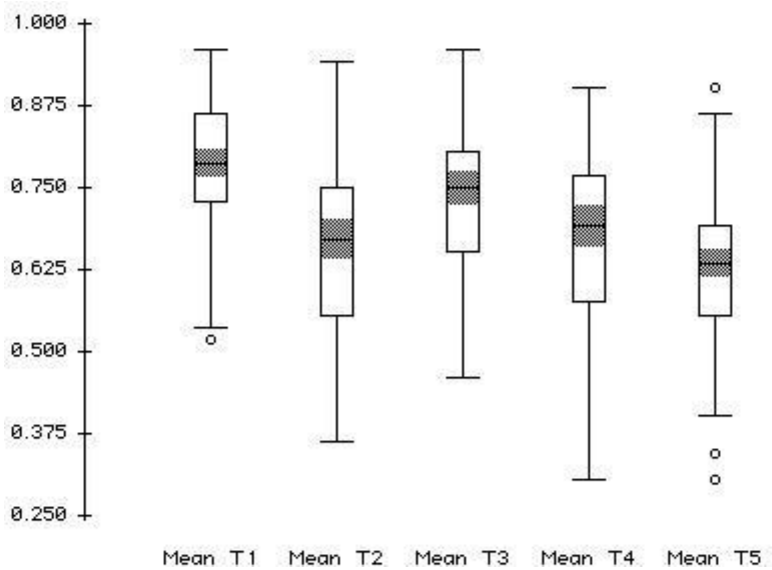

Figure 10: Box plot displaying the average result in each of the five sub-tests in the VAM application

The boxes encapsulate 50% of the recorded results. The line across the box displays the median. The shaded area in each box is a 95% confidence interval around the median. The tails extending from each box depict the range of the results. Extreme values are marked by circles.

Analysing the results obtained during the testing sessions, the main lesson seems to be, keep it simple. The worst and most varied set of results were achieved when audio and visual elements were interspersed too heavily with each other as in test five, the audio/ visual test with letters. Despite using a basic form of stimuli, the average result in test five was only 62.8%, which is lower than any of the other tests.

While audio and visual elements can both play an important part in useable computer applications, designers must be careful not to overwhelm the candidate's audio and visual Working Memory. How information is presented to candidates is a very important aspect of computer application design and one that is often overlooked. The cognitive theory of multimedia learning [Mayer & Moreno, 1998] presents some guidelines for this process and the results obtained here demonstrate its relevance. The cognitive theory of multimedia learning is described in more detail in Chapter 8.

The best overall results were achieved in the visual memory test with letters. In this test, candidates achieved an average result of 78.24% correct. This is not surprising because it is the simplest of the tests to use and understand; that simplicity is the reason it was presented first. The results of the visual memory test with letters were on average 4.71% higher than the audio memory test with letters. This indicates that most candidates achieve better results when simple information is presented in a visual format.

However, examining the data from which this table was extracted reveals some interesting results. Calculating a frequency breakdown of the difference in results between the audio and visual memory tests with letters shows that 27.44% of candidates tested achieved higher results when presented with audio stimulus as opposed to visual stimulus. This indicates that although the majority of candidates find text based stimulus the simplest to remember, there is still a sizeable proportion, over a quarter in this instance, that perform better with audio instruction.

This is even more apparent in the image based tests. The visual memory with images test produced an average result of 65.02% correct. The audio memory with images test on the other hand produced an average result of 66.29% correct. Although the difference between the results is only 1.27%, it indicates that audio instruction plays an important role in Working Memory, especially when dealing with complex forms of stimuli. These results provide support for Baddeley's belief that the phonological loop has taken on a particularly important rehearsal role in Working Memory due to our reliance on verbal forms of communication [Baddeley, 2002].

Since computer applications are primarily visual in nature, audio components can often be neglected when it comes to presenting material. Perhaps it is time to change that, or at least give candidates the choice of audio over visual presentation of information.

Finally, as expected, candidates performed significantly better in the letter based tests than in the image based tests. When letters were used instead of images, candidates achieved a higher score of, on average, 13.2% in the visual tests and 6.6% in the audio tests. This is because the cognitive load involved in processing and storing a sequence of images is significantly higher than that of processing and storing a sequence of letters. However, this does not mean images should be dismissed as having a negative impact on Working Memory.

Images place a large cognitive load on Working Memory because they hold a great deal of information [Alvarez & Cavanagh, 2004]. Candidates may not be able to store as many images as letters, but as the saying goes, a picture is worth a thousand words. Visual aids are a powerful tool in any application, but they must be treated with care. Further discussion on this topic can be found in Chapter 8.

5.3.5.3 Individual Differences in Working Memory Capacity

One final area that was highlighted when testing the VAM application was the concept of individual differences in Working Memory capacity. As discussed in the previous section, in general candidates performed better on the easier letter based tests than on the more complex image based tests, but how well did the results of each individual sub-test correlate with each other? The results of this analysis are presented in Table 17 below.

	Test 1	Test 2	Test 3	Test 4	Test 5
Test 1	1.000				
Test 2	**0.638**	1.000			
Test 3	0.583	0.504	1.000		
Test 4	0.557	0.539	**0.606**	1.000	
Test 5	0.580	0.414	0.566	0.574	1.000

Table 17: Correlation between candidates' results in each of the individual subtests. Test 1 is Visual memory with letters. Test 2 is Visual memory with images. Test 3 is Audio memory with letters. Test 4 is Audio memory with images and Test 5 is Audio / Visual memory with letters

The first thing to notice is that there is a medium to strong correlation between the results of each of the sub-tests within the VAM application. This demonstrates the common mechanisms of the Working Memory system that underpin each of these tests such as the central executive and the episodic buffer.

The two strongest correlations are firstly between test 1: the visual memory test with letters and test 2: the visual memory test with images (**r** = 0.638) and secondly between test 3: the audio memory test with letters and test 4: the audio memory test with images (**r** = 0.606). This indicates that the strongest relationships exist between those tests that make use of the same sub-systems in Baddeley's model of Working Memory, the visuospatial sketchpad for the visual tests and the phonological loop for the audio tests. The lowest correlation occurs between test 2: the visual memory test with images and test 5: the audio/visual memory test with letters (**r** = 0.414). This is because of all the subtests these two use the most different stimuli types; a sequence of complex visually presented images compared to a mixed sequence of audio and visually presented letters respectively.

Again, these results provide strong evidence in favour of Baddeley's model of Working Memory. The results also show that although on average, candidates achieved significantly higher results in the two tests that used letters as stimuli compared to those that used images as stimuli (as discussed above in section 5.3.5.2), it is the form in which the stimuli are presented (audio versus visually) not the stimuli themselves (letters versus images) that show the strongest correlative relationship in the results. This indicates that individual differences in Working Memory capacity can be observed and highlighted most easily along the audio/visual divide proposed in Baddeley's model of Working Memory.

This in turn could prove very important when designing computer applications that take advantage of Working Memory capacity; for example as e-learning applications. If the audio/visual divide is the strongest measure of individual differences in Working Memory capacity, it could open up the possibility of using Working Memory to configure e-learning courses to a particular individual's strengths and weaknesses. Again, this is discussed in more detail in Chapter 8.

5.4 Conclusions

After a rigorous and methodical set of studies designed to analyse the VAM application several main conclusions can be reached.

The VAM is an extremely reliable application as shown by a test re-test correlation of **r** = 0.79. This is well in line with Kline's [2000] recommendations that **r** for test re-test reliability should be over 0.7 and above 0.8 if possible.

The VAM application has a correlation with the results of Riding's IPI [2000] of **r** = 0.33. This is enough to show a correlation between the results of the two Working Memory tests and indicate that the VAM is a valid measure of Working Memory. A higher result for **r** would be welcome, but the result obtained could be explained due to IPI's high ceiling factor and questionable reliability.

The VAM application correlates with Raven's Matrices at a value of **r** = 0.36. This is very much in line with previous studies of the relationship between Working Memory and Raven's Matrices [Engle et al., 1999], [Conway et al., 2002], [Kane et al., 2004], [Unsworth & Engle, 2005] and indicates that the VAM application holds up well against current theories connecting Working Memory to Spearman's '*g*' [1904] and also to fluid intelligence.

When tested for reliability, Riding's IPI produced a test re-test correlation of **r** = 0.246. This is much lower than should be expected from a cognitive testing tool. This low reliability may be partially caused by the apparently low difficulty of the IPI. Unfortunately, the difficulty level in the test cannot be altered by an administrator. This demonstrates the potential usefulness of configurable tests of Working Memory.

The results produced by the VAM application are also with consistent with the cognitive theory of multimedia learning [Mayer & Moreno, 1998] and indicate that the VAM can play an important role in helping to design computer based applications, particularly e-learning applications, that work with a candidate's Working Memory to enhance recall and learning.

All of the above conclusions bode very well for the future of the VAM application and the role it can play in the future of Working Memory research and associated areas.

5.5 Review

In this chapter, the intensive testing process that the VAM application was put through was discussed. The methodology of these studies was presented along with how the sample selection was chosen and the biases that might have crept into the studies. How the results from these studies was collected, collated analysed was then examined.

Once the results were gathered, they were statistically analysed to draw some conclusions about the VAM application. In summary: The VAM application was shown to be extremely reliable. The VAM application correlated relatively well with a current computerised test of Working Memory, Riding's IPI, although there were some issues with this. When the reliability of Riding's IPI was examined, it was found to be lacking. Finally, the VAM application correlated to Raven's Matrices at a level comparable with previous studies. This confirmed a connection between the VAM application, Working Memory, Spearman's 'g' and fluid intelligence.

With these extremely encouraging results produced, some other conclusions about the nature of audio and visual Working Memory were drawn. The results produced by the VAM are consistent with the cognitive theory of multimedia learning and again indicate that the VAM can be valuable tool in many diverse areas of research associated with Working Memory.

Now that the VAM application has been shown to be a reliable, valid test of Working Memory, it is time to explore the VAM's role in a wider setting. Over the next three chapters some of the main areas in which the study of Working Memory and the VAM application can be used to more practical effect will be explored, starting with the role of Working Memory as a diagnostic tool.

Chapter 6: Working Memory as a Diagnostic Aid

6.1 Introduction

As described in Chapter 2, Working Memory plays an important role in many cognitive processes and one that is often underestimated. Working Memory is what allows us to process information absorbed from the world around us and from our own long-term memory and to manipulate that information for use in other tasks. Over the course of the next three chapters, this role will be explored in greater detail.

Three distinct areas were chosen for this study to show the value of diverse research into Working Memory. The areas chosen were the identification of Working Memory impairments, cognitive training and e-learning. All three areas were chosen because they are growth industries and ones in which the study of Working Memory and the VAM application can provide valuable information.

In this chapter, the importance of monitoring Working Memory functionality is examined. In particular, how it can be used to diagnose medical conditions and act as a safety net. Working Memory impairment can be a serious issue in itself as well as a symptom of a deeper underlying medical condition. While Working Memory capacity can fluctuate based on a number of factors, severe or continuous drops should be investigated further.

To begin with, some of the causes of long-term Working Memory impairment will be discussed, focusing on ADHD and dementia in particular. Secondly, short-term Working Memory impairments will be examined, focusing on anxiety and the dangers of fatigue. Finally, the role the VAM application can play by monitoring both short and long term changes in Working Memory performance will be explored.

6.2 Long Term Working Memory Impairment

The study of Working Memory has progressed rapidly in the last few decades. The knowledge gained has been used to better understand and improve many diverse fields ranging from education to medicine to artificial intelligence. It is unfortunate therefore, that the majority of what we have learned about Working Memory stems from studies carried out on people whose Working Memory has in some way been damaged or impaired.

Given the links between Working Memory and other cognitive processes, it is sometimes difficult to disentangle the source of cognitive problems and discover if an underlying problem is affecting Working Memory or whether the problem lies within Working Memory itself. This is particularly true in cases of damage to the frontal lobes which are thought to house many of the processing elements of Working Memory [Kimberg & Farah, 1993], [Miyake et al, 2000]. Either way, problems with Working Memory and related cognitive problems can be the first indication of a serious medical condition [Flicker, Ferris, Reisberg, 1991], [Petersen et al, 1999]. Catching these signs early can be crucial in limiting the damage caused, or if fortunate, reversing it.

6.2.1 Causes of Long Term Working Memory Impairment

Working Memory deterioration is often caused by damage to the anatomical structure of the brain. It can stem from many different sources. Some are innate, some are caused by injury, some are caused by medical disorders and others are just the result of age [Budson & Price, 2005]. Whatever the cause though, serious dysfunction can have an enormous impact on a person's quality of life. In the next section, two conditions of which impaired Working Memory is both a symptom and result are presented: Firstly, ADHD which mostly affects young people and secondly, Alzheimer's disease which mostly affects older people.

6.3 ADHD

Attention Deficit/Hyperactivity Disorder is a neurological developmental disorder. The core symptoms include inattention, hyperactivity and impulsiveness. Even though ADHD is one of the most commonly researched and the most commonly diagnosed psychiatric condition in children [Jadad et al, 2000], [Nair et al, 2006], there are few definite answers when it comes to the cause and treatment of the condition.

It is estimated that ADHD is diagnosed in between two and sixteen percent of children [Rader, McCauley, Callen, 2009], although this figure varies due to the diagnostic criteria having been revised on multiple occasions over the last few decades [American Academy of Pediatrics, 2000]. Boys are twice as likely to be diagnosed as girls [Dulcan, 1997]. It is unknown if boys are more susceptible than girls, but research suggests that they are more likely to be referred by teachers when displaying the same symptoms [Sciutto, Nolfi, Bluhm, 2004].

There are three main subtypes of ADHD [American Psychiatric Association, 2000]: predominantly hyperactive-impulsive, predominantly inattentive and combined hyperactive-impulsive and inattentive which is the most common type. The fact that inattentiveness, impulsiveness and hyperactivity are all traits within unaffected children too is part of what makes ADHD so hard to diagnose. It should also be noted that while ADHD is most commonly diagnosed and treated in childhood, it is a chronic condition and can continue on into adulthood in many cases [Van Cleave & Leslie, 2008].

While the causes of ADHD are still unclear, genetics are believed to play an important role [Khan & Faraone, 2006] and the condition is believed to be passed on through families [Faraone, et al 2005]. There are many other factors such as diet, social factors and environmental factors which researchers believe can contribute to the condition, but it is unclear if they help cause the condition or merely exacerbate the symptoms [Nigg, 2006]. Equally, many researchers are also divided on the proper way to treat ADHD. Popular approaches consist of medication, behavioural modification, counselling or a mixture of all three [Jensen et al, 2005].

6.3.1 Working Memory and ADHD

As can be expected with a condition that affects concentration and attention span, children with ADHD usually perform poorly on tests of Working Memory [Klingberg, Forssberg, Westerberg, 2002], and show behavioural signs of Working Memory impairment [Alloway, Gathercole, Elliot, 2010]. In fact some researchers believe that Working Memory impairment is a core aspect of ADHD [Barkley, 1997]. In particular, one of the main deficits of ADHD is the inability to use the inhibitory processes granted by the central executive [Rapport et al, 2008]. The inhibitory processes are what allow us to ignore irrelevant information around us and focus on the task at hand. When these processes fail, one is unable to block out external stimuli and so retention and processing of relevant information suffers as a result.

Current research also indicates that ADHD may provide further evidence for Baddeley's multi-component model of Working Memory. In a meta-analysis of twenty-six different studies on the relationship between Working Memory impairments and children with ADHD it was discovered that children with ADHD showed deficits in multiple components of Working Memory compared with unaffected children of the same age [Martinussen et al, 2005]. In particular, affected children showed a large deficit in visuospatial Working Memory and a moderate deficit in phonological Working Memory. In fact, there has been some evidence to suggest that examining different components of Working Memory could aid in gathering data on and possibly the diagnosis of the different subtypes of ADHD [Quinlan & Brown, 2003].

The connection between Working Memory and ADHD can be useful for more than just diagnosis though. In fact, improvements in Working Memory have been shown to help ameliorate the symptoms of ADHD, improving not only attention and recall, but motor activity too [Klingberg, Forssberg, Westerberg, 2002], [Klingberg et al, 2005]. It should be noted though, that these studies have since been criticised in terms of sample size and methodology [Shipstead, Redick, Engle, 2010]. Klingberg has actually created a computerised system specifically designed to help train and improve the Working Memory of children with ADHD. This technique is known as cognitive training and will be discussed in more detail in Chapter 7.

Of course, ADHD is not the only condition that can benefit from the study of Working Memory. In the next section, Alzheimer's disease will be examined, a condition synonymous with memory problems.

6.4 Alzheimer's Disease

Alzheimer's disease is a degenerative neurological condition and is the most common form of senile dementia. Dementia is a syndrome (a collection of symptoms) rather than a disease and was defined by the Committee of Geriatrics of the Royal Society of Physicians [1981] as follows:

“Dementia is a global impairment of higher cortical functions, including memory, the capacity to solve the problems of everyday living, the performance of learned perceptual motor skills and the correct use of social skills and control of emotional reactions, in the absence of gross clouding of consciousness. "

Alzheimer's was named after Aloysius Alzheimer, the man who first described the condition in 1906 [Berchtold & Cotman, 1998]. It is currently both incurable and a terminal disease. It has been described as the 'pandemic of the 21st century' and its prevalence is thought to be largely attributed to demographic changes caused by increasing life-expectancy [Jellinger, 2006]. It is most commonly diagnosed in people over the age of sixty five [Brookmeyer, Gray, Kawas, 1998] but early-onset Alzheimer's can occur at a younger age. It is predicted that by the year 2050, one in eighty five people will be living with the disease [Brookmeyer et al, 2007]. In financial terms it is also one of the most costly diseases to society [Meek, McKeithan, Schumock, 1998] with the average care-giving costs of a single patient estimated at about 60,000 dollars a year in the USA [Jellinger, 2006].

As with ADHD, no-one knows for sure what causes Alzheimer's disease, but it is believed to be a combination of many factors including age, genetics and environmental conditions [Munoz & Feldman, 2000]. Over the course of the disease, plaques and tangles are formed in the brain which lead to the death of brain cells [Tiraboschi et al, 2004]. Those suffering from Alzheimer's also have a deficit of important chemicals in the brain which exacerbates the condition [Walsh et al, 2002].

The progress of Alzheimer's disease varies from patient to patient, but one of the earliest symptoms of Alzheimer's common to all patients are memory problems; both the inability to access current memories and the inability to create new ones. Unfortunately, since Alzheimer's most often occurs in the elderly, too often the early signs are dismissed as nothing more than the side-effects of ageing [Buckner, 2004].

6.4.1 Working Memory and Alzheimer's Disease

Although Alzheimer's is currently incurable, there are some pharmacological treatments available that may slow the progress of the disease in some people. The effectiveness of these treatments is under considerable debate. The results provided thus far have been mixed and the methodologies used in many clinical studies have been questioned [Kaduszkiewicz et al, 2005], [Hansen et al, 2007], [Mangialasche et al, 2010]. Other treatments involve a more psychological and social approach. The idea behind these treatments is to keep the mind and body active in a bid to slow down the progress of the disease. Again, there is little evidence that these approaches slow the progress of the disease at all [American Psychological Association, 2007], and it has been suggested that they are more effective as a method of keeping the patients' spirits up than anything else.

Despite the lack of evidence regarding treatments for Alzheimer's, it is still important that it be diagnosed as early as possible, if only because the rate of deterioration varies from person to person and in some cases can be very swift [Teri, Hughes, Larson 1990], [Buckner, 2004]. It is better that the condition be diagnosed early so that patients have a chance to get their affairs in order before the disease begins to have a major impact on their cognitive processes. Another reason for early detection is the possibility that some of the measures listed above might indeed slow the progress of the disease. Since strides are being made each day in the direction of a cure, any delay tactics are worth trying.

Alzheimer's disease is usually diagnosed through cognitive testing followed by brain imaging scans. As Working Memory is one of the first areas to be affected by the disease, it makes sense that monitoring Working Memory functionality is a good early warning system [Baddeley et al, 1986]. In fact, several studies have shown that cognitive deficits can be detected years before the clinical diagnosis of Alzheimer's [Linn et al, 1995] and that measures of retention of information and abstract reasoning are among the strongest predictors of preclinical Alzheimer's disease [Elias et al, 2000]. While these check-ups are not enough by themselves, a sharp decline in Working Memory capacity is enough reason for likely candidates to go for further tests.

Working Memory tests can also play another role when it comes to Alzheimer's disease. There is evidence to suggest that keeping an active mind may help prevent the disease in the first place [Stern, 2006] especially when combined with an active and social lifestyle [Fratiglioni, Paillard-Borg, Winblad, 2004]. The theory is that an active mind results in a more efficient neural network within the brain which in turn makes it more resistant to damage and less likely to be affected by neurological conditions like Alzheimer's disease.

As with ADHD, there is also a growing school of thought that cognitive training might assist in the slowing down of Alzheimer’s. In this case the cognitive training comes in two varieties. Compensatory methods teach new ways to complete cognitive tasks in order to work around existing cognitive deficits. On the other hand, restorative techniques attempt to improve cognitive functions with the goal of returning them to pre-condition levels [Sitzer, Twamley, Jeste, 2006]. As with many areas of cognitive training and Alzheimer’s treatment in general, there is not yet enough evidence one way or the other to tell if these techniques work. Stricter criteria and methodological approaches have been proposed, but early results are cautiously optimistic [Clare & Woods, 2004], [Sitzer, Twamley, Jeste, 2006], particularly when combined with pharmacological treatments [Bottino et al, 2005]

6.5 Short term Working Memory Impairment

Long-term Working Memory impairment is usually a symptom of a serious underlying medical condition. Often though, Working Memory capacity and attention span can be temporarily lowered without any serious ramifications. In fact, it is quite common for people in a state of heightened emotion to be unable to think clearly and rationally. Fear and stress, in particular, can have an enormous negative effect on our ability to take in and process information [Berkun et al, 1962], [Darke, 1988], [Klein & Boals, 2001].

One area that has been especially well examined is the effect of anxiety on Working

Memory capacity. Anxiety has been shown to affect both storage and processing capacity. Other studies indicate that this may only be the case if Working Memory is overloaded by the task at hand though [Johnson & Gronlund, 2009]. Anxiety is thought to affect processing efficiency (the speed of processing) even more than the effectiveness (quality of performance) [Eysenck & Calvo, 1992]. The adverse effects of anxiety on performance have also been shown to become greater as the demands on the central executive increase [Eysenck et al, 2007] and have a greater impact on those with a lower Working Memory capacity to begin with [Johnson & Gronlund, 2009].

It is assumed that the anxiety takes up part of the processing capacity of Working Memory by filling it with information irrelevant to the task at hand and focusing attention away from what is important [Wine, 1971]. A study of academic achievement in patients suffering from adult anxiety disorder found that 49% did not graduate high school and in 24% of those cases, anxiety was given as the primary reason for leaving [Van Ameringen, Mancini, Farvolden, 2003]. This highlights an important issue in a society where so many areas in life, from college admissions to job interviews involve the use of anxiety provoking tests.

While the effects of anxiety can indeed impact heavily on a person’s life if they go untreated, there is a far more common cause of temporary Working Memory impairment that kills thousands of people each year despite being easily diagnosed and even more easily prevented - fatigue. In the next section the causes, risks and safety measures associated with fatigue will be discussed.

6.6 Fatigue

Fatigue is a fact of life. It affects each and every one of us on a regular basis. In broad terms, fatigue refers to a loss of efficiency either physically, mentally or both, and a disinclination for any kind of effort [Grandjean, 1979]. Fatigue is perfectly natural and for the most part is simply the body’s way of telling us that it needs to rest and recharge. In general, people know how much they can exert themselves before succumbing to fatigue and schedule their lives accordingly. However, this is not always the case, and ignoring or underestimating fatigue can be very dangerous both to ourselves and to others.

In this section the definition of fatigue is discussed, along with how it impacts people both mentally and physically. The effect of fatigue on Working Memory is also examined along with how the VAM can help to diagnose fatigue and in turn provide a useful tool for workers who need to be fully alert to perform their jobs successfully and safely.

6.6.1 What is Fatigue?

Fatigue is a catch-all term covering a wide range of afflictions. It can refer to anything from a feeling of general listlessness all the way to pure physical exhaustion, in which the muscles no longer have the energy to perform physical tasks [Pearson, 1957], [Berrios, 1990].

In broad terms, fatigue comes in two forms, mental and physical. Physical fatigue, also known as muscle weakness, refers to a person's inability to generate as much force in his/her muscles as could be expected given his/her fitness level [Grandjean, 1979]. This can range from being unable to reach one's full physical potential all the way down to being literally too tired to move. It can also occur centrally throughout the body or peripherally in individual muscles [Kent-Braun, 1999]. This form of fatigue is seen most often as a side effect of excessive physical exertion, but in rare cases it can also be a symptom of one or more underlying conditions.

Mental fatigue or somnolence, on the other hand, can be described as a reduced level of consciousness [Grandjean, 1979]. This can range from a mild drop in attention, to microsleeps which last up to thirty seconds and may not even be noticed, to a state of heavy sleep known as hypersomnia [American Academy of Sleep Disorders, 2001]. Unlike physical fatigue, those suffering from mental fatigue may not always notice its effects. They may also be more inclined to ignore the effects, especially if there is a tangible reward for doing so [Boksem & Tops, 2008]. As such, it can be particularly dangerous in situations that require constant focus such as driving a car, piloting a plane or operating dangerous machinery.

6.6.2 Diagnosis of fatigue

Approximately one in four patients attending a family doctor report fatigue as a symptom or report feeling tired or run-down when later interviewed [Hanney, 1978], [Cullen, Kearney, Bury, 2002]. The majority of those suffering from fatigue experience it as a result of everyday life and have no deeper underlying cause. In those few whose fatigue is a symptom of deeper issues, the main causes are either musculoskeletal or psychological in nature [Nijrolder et al 2009].

Despite fatigue being such a commonly reported symptom, studies have shown that approximately 50% of patients presenting with fatigue don't receive a diagnosis which explains it [Nijrolder et al 2009]. When attempting to diagnose reasons for chronic fatigue, physicians generally begin by examining the patient's psychological and emotional state. This may be related to the fact that of sixteen adjectives used by psychiatrists to signify sadness, six were also applied by patients to states of fatigue [Pinard & Tetreault, 1974, (as described in Lewis & Wessely, 1992)]. Often fatigue can be brought on by stress, which can disrupt a person's sleeping patterns. Questions about the patient's lifestyle may also be relevant, including details of diet and exercise habits.

If these enquiries do not provide any answers, more invasive procedures can be invoked. Blood tests are used to look for signs of infection; urinalysis is used to check for liver disease or diabetes and the functionality of the thyroid is also examined [Fukuda et al, 1994].

Obviously, this approach is only used in excessive cases of fatigue. In particular, the term Chronic Fatigue Syndrome (CFS) was coined to refer to a collection of fatigue related symptoms with no obvious underlying cause. CFS has since become a clinically defined condition consisting of a debilitating level of fatigue that lasts for over six months and cannot be attributed to other medical conditions [Holmes et al, 1988]. Although extensive research has been done into the nature of CFS, to date, no clear cause or mechanism for the condition has been concluded on. Instead, it is believed to be caused and maintained by a number of different factors including a combination of physiological and psychological elements [Afari & Buchwald, 2003].

CFS is obviously an extreme case, one estimated to affect between 0.006% to 3.0% of the population [Afari & Buchwald, 2003]. Day-to-day fatigue however, can also be dangerous if ignored and a method of testing for mental fatigue and a loss of focus could be a literal life saver in many jobs.

6.6.3 Dangers of Fatigue

As previously mentioned, both physical and mental fatigue are unavoidable side-effects of everyday life. As such, many people underestimate how dangerous fatigue can be. In particular, activities such as driving, flying planes or working with industrial machinery require constant attention on the task at hand and a lack of focus can have lethal results.

Many studies on the dangers of fatigue have been carried out, particularly in the area of driver fatigue [Brown, 1994], [Nilsson, Nelson, Carlson, 1997], [Lal & Craig, 2001]. In fact, there is evidence to suggest that fatigue could play a part in as many as twenty to thirty percent of road fatalities [Camkin, 1990].

The effect of fatigue on drivers, particularly those who transport goods or people for a living is a major concern. Commercial drivers are often subject to irregular working hours, long shifts and sleep deprivation, all of which seriously contribute to fatigue [Miller & Mackie, 1980]. As such, most countries now enforce some form of working hours control for drivers; requiring regular breaks and sleep stops for longer journeys. In Europe, drivers may not drive for more than nine hours a day (twice a week, this is extended to ten hours) and must take a forty five minute break at least once every four and a half hours. There are also further rules governing how much a driver may drive in total in any given week or fortnight [Vehicle and Operator Services Agency, 2009].

Similarly, airline pilots and air traffic controllers are also at severe risk of fatigue related accidents. Between 1994 and 1998, there were 227 schedule-related fatigue incidents reported by pilots, approximately 45 a year [Goode, 2003]. Other studies have estimated that fatigue plays a role in between 4% and 7% of civil aviation mishaps and 4% of military ones [Caldwell, 2005].

It is clear that fatigue is a huge safety concern, one that should not be ignored. Although regulating working hours is a good step forward in preventing future accidents, it is only a first step. There are far too many factors involved to be covered by even the strictest working schedule [Williamson, Feyer, Friswell, 1996]. Instead some method of screening for the effects of fatigue is required. Once again, the study of Working Memory could provide valuable insight into this matter.

6.6.4 Working Memory and Fatigue

The study of CFS (discussed above) has provided much information on the relationship between Working Memory and fatigue (see [Tiersky et al., 1997], for a review). For the most part, the level of cognitive impairment shown by CFS patients is subtle, with more of an impact on information processing efficiency over effectiveness. In other words, many CFS patients show only mildly impaired Working Memory capacity, but their response times in such tests are much higher than healthy control groups [Tiersky et al., 1997], [DeLuca et al, 2004]. Other studies have shown that capacity drops further as the complexity of information processing tasks increases [Dobbs et al, 2001]. These cognitive deficits have also been shown to interfere with the subject’s everyday functional status [Christodoulou et al., 1998; Tiersky et al, 2001].

The situation appears to be even more severe for people suffering from total sleep deprivation. Several studies have shown that even one night without sleep can significantly degrade performance on attention and Working Memory tests [Smith, McEvoy, Gevins, 2002], [Durmer & Dinges, 2005] although this varies from person to person and also seems affected by gender and age [Alhola, Polo-Kantola, 2007]. The ideal solution is to have an on the spot test for fatigue to judge how impaired a vulnerable worker may be before he/she has the chance to cause an accident. That's where the VAM application comes in.

6.7 The VAM Application as a Diagnostic Tool

The VAM test can serve two roles as Diagnostic tool. It can be used as a regular monitor in order to alert a subject to any degradation in his/her regular Working Memory capacity and it can act as a safety measure to alert subjects if they fall beneath a certain level of competence before undertaking a demanding mental task.

As explained above, deterioration in Working Memory can be one of the first signs of a serious underlying medical condition such as Alzheimer's disease [Baddeley et al, 1986]. One of the benefits of the VAM application is the ability to keep detailed records of performance as well as personal information. If enough subjects allow their results to be transmitted to a centralised location it would be possible to build up a database of average performance and response times. This database could be further broken down into categories such as gender, age, nationality etc. in order to give people a benchmark for their own current performance. Any serious deviation from this benchmark could indicate that they should seek further consultation on the issue.

Even without comparing results to a centralised database, the VAM could still provide an early warning system for people. Because detailed results could be kept each time a person uses the VAM application, he/she could build up his/her own personal Working Memory profile. Running through the tests at regular intervals would allow subjects to notice any patterns that occur in their own performance. Any consistent decline in results could serve as a warning that something might be amiss.

While the VAM could function as a long term monitoring system, it could also serve as a more immediate warning tool as well. As discussed above, there are many dangerous jobs and tasks that require an immense amount of concentration to successfully undertake. It's an unfortunate fact of life that the people who work in these areas are usually under pressure to carry out their tasks promptly, regardless of whether they are mentally prepared enough.

The VAM application could help in these situations, since it requires constant attention and focus to successfully complete. It also keeps track of both Working Memory capacity and response time, thus measuring both the effectiveness and efficiency of Working Memory.

Through further testing with the VAM, a baseline level of success could be determined which could serve as a cut-off point for tasks requiring similar levels of concentration. Fail the test and the subject could be deemed unsafe for the task at hand and more rest would be required before restarting it.

For example, it would be a simple matter to develop a version of the VAM application specifically for use by professional truck drivers. Before beginning a shift or a new leg of a journey, drivers could be required to complete the modified application in order to prove themselves alert enough for the task ahead. For added safety, the application could be used as part of the start-up sequence for the truck itself. If the driver fails to show the necessary level of concentration, the truck refuses to start. Obviously there would need to be some sort of overview system built around the start-up procedures, but it could be a good start for an occupation that has one of the highest percentages of work related fatalities in the world [Sieber, 2007].

6.8 Conclusions

Working Memory plays an important role in everyday life. As such, the impairment of Working Memory both in the short and long term can have serious consequences for those affected. Working Memory impairment can also be symptomatic of a larger problem and monitoring Working Memory performance can aid in the early diagnosis of many severe medical conditions.

Children suffering from ADHD were found to perform poorly in Working Memory tests and there is even some evidence that by training Working Memory, the impact of ADHD on affected children can be reduced [Klingberg, Forssberg, Westerberg, 2002], [Klingberg et al, 2005]. Similarly there is evidence to suggest that Working Memory analysis can help the early diagnosis Alzheimer's [Baddeley et al, 1986] and keeping an active Working Memory may even play a role in reducing the risk of developing it [Stern, 2006].

Impairments in Working Memory are not always caused by medical conditions though. In fact, one of the most common forms of Working Memory impairment comes from fatigue, a day-to-day issue that affects us all. Nevertheless, fatigue can be extremely dangerous in jobs that require constant focus such as commercial driving [Camkin, 1990]. By monitoring deviations in Working Memory capacity from baseline readings gathered beforehand, an added level of safety can be brought to these jobs.

6.9 Review

In this chapter the role of Working Memory as a diagnostic aid was discussed. Long-term impairment of Working Memory was examined, focusing on a condition that primarily affects young people, ADHD [Barkley, 1997], and a condition that primarily affects older people, Alzheimer's [Baddeley et al, 1986].

The effects of short term Working Memory impairment were also reviewed. Anxiety [Eysenck & Calvo, 1992] was noted to impair Working Memory as was fatigue [Tiersky et al., 1997]. The dangers of fatigue if ignored or underestimated were discussed, particularly relating to the fields of driving [Camkin, 1990] and aviation [Caldwell, 2005]. It was noted that fatigue impairs both Working Memory capacity and response time [Tiersky et al., 1997], [DeLuca et al, 2004].

Finally, the role the VAM application could have as a diagnosis tool for both long term and short term Working Memory impairment was explored. The VAM application can help in big scale operations like collecting data to help diagnose Alzheimer's as well as more personal operations like acting as a safety precaution for truck drivers.

The study of Working Memory and proper use of the VAM application has the potential to improve the quality of life of many people and possibly even save the lives of some. In the next chapter another way in which the study of Working Memory and VAM application could be useful is examined, this time focusing on the growing industry of cognitive training.

Chapter 7: Cognitive Training

7.1 Introduction

Cognitive training, also commonly referred to as brain training, brain fitness as well as a number of other terms, refers to the hypothesis that just as physical exercise can maintain and improve the body, mental exercise can maintain and improve the mind. The concept of cognitive training has existed for many years, but only recently has it become widely publicised. It is also still largely hypothetical, and as such can be treated sceptically in academic circles. There are many valid reasons for this scepticism; the concept itself is vague and nebulous enough to cover a range of possibilities. How exactly does one go about cognitive training? Does it require special training or equipment? Is it an on-going process? What exactly are the results? It's easy to say mental exercise improves the mind, but how are the results measured? What parts of the mind are improved and how? Does this training carry over into other areas?

Unsurprisingly in an area promising mental improvement, a growing number of products and services have become available in this field. But which, if any, actually work? Since cognitive training is still a relatively new market, there have still been comparatively few large scale studies done in the area, and those that have been carried out often produce confusing and contradictory results. There's little doubt that cognitive training has caught on in recent years, but will it become a recommended lifestyle practice like physical exercise? Or will the difficulties in proving its effectiveness cause this growing industry to diminish?

In the following sections the concept of cognitive training will be examined. The scientific evidence for and against the hypothesis will be discussed and some of the current leading products available that promote cognitive training will be reviewed. The largest independent study that has been conducted in the area so far is also examined. The connection between cognitive training and Working Memory is discussed, focusing on the use of Working Memory as a measure of intelligence. Finally the role that the VAM application can play in investigating the nature of cognitive training will be explored.

7.2 What is Cognitive Training?

The terms cognitive training and brain training have been in use for many years, often when promoting the sale of a product or service. The premise behind cognitive training is simple. An active mind is a healthy mind. In other words, regular cognitive stimulation should result in improved cognitive functions. By regularly completing cognitive tasks such as Working Memory tests and response time tests or by undertaking arithmetical or verbal tasks like Sudoku or crosswords, a person can supposedly increase Working Memory capacity and attention span, improve mental flexibility and decision making skills and even potentially lower the risk of suffering from Alzheimer's or dementia [Scarmeas & Stern, 2003].

With this in mind, it's not surprising that the market for cognitive training has grown exponentially in the last few years. The estimated market for digital cognitive training products was approximately 2 million American dollars in 2005, jumping to 80 million dollars in 2007, just a year after Nintendo released their first brain training game for the Nintendo DS [Aadmodt & Wang, 2007]. According to SharpBrains, a market research company that focuses on the emerging cognitive training market, the estimated worldwide market for digital cognitive training software was 295 million dollars in 2009, an improvement of over thirty five percent from 2008. More impressively, the same market is expected to rise to between two and eight billion dollars by 2015 [SharpBrains, 2010].

Despite these impressive figures, serious questions remain as to validity of many of these products. Many researchers argue the exact benefits provided by cognitive training. Some believe that it is still too early to tell whether cognitive training has an impact on subjects [Shipstead, Redick, Engle 2010] and there is even a recent large scale study indicating that it has no impact at all [Owen et al, 2010]. With so many conflicting reports on whether cognitive training works, perhaps it is best to start by explaining what it is supposed to do and how.

7.3 Neurogenesis and Neuroplasticity

The theory behind cognitive training is that exercising the mind improves its performance and keeps it healthy, just like exercising the body. It's the comparison of mental training to physical exercise that lies at the core of the cognitive training industry. It is easy to see how training in a specific physical activity such as jogging affects the body as a whole, improving the cardiovascular system, strengthening muscles and raising the overall fitness level of the subject. This in turn improves performance not only in jogging itself, but also in a number of related areas that make use of the same physical systems; swimming or cycling for example. Perhaps most importantly it can also have a positive impact on the overall life quality of the subject, making day-to-day physical tasks easier to accomplish and reducing the risk of a number of dangerous medical conditions [Blair et al, 1989].

The problem is that demonstrating an improvement in cognitive ability from cognitive training is much more difficult than demonstrating physical improvement from physical training [Owen et al, 2010]. Similarly, demonstrating that these improvements can carry over into associated areas or impact overall life quality can be near impossible. One major study on the effects of cognitive training on older adults [Willis et al, 2006] relied on subjects self-reporting improvements in everyday life which is not an ideal method when dealing with cognitive ability.

While the idea of exercising the brain as one would a muscle may seem erroneous, research indicates that there may be some truth to it. In fact, not only does the structure of our brains' change over the course of our lives, we may even be able to rewire our own brains based on personal experiences [Kolb et al, 2003].

In the past, scientists believed that the brain did not physically change once infancy was over. While new information could be stored and processed, they believed this was done primarily through the strengthening of connections between neurons. For a while now, scientists have known that new neurons are produced in our brains throughout our lifetimes [Altman, 1962], this process is known as neurogenesis. For many years the exact function of neurogenesis was unknown, but recent research suggests that it may play an important role in memory and learning [Neves, Cooke & Bliss 2008]. In fact, it has been suggested that increased neuronal production can lead to increased memory capacity [Becker, 2005] and that the process of learning is itself associated with neuronal survival [Gould et al, 1999].

Quite apart from generating new neurons to alter the structure of our brain, there is also evidence that our brains can alter their own structure to compensate for abnormal input [Doidge, 2007]. Contrary to the previous belief that our brains were hard-wired in a particular way, scientists now believe that our brain is far more malleable than previously thought. This theory, known as neuroplasticity opens up a world of possibilities. In particular to the world of cognitive training, it suggests that constant exposure to mentally stimulating activities can very literally expand our minds. The chance that the functionality of our brains can be improved through mental exercising has caught the imagination of the public and accordingly an entire industry has rapidly grown up around it. In particular, it was the advent of the

Nintendo DS hand held entertainment system and its series of cognitive training games that helped turn the concept of cognitive training into a worldwide phenomenon. In the next section the recent rapid growth of the cognitive training industry and some of the better known products available will be discussed.

7.4 Nintendo and the Rise of Cognitive Training

For many years, video games were the focus of negative media attention. At best they were portrayed as addictive mind-numbing entertainment for children. At worst, they were thought to encourage violence and antisocial behaviour in their players [Anderson & Bushman, 2001]. However, in the last few years, another side has been put forward; video games can actually have a positive impact on players. In particular, a 2003 study linked video game playing to an improvement in a variety of visual and attentional skills [Green, Bavelier, 2003]. From there, it was a short leap from 'video games have positive effects' to 'video games designed to have positive effects'.

At the same time that this was occurring, Nintendo were enjoying a large influx of new customers brought into the video game market by their new console, the Nintendo Wii, and their new hand held gaming device, the Nintendo DS. To date, these systems have sold 86.41 million and 146.42 million units respectively [Nintendo, 2011]. Looking for alternatives to ‘hard core’ gaming, Nintendo approached Dr Ryuta Kawashima, a Japanese neuroscientist who had previously written a book on the concept of cognitive training. Together, they released Brain Age; a puzzle based video game that makes use of cognitive training techniques [Carless, 2006]. Since then, Brain Age has sold over seventeen million copies worldwide [Nintendo, 2009], spawned several best-selling sequels, many imitators and helped bring the concept of cognitive training to a larger audience than ever before.

Tellingly perhaps, Nintendo are very careful not to make any specific claims regarding the validity of their cognitive training games. Instead they refer to them as 'entertainment products' that are 'inspired' by Dr Kawashima's work in the area of neuroscience [Arnst, 2006]. Other cognitive training systems are not so coy. In the next section we examine some of the more popular cognitive training systems currently available, focusing only on those that are peer reviewed and backed by scientific studies.

7.5 Popular Cognitive Training Systems

Searching for 'cognitive training' or 'brain training' online will yield literally millions of results. It's a growth industry and as often happens, the industry itself is outpacing the research that validated it. There are many different cognitive training systems available for a fee, but very few of them are actually backed by scientific research. Of those, even fewer have been subjected to external studies. Given the sheer amount of choices, it would be impractical to describe them all, but two of the better recognised systems are introduced below:

Cogmed: [http://www.cogmed.com]
Officially launched in 2007, Cogmed is primarily the work of neuroscientist Dr Torkel Klingberg from the Karolinska Institute in Sweden. Klingberg’s research focuses on children with attention deficits caused by ADHD and how computer based training systems can improve their Working Memory capacity and attention span and reduce the symptoms of ADHD [Klingberg, Forssberg, Westerberg, 2002], [Klingberg et al, 2005].

The Cogmed system costs between $1,500 and $2,000 for the complete package. There are three separate systems available. One for children aged four to six, one for children over seven and one for adults. The adult program involves an intense series of forty minute computer based training sessions. There are twenty-five sessions in all, spread out over a five week period. These sessions consist of undertaking a rotating series of tasks, thirteen in total, that cover both audio and visual Working

Memory. The difficulty level of these tests varies depending on the users' performance in order to present a constant challenge and maximise results. Cogmed is only available through licensed medical doctors and psychologists and provides coaches who guide clients through the process so they can get the most out of their training [Cogmed, 2011].

Cogmed is one of the better examined systems available with several studies available documenting its impact on children with learning disabilities and Working Memory deficits. Ultimately though, these studies largely originate from or are associated with the Karolinska Institute itself and independent research on the Cogmed system is difficult to find. There have also been questions raised about the small sample sizes used in Klingberg's research as well as the methodology of the studies [Shipstead, Redick, Engle, 2010]. Later studies trying to replicate the effect on healthy children who do not suffer from ADHD have also had limited success [Thorell et al, 2009]. Whether these successes can be repeated independently and whether the benefits can really carry over into other areas or have an impact on those not suffering from Working Memory impairment remains to be seen.

Posit Science Brain Fitness Program: [http://www.positscience.com]
Posit Science was co-founded in 2003 by Dr Michael Merzenich, a professor in neuroscience from the University of California. Unlike the specific focus of Cogmed, Posit Science takes a more general approach to cognitive training. It promises improved mental processing speed and sharpness for both audio and visual information. It also has a much more relaxed training schedule than Cogmed, claiming that although the more time spent on the products the better, benefits can be seen from as little as fifteen minutes usage a day [Posit Science, 2007].

Posit Science offers several software packages designed to improve cognitive processing abilities in healthy and ageing adults. The total package - which combines both audio and visual applications, retails from $690 and is available to anyone. The total package is itself made up of two separate applications: The Posit Science Brain Fitness Program which contains six computer exercises focusing on auditory processing and memory, and the InSight program which contains five computer exercises for visual processing and memory. In total there are over one hundred hours of unique training material available in the package [Posit Science, 2007].

According to the Posit Science website, over thirty studies have been carried out regarding the effectiveness of the Posit Science system. Of these, two main studies are noteworthy: IMPACT (Improvement in Memory with Plasticity-based Adaptive Cognitive Training) and ACTIVE (Advanced Cognitive Training in the Independent and Vital Elderly). Both claim improvements in information processing speed, improvement in performance on standard memory tests after use and self-reported positive changes in everyday life [Willis et al, 2006], [Smith et al, 2009]. As with the Cogmed system, these studies and many of the others listed on the Posit Science website were carried out by Posit Science themselves or by people associated with them in some way. Both the IMPACT and ACTIVE studies also focused mainly on older adults and relied heavily on self-reported improvements for their results. While the studies boast promising results, the question remains whether they can be validated by independent study and whether the benefits apply to everyone or just the specific target groups.

Others:

While the two programs listed above are among the most widely regarded of those available, there are many other cognitive training systems.

The Jungle Memory system is available online at [www.junglememory.com]. It shows promising initial results, demonstrating both improvements in Working Memory and transferable benefits to academic achievement [Alloway & Alloway, 2009]. However, the study only focuses on children with learning disabilities and suffers from a small sample size.

Cognifit [www.cognifit.com] has a few published studies indicating its effectiveness. Again these studies mostly focus on groups with learning disabilities such as students with dyslexia [Horowitz-Kraus & Breznitz, 2009].

Dakim Inc [www.dakim.com], LearningRx [www.learningrx.com] and many others all claim scientifically designed systems and improved cognitive performance as a result of using their products, but independent scientific research backing these claims is sparse or currently unavailable.

With so many companies offering cognitive training services and proclaiming its benefits, it is no wonder that many people are signing up. However, despite its popularity, there are still several issues surrounding the subject that need to be addressed. In the next section some of the main counter-arguments levelled at cognitive training will be addressed. These arguments show that not everything about cognitive training is as straightforward as many people think.

7.6 Issues Regarding Cognitive Training

It's only within the last ten years that the area of cognitive training has moved from a small niche market into a worldwide multi-million dollar industry. As such, it's not surprising that comparatively few studies have been carried out to examine its effects. On the one hand, as documented earlier in the chapter, there is some evidence to support the idea that cognitive training can help in specific circumstances such as children with Working Memory deficits caused by ADHD, or elderly adults suffering from age related cognitive impairment. The question is, are these special cases or can these same benefits carry over to unimpaired adults and children? Does cognitive training actually improve our brainpower or does it instead help people to work around pre-existing problems?

Another point about the studies mentioned above is that the majority of the research on cognitive training comes from those in the cognitive training industry itself. Many studies in the area are well researched and peer reviewed, but independent studies confirming their findings are still scarce. This is not surprising though, since examining the efficacy of cognitive training is still a relatively new field.

Another contentious issue regarding cognitive training is whether any of the supposed benefits carry over to tasks not directly examined by the application. In other words, by constantly using a test designed to examine Working Memory capacity, one may get better results in the test itself, but will those effects carry over into other associated activities? Is Working Memory capacity actually increased or are the improved results caused by developing techniques that assist in the testing process? Does cognitive training make you smarter, or just better at taking tests [Shipstead, Redick, Engle, 2010]?

Finally, if cognitive training applications do cause improvement in cognitive abilities, are they any more effective than the benefits which can be gained from keeping mentally active in everyday life? Is it better to undertake an intense cognitive training program, or can the same results be achieved by doing the daily crossword or taking up an activity like learning a musical instrument [Scarmeas & Stern, 2003]?

7.7 A New Study

In 2010, a new study was carried out by a team of British researchers in association with the BBC science programme 'Bang Goes the Theory'. Viewers of the programme were encouraged to visit the BBC Lab UK website and participate in a study on cognitive training. The study ran for six weeks and in the end over 11,000 people aged between eighteen and sixty completed the tasks successfully; making it the largest study on cognitive training yet carried out [Owen et al, 2010].

The methodology behind the study was as follows: After initially logging in to the system, each subject was required to complete a number of different tests including reasoning tests, visual and audio Working Memory tests and paired-associates learning (PAL) tests. These tests were used as a benchmark assessment of the subjects' cognitive abilities before the study. Once they had completed the initial assessment, subjects were randomly assigned to one of three groups. Each group was then required to practice six training tasks for a minimum of ten minutes, three times a week by logging on to the website.

The first group's tasks emphasized reasoning, planning and problem-solving abilities. The second group covered a much broader range of arithmetic, audio, visual and executive processing tasks such as would be observed in most commonly available cognitive training packages. The difficulty of these tasks rose as the subjects' performance improved in order to constantly tax their abilities and maximize any improvement gained. The third group acted as a control group and instead of focusing on cognitive tasks, they were asked a series of obscure questions on six different random subjects and encouraged to find the answers themselves using any online resources they wished. After six weeks of training in this manner, the initial assessment tests were repeated and the difference between pre and post training test scores were used as a basis for measuring any cognitive improvement.

When the results were analysed it was noticed that there was little improvement in results of the benchmark tests for any group. In fact, the control group showed the greatest improvement - although in each case the improvement was small enough to attribute mostly to test re-test familiarity. The researchers also compared the results of the subjects' first cognitive training session with the results of their final training sessions and noticed a statistically significant increase in the results of the final session. Even the control group showed a slight increase in their obscure knowledge levels. From this, it was concluded that any cognitive improvement gained from undertaking the training course related only to the tasks being directly trained and did not carry over into the generalised benchmark tests. In the words of the authors, the "results confirm that six weeks of regular computerized brain training confers no greater benefit than simply answering general knowledge questions using the internet."

Understandably enough, the results of this study have been challenged by a number of cognitive training companies on several fronts. Firstly, the study excluded children and elderly people, groups shown to have benefited from cognitive training in prior studies. Secondly, there were claims that ten minute sessions, three times a week is far too little training to show any measurable results. The biggest issue many trainers had with the study was the fact that just because the training course used in the test failed to provide results, it does not mean that all training courses do. The developers behind the Cogmed system themselves predicted that the study would conclude that cognitive training provided no tangible benefit. However, they hope the study encourages people to differentiate between "ineffective games" and "evidence-based cognitive training" instead of dismissing the idea of cognitive training entirely [Cogmed, 2010]

As can be seen, the debate over the effectiveness of cognitive training is far from over and only time will tell how it will end. In the next section, the link between cognitive training and Working Memory will be explored, focusing on the link between Working Memory and intelligence. Following this, the role the VAM application can play in the study of cognitive training will be discussed.

7.8 Working Memory and Cognitive Training

As discussed in Chapter 2, Working Memory is a limited capacity storage system which also functions as a mental workspace used to manipulate information for ongoing cognitive processes [Baddeley, 2002]. As such, the capacity of one's Working Memory is thought to be a key factor in one's ability to carry out a wide variety of cognitive tasks [Engle et al, 1999], [Kane et al, 2004]. Therefore logically, by increasing the capacity of Working Memory, the ability to carry out associated tasks will also increase. This is the core of cognitive training. As discussed above and in Chapter 6, there have been several studies that suggest that cognitive training can improve the condition of people with impaired or diminished Working Memory capacity including children with ADHD [Klingberg, Forssberg, Westerberg, 2002], [Klingberg et al, 2005] and adults with Alzheimer's disease [Clare, Woods, 2004], [Sitzer, Twamley, Jeste, 2006]. In order to demonstrate improvements in cognitive processing ability, these studies require that the subjects have their cognitive abilities measured both before and after the training. This is done through the use general intelligence tests such as Wechsler's Adult Intelligence Scale (discussed in Chapter 3) or Raven's Progressive Matrices (discussed below). But if Working Memory is such a key component to cognitive processing, how exactly does it differ from intelligence?

7.8.1 Working Memory and Intelligence

The term intelligence is used variably to refer to a number of cognitive abilities including: reasoning skills, communication skills, learning, problem solving, emotional intelligence and many others [Cianciolo & Sternberg, 2004]. As with Working Memory, the structure of intelligence is still largely theoretical, with plenty of theories and few certainties regarding its exact nature [Neisser et al, 1996].

One of the more popular theories began with Charles Spearman [1904] who found that people who performed well in one intellectual task generally performed better in others too. He proposed that this correlation suggested a common underlying factor, which he called '**g**', which is measured by all tests of intellectual ability. Spearman referred to this factor as 'a general fund of mental energy' [Spearman, 1914]. Spearman later noted [1938] that this factor '**g**' was well represented by individual differences in the results of what later became known as Raven's Progressive Matrices [Raven, Court, Raven, 1989]

Raven's Progressive Matrices were developed in 1936 [Penrose & Raven, 1936] and are a non-verbal test of reasoning and analytic intelligence. The test comes in three separate formats; the Coloured Progressed Matrices which are used primarily for children, the Stanford Progressive Matrices which are suitable for people from ages six to eighty and the Advanced Progressive Matrices which are designed for above average adolescents and adults. The Advanced Matrices consist of 36 individual tasks arranged by difficulty. Each task consists of a three by three grid of geometric patterns, with the bottom right pattern missing. Below each grid is a set of eight alternative patterns, only one of which completes the grid successfully. Candidates are allowed thirty minutes to complete as many of these tasks as possible and their recorded score is the total number of grids they complete successfully.

Raven's Advanced Progressive Matrices have since become closely linked with Spearman's '**g**' and have been used in countless studies of intelligence over the years. They have had their reliability and validity demonstrated many times over the years as well [Pearson Inc., 2007]. Numerous studies have likewise shown the correlation between the results produced by Raven's Matrices and those produced by Working Memory tests [Engle et al., 1999], [Conway et al., 2002], [Kane et al., 2004], [Unsworth & Engle, 2005].

The notion of Spearman's '**g**' has become so prevalent over the years it is often thought to refer to general intelligence itself. Some researchers believe it to be a more abstract concept though. Ackerman, Beier and Boyle [2005] refer to it as "a generic representation for the general efficacy of intellectual processes" and Jensen [1998] states that "it is wrong to regard '**g**' as a cognitive process, or as an operating principle of the mind, or as a design feature of the brain's neural circuitry"

In an effort to pin down the elusive '**g**' factor, Raymond Cattell [1943] proposed that general intelligence was made up to two main types, crystallized intelligence (Gc) and fluid intelligence (Gf). Crystallized intelligence refers to the ability to use knowledge and skills acquired in the past. It is not the same thing as Long-Term Memory, although it does draw heavily on that system. Fluid intelligence on the other hand refers to the ability to handle new situations where previous knowledge is only of minimal use. Raven's Matrices is an example of a test that measures fluid intelligence [Carpenter, Just, Shell, 1990]. It should be noted that there is evidence to suggest that fluid intelligence is virtually indistinguishable from Spearman's '**g**' when examined [Gustafsson, 1984].

The link between fluid intelligence and Working Memory has been investigated in detail [Kyllonen & Christal, 1990], [Engle et al., 1999], [Conway et al., 2002], [Kane et al., 2004], [Unsworth & Engle, 2005]. These studies found that Working Memory capacity correlated highly with fluid intelligence, with some even going so far as to claim that Working Memory is the basis for fluid intelligence, or that the two concepts were interchangeable.

While some of these studies have been criticised [Suß et al, 2000] because the methods of measuring of Working Memory and intelligence were quite narrow and sometimes employed similar testing methods, even the critics could not deny the connection. Suß et al even commented that “Working Memory capacity is the best predictor for intelligence that has yet been derived from theories and research on human cognition.”

So is it possible to improve Working Memory capacity? More importantly, will this improvement carry over into other areas and raise intelligence levels? As mentioned above, the results so far are inconclusive. There are too many factors involved and more research is needed [Buschkuehl, Jaeggi 2010], [Shipstead, Redick, Engle, 2010].

A good suggestion, however, is that instead of focusing on whether all-in-one cognitive training packages work, instead the research should focus on individually targeted systems. A single cognitive training system may not be of benefit to everyone, but perhaps focused training styles or regimens might produce noticeable improvements and transfer effects in specific people [Jaeggi et al, 2011], [Morrison & Chein, 2011].

7.9 The Role of the VAM Application in Cognitive Training

The VAM application has many similarities to commercial cognitive training applications. Indeed Working Memory tests form the core of many cognitive training products because Working Memory has been shown to be an extremely important element of fluid intelligence [Kane & Engle, 2002], [Engle et al, 1999]. Unlike these products though, the VAM application's main role is to gather data for analysis. As well as giving an overall result which can be used as a measure of Working Memory capacity, the VAM keeps records on each candidate's individual responses to each round and his/her response times during those rounds. This level of detail could form a solid basis for measuring any benefits gained from completing the VAM application on a regular basis. Similarly the focus on audio and visual Working Memory in the VAM ensures that any improvement documented can be clearly attributed to training on a specific task.

Another important use for the VAM could be as a benchmark test for studies into different cognitive training systems. One criticism levelled at studies of cognitive training products is the variety of methods they use to test for cognitive improvements [Shipstead, Redick, Engle, 2010]. The VAM provides a free, quick, easy to use and independent method of examining changes in Working Memory capacity. It is therefore especially suited to examining whether a cognitive training system provides any noticeable improvement in Working Memory. If independently conducted studies all make use of the VAM application to test Working Memory, the results obtained can also be directly compared. Any explicit improvements caused by the different approaches of different cognitive training systems will therefore stand out.

In conclusion, while the VAM itself could indeed be viewed as a basis for a cognitive training application itself, it would be better served as an investigative tool to analyse the effectiveness of other cognitive training systems and hopefully provide some useful results on what benefits they confer.

7.10 Conclusions

The field of peer-reviewed and scientifically based cognitive training is still relatively young. Only recently has it become popular and lucrative enough to warrant serious investigation [SharpBrains, 2010]. There is still fierce debate on both sides about what exactly cognitive training achieves. There have been studies showing that cognitive training can have an impact in specific cases such as children with ADHD [Klingberg, Forssberg, Westerberg, 2002] and the elderly [Willis et al, 2006], [Smith et al, 2009]. There have also been studies questioning the current methods used to examine cognitive training systems [Shipstead, Redick, Engle, 2010] and even studies indicating that cognitive training has no measurable effect when not targeting a specific problem [Owen et al, 2010].

Although the promise of current cognitive training systems may be in doubt, the role of Working Memory in the industry is clear. The link between Working Memory and fluid intelligence has been shown repeatedly [Kyllonen & Christal, 1990], [Engle et al., 1999], [Conway et al., 2002], [Kane et al., 2004], [Unsworth & Engle, 2005]. By better understanding the nature of Working Memory, in terms of both function and capacity, the benefits of cognitive training may finally become clear.

In the meantime though, unless some conclusive evidence against cognitive training's efficacy is brought forth, and perhaps not even then, the cognitive training industry is likely to continue growing. Testing the effectiveness of cognitive training requires serious time and resources. The VAM application can provide an important contribution to the area, and will hopefully do so in future studies.

7.11 Review

In this chapter, the emerging field of cognitive training was discussed. It was shown to be a fast growing field [Sharpbrains, 2010], particularly after Nintendo released a line of brain training games for their Nintendo DS system [Nintendo, 2009]. Some of the more scientifically tested systems such as Cogmed [2011] and Posit Science [2007] were reviewed. Both systems showed favourable results when focusing on particular target groups [Klingberg, Forssberg, Westerberg, 2002], [Klingberg et al, 2005], [Willis et al, 2006], [Smith et al, 2009].

The main issues surrounding the field of cognitive training were discussed along with evidence from the biggest study yet conducted in the area that suggests that the results of cognitive training do not transfer well to a wider field [Owen et al, 2010].

In addition to exploring the concept of cognitive training, its connection to Working Memory was also discussed. The varied concept of intelligence was introduced focusing on Spearman's '**g**' factor [Spearman, 1904] and the use of Raven's Progressive Matrices [Raven, Court, Raven, 1989] as a measure of '**g**'.

The subdivision of '**g**' into crystallized intelligence (Gc) and fluid intelligence (Gf) [Cattell, 1943] was described before showing the well-documented crossover between Gf and Working Memory [Kyllonen & Christal, 1990], [Engle et al., 1999], [Conway et al., 2002], [Kane et al., 2004], [Unsworth & Engle, 2005].

Finally, the role that the VAM application can play in investigating the field of cognitive training was discussed showing why the VAM is a perfect tool to gather evidence about the subject.

In the next chapter another area where the VAM application's detailed structure and analytic capabilities could be of benefit will be discussed; the area of e-learning.

Chapter 8: E-Learning

8.1 Introduction

In Chapter 7, the concept of cognitive training was discussed. Cognitive training is a growing industry in which the goal is to enhance cognitive functionality, primarily through the use of computer based training courses. While there is still plenty of debate about what lasting impact these systems have on users, there is little doubt that computers can be valuable tools for learning and improving our minds through knowledge. In this chapter, the field of e-learning is introduced and examined. The importance of Working Memory to this discipline and the role the VAM application can play in its improvement are also discussed.

E-learning, also known as computer based training/learning, web based training/learning and any number of written variations of eLearning, is the practice of using computer and communication based technology to facilitate and enhance the learning experience. Many different technologies are used within this field, including web-cams, digital televisions, e-mail, chat rooms, DVDs and nowadays even mobile phones. The benefits of e-learning are clear. E-learning allows students to learn on their own time, from their own homes and at their own pace. The goal of e-learning should be to support traditional methods of learning by designing systems that allow students to focus their studies while providing a high level of interaction to simulate the benefits of the classroom environment. Over the course of this chapter the concept of e-learning will be discussed; where it started, how it has developed and its advantages and disadvantages. The important role Working Memory has to play in an e-learning environment will also be examined along with how the VAM application can be used to investigate computer based learning techniques and even act as a configuration tool for e-learning courses.

8.2 What is E-learning?

E-learning is really a catch-all term for a spectrum of technologically aided learning styles [Bates & Poole, 2003], [Romiszowski, 2004]. E-learning can refer to anything from using a computer as a teaching aid for notes and group discussions to courses run entirely online, including lectures carried out via webcam and assignments distributed, collected and marked digitally. It can be applied to almost any level of education and is also gaining popularity as a tool in the workplace [Simmons, 2002].

The fact that the term e-learning has been used to cover such a broad spectrum of learning systems and techniques has unfortunately meant that the word has lost some of its original impact and even in peer reviewed studies it is sometimes unclear what form of e-learning is being discussed. With this in mind, it is probably a good idea to break the spectrum of e-learning down into a few more specific types. Note that this breakdown is merely for informational and clarity purposes and should not be viewed as an official scale.

8.2.1 Tier 1: Computer Assisted Learning

The simplest form of e-learning refers to the use of computers in a traditional learning environment. As such, it is sometimes referred to as computer assisted learning. While the learning is still taking place in a traditional classroom based system, computers are being used more and more as a resource to enhance teaching. This can refer to as little as using computers to look up additional information for use in class up to using Content Management Systems (CMS) and Learning Management Systems (LMS) to bolster the educational process.

LMS and CMS in this case refer to computer applications designed to be used in conjunction with a classroom environment. They allow educators to store course notes online, provide supplemental information that may not have been covered in class and a way to communicate with students outside of the classroom environment. They can also allow students to communicate with each other (usually through bulletin boards, chat rooms or blogs), share information and form virtual study groups. These systems are normally secured and require students to log in before they can access the content. Examples of these types of system include the basic of functionality of Moodle [http://moodle.org/] and WebCT/Blackboard [http://www.blackboard.com/].

8.2.2 Tier 2: Computer Based Training Systems

While the first tier of e-learning described above uses technology to supplement traditional learning environments, this type of e-learning uses technology to replace them to a greater or lesser extent. Computer Based Training (CBT), as it is sometimes known, refers to self-paced learning courses accessible through computers, or increasingly, through hand-held devices. These courses can be delivered via an application or more commonly over the web (Online Learning). They are also a form of distance learning; the educator and student do not have to be in the same location or even directly interact.

CBT courses started out quite simply. Information on a specific topic was stored in a digital format that could be distributed to students for learning purposes. At the end of the course, there may have been some form of assessment, generally a selection of multiple choice questions to gauge how much the student learned. Of course, much has changed since the advent of CBT. With computers growing in power and high speed internet connections becoming standard, CBT courses now have greater potential than ever. Rich, multimedia based courses allow students to learn in a variety of ways and through the use of many different formats including text, images, audio and video. Increasingly, CBT courses also allow a much greater level of interactivity than before.

CBT courses are usually custom built to focus on a particular subject and so rely on close collaboration between designers and educators in order to be successful. This, combined with the cost involved in designing and building these courses mean that CBT is rarely used to its fullest potential, but the process is becoming increasingly popular; particularly in the corporate and educational sectors [Simmons, 2002], [Ambient Insight, 2011].

8.2.3 Tier 3: Computer Supported Collaborative Learning

Another approach to e-learning comes from the communicative potential of computers. Whereas Computer Assisted Learning and Computer Based Training are both primarily about the transfer of information between the educator and the student, Computer Supported Collaborative Learning (CSCL) instead focuses on allowing students to work together and learn as a group. While the benefits of collaborative learning have long been established [Johnson & Johnson, 1986], [Slavin 1989, 1996], [Gokhale, 1995], [Dillenbourg, 1999], CSCL allows the added dimensions of distance learning and detailed record keeping.

CSCL allows students from around the world to come together, share information and help each other learn. CSCL, sometimes referred to as e-learning 2.0 [Downes, 2005], takes advantage of the proliferation of user generated content on the net. Tools like wikis, blogs and the Learning Management Systems mentioned above allow information to be shared and exchanged in new and complex ways. Technology like video conferencing software and Skype allow people in distant locations to communicate in real time for the purposes of discussion and debate. Like CBT, these courses can take place completely online; unlike CBT they do not require the direct intervention of an educator to guide, moderate and evaluate the learning process.

As can be seen, the potential covered by the banner of e-learning is enormous and continuing to grow. In the next section, how the concept of e-learning originated and the impact it has had on the world since are examined.

8.3 The Rise and Fall and Rise of E-Learning

When discussing the origins of e-learning it is difficult to decide when to begin and what to include. E-learning has grown from many different sources both educational and commercial and, as explained above, has referred to many different concepts. A full detailed history of e-learning would take too long to describe, but here are a few of the important steps towards what we now think of as e-learning.

In order for something like e-learning to come about, many disparate events had to take place. Perhaps one of the first that occurred was the popularisation of distance learning back in the 1840s when Isaac Pitman offered courses in short hand by post [Moore & Kearsley, 2005]. Another important event occurred in 1924 when Sidney Pressey developed the first 'teaching machine' which allowed students to answer multiple choice questions by pressing the correct button [Pressey, 1927, (as described in Benjamin, 1988)]. In 1953, the University of Houston started offering college courses via a public television station [HoustonPBS, 2011]. All these events paved the way for e-learning, but it was the introduction and proliferation of the personal computer and later the dawn of the internet age that showed the obvious possibilities of computer assisted learning.

By the late eighties and early nineties, organisations around the world - both educational and industrial, were using networks to share information and resources.

In 1993, William D Graziadei described a project involving lectures, tutorials and assessments, all carried out via computer. The project was conducted via e-mail, the Mosaic internet browser and several other software applications designed to create a virtual classroom atmosphere [Graziadei et al, 1997]. More and more, the computer was becoming a tool of education and as can be expected, many people saw the potential for profit in the area.

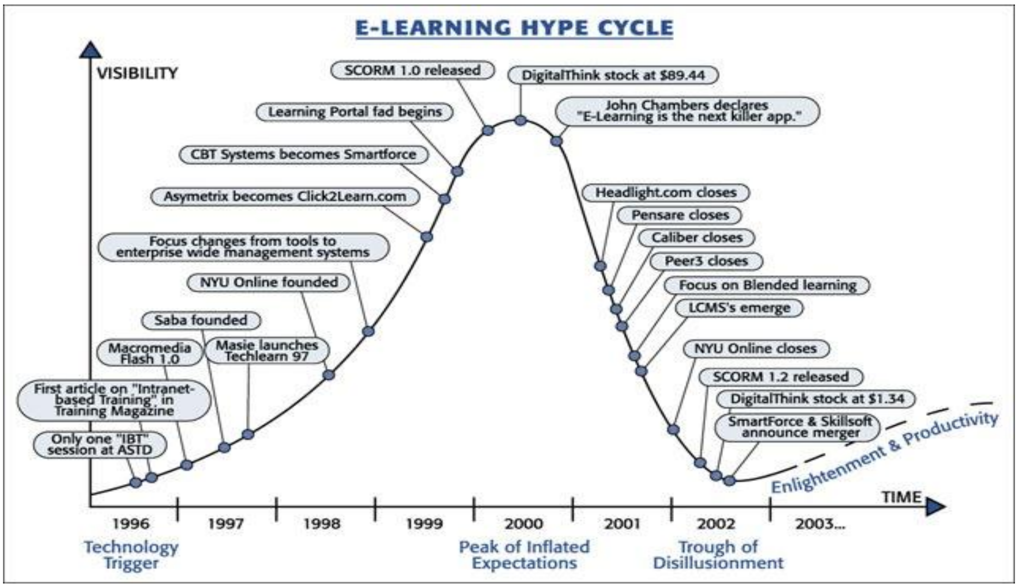

Figure 11: The E-Learning Hype Cycle [Kruse, 2004] based on the Gartner hype cycle model [Fenn, 1995]

It was in the mid-1990s when things really began to change. The above chart (Figure 11), created by Kevin Kruse in 2004, documents the enormous growth of the e-learning industry in the mid-1990s and its later fall. The main points in the chart are described below (Summary based on [Kruse, 2004] and [Fournier, Dragne, Romila, 2006]):

- In 1996 at an ASTD (American Society for Training & Development) conference, a workshop devoted to intranet-based training was unexpectedly attended by more than 500 participants. The workshop led to a series of articles, speeches and million dollar contracts.

- In 1997 big e-learning companies like Techlearn and Saba (created by ex-executives from Oracle) were founded and e-learning began to be marketed as the way forward for corporate training.

- Between 1998 and 2000, a new set of e-learning specifications and standards were developed called SCORM (Shareable Content Object Reference Model) enabling the reuse of web-based learning content across multiple environments. Unrealistic values for shares of e-commerce companies, e-learning providers and technology stock in general began to become common.

- In 2001 the unrealistic standard set for e-learning finally began to catch up with it. E-learning became a victim of its own hype. Just as may happen with the cognitive training industry (described in Chapter 7), the demand for the technology spurred a proliferation of e-learning systems that outpaced the research behind them. This demand led to inflated expectations, which in turn led to a backlash when the expectations were not met.

- The backlash against e-learning, coupled with the 'dot-com' crash in 2000, crippled many e-learning companies and discredited the concept of computer based learning systems. Several high-profile e-learning providers shut their doors and many more announced large-scale layoffs due to missed revenue targets and crashing stock prices. E-learning advocates retreated to the more defensible ground of "blended learning" approaches which combine e-learning with traditional learning techniques.

Since the crash, the e-learning industry has recovered and started to grow again; this time with clearer expectations and a more realistic approach regarding the role of computers in education. According to a report by Ambient Insight, the estimated market value of self-pacing e-learning products and services was 32.1 billion American dollars in 2010 and that is expected to rise to 49.6 billion dollars by 2015 [Ambient Insight, 2011].

As with the study of Working Memory itself; researchers from a number of different fields are currently working together to find a balance between the benefits of technology and the benefits of traditional educational methods. In the next section some of the advantages of e-learning systems as well as some of the issues that still need to be resolved will be discussed.

8.4 Advantages and Disadvantages of E-Learning

E-learning has come a long way since its inception and it has the potential to go much further. It is extremely unlikely that computer based learning will ever disappear now that it has been introduced and shown its value. Equally though, it is unlikely that computer based learning will ever fully replace traditional learning methods, at least not with our current level of technology. Like every other tool at an educator's disposal, e-learning has its advantages and disadvantages. It is important to consider these factors fully before deciding what form of computer assisted learning is best suited to a particular situation.

8.4.1 Advantages

The main advantages of e-learning revolve around its flexibility. Students can learn at any time during the day or night and so arrange their studies for when they feel alert and ready. They can also learn from the comfort of their own homes as long as they have access to a computer and the internet. This opens learning courses up to a whole host of new students, be they part-time students, mature students or just students unable to physically attend classes.

The level of flexibility inherent in e-learning courses can also benefit the developers and teachers. It allows experts in any field, as well as the best teachers, to share their knowledge and skills with a large cross section of society, regardless of location. Equally, courses can all be maintained, updated and distributed from a centralised location. This reduces time and costs for educators.

With e-learning courses, students are also much more in control of their own learning. If a student finds the current content too simple or irrelevant to his/her needs, he/she can simply move on to another section of the course. Students can learn at their own speed without being held back or thrust forward depending on the needs of others. Well-designed e-learning courses also allow the facilitation of different learning styles through the use of different media and training activities.

Another area which benefits greatly from e-learning is that of corporate training. After the initial investment in the computer based training course, companies can train as many employees as they wish with minimal overhead. Employees receiving this training all get the same standard of training while eliminating instructor costs, travel costs, meeting room rental costs, and minimising the time the employee is away from work.

Perhaps the most interesting advantage of e-learning is its potential. E-learning allows many different formats and styles to be used in the education process. Text, images, speech, music and movies are all easy to incorporate into e-learning courses. Games, quizzes, tests and other interactive elements can also be implemented

Relatively speaking, e-learning is still a young field. Every year enormous amounts of research are conducted as to how to get the most out of e-learning and every year technology continues to improve. With virtual reality looming in the future and new ways to interact with machines found every year, who can say what the end result of e-learning might be? In the meantime though, e-learning still has its share of problems and these should also be addressed in the interests of fairness.

8.4.2 Disadvantages

While e-learning allows students to take control of their own learning, this is not always a good thing. Lack of motivation on a student's part or poor study skills can easily cause him/her to fall behind and so the student may not get as much out of e-learning courses as he/she would in a more traditional environment.

Likewise, for the most part, students using e-learning courses do so alone and on their own time. If they encounter any problems along the way or struggle with the material in the course they have limited options when looking for assistance. Even if there is a system in place for asking questions, the nature of distance learning means that answers may take time to reach them, which can disrupt the flow of learning as well as demotivate the student. This problem can be lessened somewhat by using collaborative learning methods as described above, but they still rely on the student to actively seek out assistance.

The social aspect of traditional learning methods is one that cannot be overlooked either. The impersonal nature of computer based learning is liable to cause feelings of isolation and reduce the benefits of peer-to-peer learning if not handled correctly.

Another problem for students is that they are dependent on the technology for success. Computer problems, slow internet connections or just lack of access to a computer can cause the learning process to grind to a halt and again frustrate and demotivate the student. It also requires that students already have a suitable level of computer skills in order to get the most out of their learning experience.

From a business point of view, e-learning also has its drawbacks. Firstly it requires an enormous investment upfront, in terms of time and money. Training courses for specific topics need to be designed and built with the target audience in mind. It also requires close communication between those who provide the content and those who design and build the course itself. Both sides must be aware of the guidelines and limitations inherent in the e-learning course system as well as the guidelines and limitations inherent in the field of education itself in order to produce a useful system.

Finally, e-learning does not translate well to all topics. Many subjects require a hands-on or practical based approach to learning in order to be successful and in many cases e-learning is simply not up to that standard; not yet, at least.

So do the benefits of e-learning outweigh the drawbacks? The growing use of computer assisted learning systems seem to indicate they do, but there are many factors that can influence whether a particular subject or student is suited to a computer based learning approach. Like many emerging trends, e-learning is still largely unproven. There are many claims on both sides of the debate about whether e-learning is better, worse or the same as traditional learning methods when it comes to results; see [Bernard et al, 2004] for a review. Some argue that the format or media itself is just a vehicle and irrelevant compared to the learning strategies that are built into it [Clark, 1983, 2001], while others argue that certain approaches and styles of learning are only possible due to the media involved and so the medium does affect the learning process [Kozma, 2001].

A lot of time and effort has gone into ensuring that traditional learning methods achieve the desired results and there are several research disciplines devoted exclusively to studying how people learn. Now that the e-learning hype has faded and its potential is being looked at in a more realistic fashion, it is time to ensure that e-learning proves itself worthy and makes use of educational psychology as well as emerging technologies to produce the best possible results. One of the key elements involved in this process is the study of Working Memory.

8.5 Working Memory and E-Learning

As previously explained, Working Memory is responsible for, amongst other things, storing and processing information and focusing attention (see Chapter 2). It is also strongly connected with measures of intelligence (see Chapter 7). It's no surprise then, that Working Memory plays an important role in the learning process.

Over the years, many different studies have been carried out linking Working Memory capacity to reading ability [Swanson & Alexander, 1997], [De Jong, 1998], arithmetic ability [Bull & Scerif, 2001], [Passolunghi & Siegel, 2001] and language acquisition [Baddeley, 2003b]. Similarly, low Working Memory capacity has been linked to low scores in predictive academic assessments at an early age [Gathercole, Brown, Pickering, 2003] as well as at later stages such as college entrance exams [Daneman & Carpenter, 1980], [Jurden, 1995]. In fact, Working Memory is now thought to be a better predictor of learning ability than IQ [Alloway, 2009], [Alloway & Alloway, 2010].

The connection between Working Memory and learning is especially noticeable in children with learning difficulties. In Chapter 6, ADHD was discussed, along with how afflicted children suffer from a Working Memory capacity impairment. This holds true for children with other learning difficulties too. In particular, while children with behavioural or emotional problems perform normally on Working Memory assessments, those identified as having general learning difficulties that include both literacy and mathematics perform poorly [Pickering & Gathercole, 2004], [Alloway et al, 2005].

Due to the importance of Working Memory in the learning process, care must be taken when designing courses not to overload the students' Working Memory capacity and so inhibit learning. This is especially important for e-learning courses where there isn't usually an instructor on hand to assist if the student is overwhelmed. The amount of information processing and attention required for a particular task and the stress this places on Working Memory is known as the cognitive load.

The theory of cognitive load was developed by John Sweller in 1988. Sweller proposed that problem solving was not the most appropriate tool for learning because both processes placed considerable strain on processing capacity, meaning that the mental effort required to work through a problem left little room for the process itself to be learned. Instead, Sweller suggested that it was more efficient for the load on processing capacity to be reduced through the use of worked examples or goal free problems. This would allow the total processing capacity to be focused on the learning process instead, which Sweller believes is based on the use of schemata. In this instance, a schema refers to a cognitive structure that is built up from prior experiences and knowledge. These schemata are then automated, allowing people to identify existing patterns in new situations or information and deal with them more easily.

Sweller's theory has been updated several times since, and in doing so, been applied to a broader canvas. By 1998, Sweller referred to the cognitive load theory as "designed to provide guidelines intended to assist in the presentation of information in a manner that encourages learner activities that optimize intellectual performance" [Sweller, Van Merriënboer, Paas, 1998].

According to Sweller's proposed guidelines, there are three main types of cognitive load that have an impact on processing capacity and hence Working Memory:

- Intrinsic cognitive load refers to the inherent difficulty of the material being presented. This cognitive load cannot be altered by the instructor, but can be spread out by breaking the material down into smaller parts before recombining it at the end.

- Extraneous cognitive load refers to the cognitive load associated with how the material is presented and what it requires of the student. Poorly thought out or presented material places a greater load on Working Memory and it is the responsibility of the instructor to limit this load.

- Germane cognitive load refers to the load placed on Working Memory by the creation, processing and updating of the schemata used in the learning process. In other words, by keeping presentation format and teaching methods consistent, students can work with existing schemata to process new information more easily.

Sweller suggests that instructors focus on reducing extraneous cognitive load and focus students' attention on the construction and use of schemata. In the context of Baddeley's model of Working Memory [Baddeley & Hitch, 1974], this means special attention needs to be paid to how information is likely to be processed by the phonological loop, the visuospatial sketchpad and the central executive. When choosing a format in which to present important material, extraneous cognitive load can be reduced by limiting the amount of material presented at once and limiting the number of different ways it is presented in. This will allow the material to work within the limits of the Working Memory system.

As such, presentation format should be a consideration for any e-learning course designer. To design a successful, multimedia enriched e-learning course requires a solid underlying knowledge of cognitive load theory and Working Memory. With so many different technologies available to designers, the temptation is to use as many as possible, to use different types of multimedia to make the course appear interesting and detailed. However, it is far more important to focus on using the different aspects of multimedia: the text, the movies, the images and the sound carefully, so that they complement each other. This is referred to as the cognitive theory of multimedia learning [Mayer & Moreno, 1998], [Mayer, 1997, 2001].

The goal of multimedia learning is discovering the best way to present each aspect of a multimedia enhanced course so that they have the greatest impact on the student's learning. According to Mayer's theory, there are several principles that need to be upheld when it comes to multimedia learning in order for students to get the best out of the course.

The main principle of Mayer's theory is known as the modality principle and follows Baddeley's model of separate audio and visual stores in Working Memory. Using these stores in parallel should enhance learning when compared with overloading a single store. As an example of this, Mayer's demonstrated that students performed better when information was presented via speech (audio) and diagrams (visual) than via text (visual) and diagrams (visual) [Moreno & Mayer, 1999].

The second main principle is that of redundancy. Students perform better when information is presented using necessary formats only. For example, students benefit more from material presented via animation and narration than from animation, narration and text together [Mayer, 2001].

The cognitive theory of multimedia learning is a useful guide and brings to light several important issues with regards to e-learning, but it tends to diminish the impact of individual differences in students learning methods and Working Memory capacity. While monitoring the use and interaction of different forms of media within an e-learning course is a sensible precaution, it seems overly simplistic to assume that the same format works best for everyone. A better idea may be to use Working Memory as a guide to personalise an e-learning course towards a particular student's strengths.

One of the most exciting aspects of e-Learning is its potential for adaptability. Adaptive Educational Hypermedia (AEH) is the term used to describe the personalisation of an educational, multimedia based environment to better suit a user's needs and abilities, while maintaining the core material of the course [Brusilovsky, 1996, 2001]. A lot of research into AEH initially revolved around adapting courses to fit a student's interests and enabling them to seek out useful pieces of knowledge in an easier fashion [Brusilovsky, 2001], but over the last few years, the potential to adapt courses based on users' cognitive styles has become more popular, see [Gilbert & Han, 2002], [Papanikolaou et al, 2003], [Kelly & Tangney, 2006] and many others.

With this in mind, the potential role Working Memory can play in the adaptive process could be of great interest. As previously described, Working Memory plays an important role in the learning process and has been linked to many varied academic subjects. Working Memory has also been shown to be important in hypertext and hypermedia learning [Dutke, & Rinck, 2006], [DeStefano & Lefevre, 2007]. Can Working Memory therefore be used as a basis for adapting e-learning courses? In particular can the investigation of visual and audio Working Memory form a basis for assessing individual differences in students' capacities and from there help personalise courses to make the most of these capacities? So far, not a lot of research has been conducted in this area, but a recent study has produced some positive results and indicated that the area is worth exploring further [Tsianos et al, 2010].

In order to test these hypotheses further, a reliable tool for investigating audio and visual Working Memory is needed. With this in mind, in the next section the role the VAM application can play is supporting and improving computer based learning will be examined.

8.6 The VAM Application and E-Learning

The VAM application has the potential to bring many benefits to the area of e-learning. As discussed above, the ultimate goal of e-learning is to produce useful content and present it in such a way as to maximize a student's learning potential. One of the ways of doing this is to present information in a format best suited to a student's learning style whether it is through text, image, sound or video. The temptation in these cases is to make use of the technology available and simply present information in all formats, but that can be confusing and counterproductive to the learning process. The VAM application can help simplify and focus this process.

As previously explained, the VAM application focuses on examining both audio and visual Working Memory. It provides detailed information on a candidate's strengths and weaknesses in these areas. With this in mind, the VAM can act as an exploratory tool for e-learning. The VAM can be used to investigate audio and visual interaction in a computer based environment and examine how users react to different combinations.

Another potential and exciting use for the VAM application is to serve as a configuration tool for e-learning courses. Before beginning a course, a student could complete a short version of the VAM application. The results produced could then be fed into the computer based training course (or saved for future courses) so that the content of the course would be presented in a manner that works with the student's Working Memory capacity and style. If the student shows an affinity for audio Working Memory, more speech and audio tracks can be used during the training course. If the student scored higher on the visual tests, images and diagrams would be substituted instead.

Of course, the situation is hardly black and white, most students probably lie somewhere in between the two extremes and prefer to work with both audio and visual material. But even small changes could have an impact on both the attention and the retention of the student: a small audio cue here to highlight an important concept, a quick image or diagram there to reinforce a previously stated idea. It is small changes like these, geared towards a specific student that could help keep a student interested in the course and help him/her remember what he/she has learned during it. Using the VAM application as a starting point, this approach can be realised.

8.7 Conclusions

E-learning is a fast growing industry [Ambient Insight, 2011]. Its potential has yet to be fully realised, but already its uses are clear. E-learning allows students to work outside the bounds of traditional learning systems, both physically and mentally.

The expectations associated with e-learning are high. There are many advantages distinct to e-learning and these advantages unfortunately led to the e-learning industry try to go too fast, too soon, with predictable results [Kruse, 2004]. The problem wasn’t with e-learning as a concept though; the problem was focusing on the advantages of e-learning to the deficit of everything else.

There are literally hundreds of years of research available on learning in general. Instead of focusing on how e-learning is competing with traditional methods, the focus should be on how it can complement these methods and use technology to apply what we already know about learning in new and novel ways.

Working Memory plays an important role in the learning process [Alloway, 2009], [Alloway & Alloway, 2010]. The theory of cognitive load describes how much of an impact different combinations of materials can have on Working Memory [Sweller, Van Merriënboer, Paas, 1998]. The cognitive theory of multimedia learning [Mayer & Moreno, 1998] in particular makes use of Baddeley's model as a guide for designing multimedia rich e-learning courses. By abiding by this theory, courses can be designed that work with our Working Memory systems to produce better results.

The above theories can also be applied in a more practical fashion through Adaptive Educational Hypermedia (AEH). These systems involve using knowledge of the user to configure courses to his/her specific needs and styles [Brusilovsky, 1996, 2001]. The use of Working Memory capacity as an adaptive technique [Tsianos et al, 2010] is still new and largely unproven. The VAM application can help with this.

8.8 Review

In this chapter, the concept of e-learning was explored. The main different types of e-learning were introduced, differentiating between computer assisted learning, computer based training and computer supported collaborative learning. Some history on the e-learning industry was given, showing how its explosive growth led the industry to crash [Kruse, 2004] and how it has since made a comeback [Ambient Insight, 2011].

The main advantages and disadvantages of e-learning were also reviewed along with e-learning's connection to Working Memory. The link between Working Memory capacity and learning abilities was established [Alloway, 2009], [Alloway & Alloway, 2010] along with how cognitive load theory [Sweller, Van Merriënboer, Paas, 1998] can be used to ensure that e-learning courses can be designed so as to not overwhelm a student. Finally, the benefits the VAM application could bring to the e-learning industry were discussed along with a hopeful role for its future.

Over the last three chapters, the versatility of the VAM application and the valuable role it can play in a number of fields has been espoused. In the next and final chapter some closing remarks on this study will be included along with a review of what was gained from it, what problems were encountered during it and finally some proposals for future research directions using the VAM application.

Chapter 9: Discussion

9.1 Introduction

Over the course of this thesis the concept of Working Memory was thoroughly examined, popular methods used to test Working Memory were reviewed and these methods were used as a base for the VAM (Visual & Audio Memory) application.

The VAM application is a new testing suite designed to explore audio and visual Working Memory in a manner that works with a candidate's natural storage and recall processes. It is a computer based test that can be completed without supervision or one-to-one interaction with a trained professional. It provides detailed results that can be of use in numerous areas. It is extensively configurable which further increases its range of possible applications. The VAM can and hopefully will be a valued research tool in years to come and serve as a benchmark for further testing applications of this type.

After being implemented, the VAM application was rigorously tested in order to prove that it is a reliable, validated test of Working Memory that compares favourably with others in the same field. Using the VAM application as a springboard, a number of wider areas that intersect with the study of Working Memory were then explored, focusing on health and safety, cognitive training and e-learning. The potential for the VAM application as a tool in these areas and the potential benefits it could provide were espoused. Through of all this, the VAM application was shown to fill an under-populated niche in the field of researching Working Memory.

In this chapter, the information gathered in this thesis is summarised. The contributions to knowledge obtained from this thesis are then discussed along with their implications. Finally, some of the problems that occurred over the course of this project are reviewed along with some suggested directions for future research.

9.2 Summary of Thesis

The genesis of this thesis came from the lack of independent, scientifically tested computer based tests of Working Memory commonly available. The majority of research carried out on Working Memory makes use of traditional paper based one-to-one tests of Working Memory. When computerised tests are used, they are often just coded versions of existing tests, designed for a specific study and with little thought for the true potential of computerised testing. In other words, the tests are built as a means to an end, not as a potential source of future research themselves.

Of those few well designed and well-recognised tests that do exist, several limitations still exist. Riding's IPI [Riding 2000] has the benefit of being fully automated without the need for an administrator, but is limited by its unitary view of Working Memory, its fixed design structure and its questionable reliability. The Automated Working Memory Assessment [Alloway, 2007] benefits from its thorough analysis of the Working Memory system and its well established reliability and validity, but is limited by its reliance on individual administration and again by test structures that cannot be extensively configured.

The VAM application was conceived as a remedy to these limitations. The VAM application is an independently designed suite of tests that makes use of existing knowledge and is:

1. Rooted in the current theories of audio and visual Working Memory, focusing on Baddeley's multi-component model [Baddeley & Hitch, 1974].

2. Designed and built by referencing popular existing methods for testing Working Memory, both traditional and computer based.

3. Able to be used by multiple people simultaneously without the need for one-to-one administration.

4. Able to provide detailed results on both audio and visual Working Memory that can be of use in numerous different research areas.

5. Extensively configurable in a number of different ways, allowing it to be used by many different types of candidate and in many diverse fields.

6. Backed up by rigorous scientific testing to show that it is a reliable, validated test of Working Memory and so can be safely used in future research studies.

An analysis on the literature (Chapter 2) showed that Baddeley's model of Working Memory [Baddeley & Hitch, 1974] was an appropriate base for designing a new test of Working Memory. Baddeley's model specifically lays out the groundwork for both audio and visual components of Working Memory as well as separate processing and additional storage units [Baddeley, 2000]. This model explicitly showed what needed to be analysed by the new test.

Looking at various methods of examining of Working Memory that are currently available (Chapter 3) it became clear that there were many vastly different ways to test Working Memory. Popular testing systems include the Recognition Memory Tests [Warrington, 1984], Wechsler's Adult Intelligence Scales [Wechsler, 2008], Riding's Information Processing Index [Riding, 2000] and Alloway's Automated Working Memory Assessment [Alloway, 2007].

One extremely common element however, was the prevalence of variations on the digit span test. The fact that this method has persevered for so long indicates its popularity and usefulness. With a few tweaks to expand it to fit in with Baddeley's model, it was used as a basis for the new application.

The VAM (Visual & Audio Memory) application as it became known began to take shape. In Chapter 4, the design and implementation of the VAM application were discussed. The VAM is composed of five separate tests, each based on variations of the digit span test. Two visual tests were designed to examine visual Working Memory, one using letters and one using images as stimuli. Two audio tests were designed to examine audio Working Memory, again one using spoken letters and one using words to describe images as stimuli. Finally a mixed audio/visual test was designed to explore the interaction between audio and visual elements in Working Memory, this one using a mix of spoken or printed letters as stimuli.

One of the major design principles of the VAM application was that it should be extensively configurable. To this end, administrators are given the option to change many of the settings involved in the above tests including: the maximum stimulus sequence length and the number of attempts per round, the display time of the stimulus sequence, whether the user has to re-enter the sequence in reverse order or as presented, and where the results of the application are stored

With the VAM application designed and built it was time to make sure that the VAM application performed as intended (Chapter 5). A detailed and rigorous testing process was carried out in order to examine the reliability of the VAM application and its validity when compared to Riding's IPI [Riding, 2000] and the well-recognised test Raven's Progressive Matrices [Penrose & Raven, 1936]. In each case the VAM application performed well. It was demonstrated to have excellent test re-test reliability. It correlated to a modest degree with Riding's IPI, which has some problems of its own. It also correlated with Raven's Matrices at a level consistent with similar studies in the area.

Once the VAM application had proven itself, it was decided to explore a few wider areas where the study of Working Memory and the VAM application in particular could be of use. Three distinct areas were identified where the VAM application could provide useful insight. These areas were chosen because they are all rapidly growing industries and will likely continue to grow in importance in the future.

The first area chosen was that of medical diagnosis and safety (Chapter 6). Here it was noted that long-term impairment of Working Memory capacity can be an indication of serious medical conditions such as ADHD [Barkley, 1997], [Klingberg, Forssberg, Westerberg, 2002] or Alzheimer's disease [Baddeley, 1986]. There is even some evidence that training Working Memory can actually assist in the treatment of ADHD [Klingberg et al, 2005] and delay the onset of Alzheimer's [Stern, 2006]. With this in mind, the role of the VAM application as an early warning system for these conditions was explored. Similarly, the dangers of short-term Working Memory impairment caused by fatigue [Tiersky et al, 1997] were discussed along with how the VAM could detect these impairments and so act as a safety feature due to its portability and versatility.

The second area where the VAM could prove useful was the relatively new area of cognitive training (Chapter 7). The scientific research behind cognitive training was examined along with its rise to popularity. Some of the main cognitive training applications were also reviewed. Again the role of Working Memory in this area was examined with emphasis on the relationship between Working Memory, fluid intelligence [Kyllonen & Christal, 1990] and Spearman's '**g**' factor [Spearman, 1906].

It was then explained how VAM could be of assistance in this area, mainly due to the controversy over the actual effectiveness of cognitive training [Owen et al, 2010] and the methods used to study it [Shipstead, Redick, Engle, 2010]. The VAM could therefore be useful in such studies due to the fact that it can be completed independently and provides detailed results which would notice any change in Working Memory as a result of cognitive training.

The final area chosen was that of e-learning (Chapter 8). E-learning refers to the use of information technology in education and comes in many different varieties [Bates & Poole, 2003], [Romiszowski, 2004]. The e-learning industry is currently recovering after a major crash; one which was largely due to failing to live up to its own hype [Kruse, 2004]. Now instead of attempting to replace traditional learning methods, the e-learning industry is beginning to make use of them. The link between Working Memory and learning was discussed in detail here [Alloway, 2009], [Alloway & Alloway, 2010] and with it, the role the VAM application could play in the area. It was shown how the VAM application could function as a research tool for e-learning. Perhaps more importantly, the VAM could be used as a configuration tool to help create adaptable e-learning courses that make the most of a student's individual audio and visual Working Memory capacity [Tsianos et al, 2010].

9.3 Contributions to Knowledge

Design and implementation of the VAM Application: The main contribution to knowledge provided by this thesis is the VAM application itself. The VAM application is based on a solid theoretical understanding of Working Memory, using Baddeley's model as a basis for its design. The VAM application was implemented and modified based on existing tests of Working Memory. The VAM application, as far as could be ascertained, is the only fully automated, fully independent, extensively configurable, computer based test of audio and visual Working Memory currently available. The VAM application has been shown to be a reliable, valid test of Working Memory and fills the need for a versatile computer based research tool admirably.

The unreliability of the IPI test: Previously, there was little data available on the reliability of Riding's IPI. One previous study suggested the unreliability of the IPI application [Parkinson et al, 2002], but that study had a relatively small sample size of **n** = 51. The results of the reliability analysis performed as a part of this thesis (see Chapter 5) had a much greater sample size of **n**= 163 (**n**=157 with outliers removed) and definitively demonstrated the unreliability of the IPI.

The importance of accommodating Working Memory capacity in application design: The results generated from the testing of the VAM application clearly show the dangers of mixing audio and visual stimuli in computer applications. Candidates produced the lowest results when presented with a mixture of audio and visual stimulus, even though the letters used as stimuli had generated the highest results when used independently as stimuli. These results can help build on Mayer's cognitive theory of multimedia learning [Mayer & Moreno, 1998] and demonstrate the importance of not overloading Working Memory when designing multimedia based applications, particularly in areas like e-learning.

The benefits of computerised tests of Working Memory: This study also helps demonstrate the benefits and convenience of computerised testing. When testing the VAM, the results of a small percentage of the overall sample were unfortunately lost. However, this was largely due to the inexperience of the researcher involved. The researcher had never carried out a testing project of this magnitude before and so was not prepared for, or equipped to handle some of the problems that arose (some of these problems are discussed in more detail below). Future studies will be altered to ensure that these problems do not occur again or are minimized. In the meantime, the VAM shows how easy it is to test multiple candidates simultaneously and to gather, collate and analyse results that are all already in a digitised format.

9.4 Limitations and Problems

During the development of this project, several problems arose which needed to be overcome, particularly during the implementation and testing stages. In this section, some of the main problems and limitations are discussed.

The biggest problem that occurred during this project was the difficulty in locating an independent, peer reviewed test of Working Memory to act as a benchmark for validating the VAM application. Many of the more recognised tests of Working Memory are available only to fully qualified researchers with appropriate PhD degrees. Those that are commonly available are often commercial in nature with costs ranging from several hundred to several thousand Euros and are often charged on a per candidate basis. These conditions were a major limitation for a relatively small-scale research project such as this.

Locating a suitable benchmark test was also difficult due to the nature of the VAM application. To be a suitable match for the VAM, a test was required that was computer based, had already been validated and had been used in research studies itself. The benchmark test also needed to match the VAM in terms of independence. The test had to be able to be completed without requiring a direct administrator who might unintentionally impact the results. In the end, Riding's Information Processing Index [Riding, 2000] was selected because it is a validated, affordable, independent computer based test. The IPI came with its own set of problems though including a noticeable ceiling effect and low reliability. Hopefully, future studies will provide access to further suitable validation tools to compare the VAM against.

Another set of problems arose during the testing phase of the study. Testing the audio Working Memory of a roomful of candidates at once was problematic, largely due to the inexperience of the researcher involved in organising the testing. Each candidate was provided with a set of headphones to minimise the noise levels in the testing room. The headphones needed to be checked and tested before being presented to the candidates. The volume level of the application needed to be carefully controlled so that candidates could hear his/her own test clearly while not distracting other candidates by being too loud. Despite these precautions there were several occasions when the headphones had to be changed or the sound level altered during the test sessions. This in turn may have distracted other candidates and so impacted on their results.

Another difficulty during the testing process was the distribution of the test to each candidate and safe storage of his/her results. The application was initially developed as a web-based test. Each candidate would log on to the website, complete the application and have his/her results sent back to a central database. After consideration however, this format was not used over fears that a large group of candidates accessing the website and sending data at once might cause the site or database to fail. Instead a separate copy of the application was placed on a CD for each candidate and the results were sent to a blank disc in the computer.

Although the equipment was checked before the candidates began the tests, in a small number of cases the application failed to write the results correctly due to computer problems. Unfortunately when testing the reliability of the VAM, if a candidate's results for either session were lost, he/she could not be used in the overall analysis. This made each loss even more significant. Approximately ten percent of the total results were lost in this fashion. On the other hand, this loss was deemed acceptable compared to the alternate risk of the server failing during a test session. This is a limitation that needs to be addressed in future research.

One further limitation also needs to be addressed. The VAM application was initially implemented using the Authorware computer programming system. Unfortunately, this system has now been discontinued. While all testing was successfully carried out using the Authorware designed application, this situation must be rectified in future studies in order to continue improving the VAM.

9.5 Future Research Directions

Now that The VAM application has been shown to be a reliable, validated computer based test of audio and visual Working Memory, it opens up a wide range of possibilities for future work in the area. Over the last three chapters, several possible research directions for the VAM application were discussed in detail. In this section, those suggestions are reviewed along with some further suggestions for future research

In Chapter 6, the role of the VAM application as a diagnostic tool was discussed. This discussion focused on identifying long-term Working Memory impairments caused by conditions like ADHD and Alzheimer's and short-term impairments caused by fatigue. Due to the detailed nature of the results it produces and its ability to be completed without direct supervision, the VAM can be used to keep track of changes in a single person's Working Memory capacity over a protracted period of time. This could be extremely useful in studies focusing on the cognitive decline of patients with Alzheimer's where the VAM could help identify any downward trend.

Similarly, because the VAM is ideally suited to testing multiple candidates at once, the VAM can be used in studies that focus on investigating the Working Memory capacity of different populations. In particular, large groups of children or elderly candidates can be quickly and easily examined to build a central database of results across different age-groups. By identifying a standard level of performance for a particular population, severe deviations from that standard will be noticeable enough to help identify candidates in need of further examination.

In Chapter 7, the emerging cognitive training industry was discussed. There is still a lot of controversy over the effectiveness of cognitive training with criticism often focusing on the methods used to identify improvements in cognitive processing. The VAM is a freely available, quick and easy method of assessing Working Memory. It is therefore ideally suited for use in disparate studies on cognitive training. If independently conducted studies all make use of the same application to test

Working Memory, the results obtained will be much easier to compare. Any explicit changes caused by different cognitive training systems will also stand out.

In Chapter 8, the concept of e-learning was explored. Because the VAM makes use of common forms of stimulus like letters and images, it can be of use in studies relating to how these different forms of media affect the learning capacity of different people. Similarly, the emergence of Adaptive Educational Hypermedia means the VAM can be used as a tool to actually adapt courses to focus on a style that suits a particular user's Working Memory. Recent studies in the area such as Tsianos et al [2010] have had problems locating suitable audio and visual Working Memory tests for this task. The VAM application could provide a solution to this situation.

All of the above suggestions focus on using of the VAM application as a tool in other studies, but there is also plenty of research to be done on improving the VAM application itself. Currently, the VAM focuses on audio and visual Working Memory. In Baddeley's model, the visuospatial sketchpad is not only concerned with processing imagery, but also with spatial relations. In future incarnations the VAM could be expanded to explore the spatial component of Working Memory, although this would be difficult without varying from the homogenous nature of the current tests.

Similarly, the images chosen for the test were designed to be easily identifiable and so susceptible to phonological recoding. A case could be made that in order to fully explore visual Working Memory, the ability to use phonological cues to remember images should be removed. As explained in Chapter 3, this can be achieved with articulatory suppression, which denies the candidate the ability to subvocalize and rehearse audio cues. This process is not built into the VAM application though and relies on the candidate to suppress his/her own subvocalization. Perhaps future versions of the VAM could include a subtest dedicated to visual stimuli that can't be easily vocalised, such as random patterns.

One of the greatest advantages offered by the VAM application is that it is freely available, can be used in a variety of different areas related to Working Memory and has massive potential for future growth in terms of functionality. The VAM application itself is the most important contribution offered by this thesis. It is hoped that the VAM can become a new standard for testing Working Memory.

As previously explained, the study of Working Memory can impact a number of different research areas and there is a real need for a standardised measurement tool that can produce readily comparable results across a number of different studies. The VAM application can fill this need. The VAM is also particularly important to small studies that cannot afford to purchase the often prohibitively expensive Working Memory tests that are currently available. It is also hoped that the VAM will encourage others to design and implement their own Working Memory tests so that the usefulness of independent computer based tests will become more widely known.

In order for this to occur though, the VAM itself must first become more widely publicised. The first step in this direction will be to publish journal papers on the VAM itself and its potential for computer based testing. The main journal of interest here will be the Journal of Experimental Psychology: Learning, Memory & Cognition. There are also several journals of Educational Psychology and journals of Cognitive Psychology that may also be interested.

The next step will be to update the VAM itself. As previously explained, the VAM application is currently implemented in Authorware, a language that has unfortunately been discontinued. A new version of the VAM would ideally be implemented in a relatively recent and growing language such as HTML 5. The new VAM will continue to be freely available both as a finished product and as an open source development platform for future tests of Working Memory.

9.6 Concluding Remarks

The relationship between Information Technology and Working Memory is clearly mutually beneficial. Scientifically tested, computer based applications that explore Working Memory are still relatively rare despite being quick, efficient and capable of providing extremely detailed results. Over the course of this study only two widely recognised computerised tests of Working Memory were available for examination. The VAM application designed in this study has been shown to be a reliable and valid test of Working Memory and can therefore help remedy this lack.

The VAM application was designed as a tool to examine Working Memory capacity and the differences between audio and visual Working Memory. It gathers detailed information on the candidates' responses and records them in two separate formats. One which is designed to be examined in detail and one designed to be imported into spread sheets or statistical packages. With so few computerised tests of Working Memory currently available, the VAM application can be used as both a benchmark for future testing as well as an exploratory tool in its own right.

The VAM application is based on a sound theoretical base and was designed with reference to previous efforts in the field. It is a versatile research tool that can be completed without direct supervision by an administrator. It is also extensively configurable in terms of functionality and difficulty. It can be used by many different people in many diverse research areas and provide consistent results. The VAM is a unique and powerful tool that can aid the study of Working Memory and its many roles in our lives. These studies can in turn aid the design and evolution of the VAM and other computer applications. The VAM application has a lot of potential and this is hopefully the first step in seeing it realised.

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Appendix A: Reaction Time Tests

A.1 Introduction

The format of the VAM application underwent many changes during the course of this study. Several different types of tests were implemented and then discarded after initial trials suggested they were not suitable for the task at hand. The original plan for the study called for a series of reaction time tests to be implemented. These tests were analysed along with the tests of Working Memory in the VAM application. Only after the reliability analysis provided doubtful results for the reaction time tests, were they removed as part of this study. The results gathered during the testing process suggested that reaction time is too variable to test. Although the reaction time tests were left out of the final analysis, they remain a part of the VAM application.

The reaction time tests were included in the VAM application to allow researchers to calculate the actual time spent processing the stimuli during each of the Working Memory tests. The theory was that the candidate's reaction speed could be used as a gauge to estimate how much time was spent thinking about the stimulus as opposed to re-entering it into the application.

For example, if a candidate was required to store and re-enter a sequence of four images, then the processing time for that sequence would be the response time recorded by the Working Memory test, minus five times the average reaction time. The value of five times the average reaction time is based on the candidate pressing five buttons to re-enter the sequence (the four stimulus buttons followed by the continue button). It was hoped that by measuring the processing time of each stimulus type, it would be possible to estimate the complexity of text, audio and image based stimulus.

Unfortunately, the reaction time tests did not work out as planned. The reaction time tests were included as part of the reliability testing sessions, but when it came to analysing the results of the reaction time tests there was very little evidence to suggest that users achieved the same average reaction speed each time they used the tests.

Although the reaction time tests were deemed to be unreliable, it was felt that this is largely the nature of reaction speed rather than any fault in the application. Too many variables can affect a candidate's reaction time, from fatigue [Welford, 1968, 1980] to breathing [Buchsbaum & Calloway, 1965] to inherent finger tremors [Brebner & Welford, 1980]. Nevertheless, the reaction time tests could prove useful in come alternative capacity, and as such, they remained part of the VAM application. The reasons for this will be discussed in greater detail below, but first a summary of the different reaction time tests will be given.

A.2 Layout of the Reaction Time Tests

The reaction time tests contained in the application are designed to test the candidate's reaction speed under differing conditions. The goal is to gather enough data to give a good estimate of the candidate's average reaction time. There are three reaction time tests in all; the simple reaction test, the go/no go reaction test and the choice reaction test.

A.2.1 Simple Reaction Test

The first test, the “simple reaction test” is the most basic of the three reaction time tests. Upon starting the test the candidate is presented with an introduction screen explaining the concept of the test. The concept is simple; hit the space bar when the stimulus screen appears.

The structure of the test is also very simple. In each round, the candidate is presented with a waiting screen that will stay up for a random period of between one and three seconds. After this random waiting period is over, the screen will suddenly switch to the stimulus screen. Upon viewing the stimulus screen the candidate is required to react by pressing the space key on the keyboard. The program will then measure the time between the stimulus screen appearing and the candidate responding. The time measured is taken as the candidate’s reaction speed and the candidate is moved onto the next round.

Should the candidate respond too early, he/she is issued a warning and is taken back to the waiting screen. The default number of rounds to be completed in this test is ten. The average response time of the ten rounds is assumed to be the candidate’s mean reaction time.

A.2.2 Go/No Go Reaction Test

After completing the simple reaction test, the candidate is moved onto the second of the three tests, the “Go/No Go” test. The goal of this test is to measure the difference in response time when the candidate is faced with two different stimuli, one of which should be ignored. The basis of the Go/No Go test is that the candidate not only has to respond as fast as possible, but also has to pay attention to what he/she is responding to.

In terms of implementation, this test is similar to the simple reaction test. The candidate is again presented with a waiting screen but this time after the random delay the candidate will either be presented with either a "Go!" screen or a "No!" screen. Upon seeing the "Go!" screen, the candidate must press the space key within three seconds to complete the round successfully. If, however, the "No!" screen is presented, the candidate should not react. If the space key is pushed during a "No!" screen, the candidate has failed that round. If the candidate has not made any response after three seconds he/she has passed the round and is moved on the next one. Candidates are told when they make a mistake - to ensure that they are clear on the rules.

The round structure of this test is slightly different from the previous one. In the simple reaction test, there are a set number of rounds, but in this test, the candidate is required to complete a set number of "Go!" rounds before finishing. Using the default ten rounds, this equates to having to wait for ten "Go!" screens and succeeding at each one. The reason why succeeding in a "No!" round is not considered a completed round is because it does not yield a measurable reaction time. There is an equal chance of a "Go!" or "No!" screen appearing in any round, so it is likely that this test will take longer to complete than either of the other two reaction time tests.

A.2.3 Choice Reaction Test

The third and final reaction time test is known as the "choice" reaction test. This test is similar in structure to the "Go/No Go" test. There is an equal chance of two different stimulus screens appearing. The difference is, in this test, both of the stimulus screens require the candidate to respond, each in a different way.

After the usual waiting screen, the candidate is presented with a screen containing either the stimulus 'A' or the stimulus 'B'. The candidate must then react differently according to each of the presented stimuli. If the candidate is presented with the stimulus 'A', he/she is required to press the left arrow key on the keyboard to succeed. Similarly if the candidate is presented with the stimulus 'B', he/she must press the right arrow key to succeed. If the candidate chooses the wrong button, he/she is given feedback telling him/her that he/she has made a mistake. The feedback screen also informs the candidate what button he/she should have pressed. No positive feedback is given if the candidate succeeds in a round.

The basis for this test is to see how fast the candidate can respond while maintaining a clear distinction between two different types of stimuli. This test, like the simple reaction test, has a default of ten rounds.

After completing the third and final reaction test, the user is congratulated and presented with a summary of his/her reaction test results. The summary contains his/her average reaction time for each test, and if appropriate, the percentage of correct answers given. The user is also informed that his/her full results have been stored in a file and is invited to view them when he/she has finished.

A.3 Conclusions

Despite the unreliable nature of reaction speed, it was decided to leave the reaction tests as part of the application. There were three main reasons for this:

Firstly, the reaction tests themselves add little time to the overall testing process.

Secondly, although the reaction speed of a candidate may vary from day to day, it is plausible that reaction time and Working Memory response time that are measured during a single session might still be connected.

Thirdly, the quick-paced nature of the reaction tests, forces the candidate to focus on the task at hand. Stimulating the candidates in this way provides a good lead-in to the tests of Working Memory; the candidates can begin the tests already alert and focused.

Appendix B: Running the VAM Application

To run the VAM application which forms the basis of this thesis, simply run the CD included in the back of this report on a convenient PC or laptop. To use the VAM application, just copy the entire folder 'VAM Application' onto the host computer (The Desktop is a perfect location for this).

Please ensure that all the files in this folder are transferred before running the application. Please also ensure that there is enough room on the hard drive to store the result files generated by the program. Result files are written directly to the folder containing the VAM Application

The default settings for the applications are as follows:

- A backup location for storing results can be specified. This location defaults to C:\
- The Reaction Tests are set at 10 rounds each
- The Working Memory tests are set at 6 rounds each with 4 trials per round
- Reverse Mode is active

To enter the administrators' level of this application, simply type 'ADMIN' when prompted at the password screen. This is only the default password and can be changed as required.

The application can be closed at any time by pressing crtl+Q