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Developmental Aspects of Temporal Visual Attention

By

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Summary

The Attentional Blink (AB) is a measure of temporal visual attention (Raymond, Shapiro and Arnell, 1992) and the primary concern of present thesis was how the duration of the AB varied over increasing age and stages of cortical development. The involvement of the working memory and associated frontal cortical areas suggested that younger participants would yield poorer performance on this task than would adults. Results from investigations with frontal lobe patients (Richer and Lepage, 1996) suggested a deeper and more protracted AB at early stages of frontal lobe development, before full connections with the cortex are established (Hashimoto et. al, 1995; Hudspeth, 1987 and Stuss, 1992). This thesis finds a progressively reduced AB in participants across the range of 7-years of age to adult and this is attributed to poorer working memory function in children - a claim that is supported by the results of subsequent working memory investigation. A broader picture of visual attentional development is provided in a second set of experiments demonstrating that, unlike temporal attention, spatial attention is adult like by the age of 7-years old. The visual search tasks employed also utilise working memory (Duncan and Humphreys, 1989), but of a different nature to the AB and operating in different cortical networks. This finding suggests that the varying functions of the frontal cortex develop at differing rates.

The final set of experiments demonstrates that the developmental differences seen in visual attention and executive function are not limited to the controlled setting of the laboratory. It is important to show ecological validity for these claims and this is achieved with the use of video games. Developmental improvement on two novel games requiring executive skill, suggests frontal development and this claim is reinforced by the illustration of a significant inverse relationship between video game playing score and total AB magnitude. This finding supports recent claims by Green and Bavelier (2003) that training on an action video game leads to faster recovery of temporal attention during an AB task.

Results presented within this thesis have significant implications for future research within the field of visual attention, specifically the advancement of knowledge regarding frontal executive functions and their development. The video game investigation brings this research into the domain of socially relevant questions and modern technology and allows clinical and educational hypotheses to be drawn.

Chapter 1 — Introduction.

What is Attention and why do we need it?

As we move around and interact with our environment our senses are bombarded with information. There are constantly changing sights, sounds and physical sensations. For us to implement goal directed behaviour specific to an immediate task, we have to be able to select, and attend to, the particular information that is appropriate for that task and ignore any distracting information —this requires attention. Attention covers a wide range of psychological phenomena that can, and often do, interact with each other. In vision there is a limit on how much information we can reasonably take in at any one moment in time. For example we are unable to look in two directions at a time, and yet we can chose one of a range of spatially coincident items or regions of information. This involves 'selective attention'.

Selective Attention.

Not all objects within a given scene are perceived with the same clarity. We are aware of objects in our periphery, but their image is not as detailed as the image of those in our central vision (Gazzaniga, Ivry and Mangun, 1988). When we wish to act on an object we need to direct our attention towards it so we can process its features or guide our actions towards it. This usually occurs when we move our eyes and focus on the target object. However attention is not always directly linked to eye movements, and indeed we can re-direct our attention without moving our eyes. The mechanisms that control eye movements are independent from the mechanisms that control shifts of attention (Remington, 1980; Shulman, Remington and McLean, 1979; Tsal, 1983). This is referred to as covert orienting of attention and is in contrast to overt attention where attention follows eye movements (in the visual modality).

Selective attention can be defined as the selection of a single source of information from among multiple sources (Pashler, 1998). In contrast divided attention involves the uptake or monitoring of multiples sources of sensory information simultaneously, or uptake from multiple sources over a very short period of time. Cherry (1953) used a dichotic-listening paradigm, known as the split-span technique to investigate selective attention in the auditory modality. Cherry (1953) asked participants to shadow a message that was presented to one ear, whilst ignoring information presented to the unattended ear. Participants were completely unaware of the semantic information in the unattended stream. Broadbent (1958) gave another account of this all or nothing attentional selection and proposed the existence of an attentional filter, which prevents processing of information from an unattended channel. This theory is known as Broadbent's Filter Theory and represents an 'early selection model'. This means that information from different sources enters the model in parallel, and is temporarily held in a buffer store. Items reserved for further processing are then passed through the filter into the limited capacity channel. Information that is not selected then decays. Items are only identified once they have been passed through to the serial processor. Only the physical properties of the unattended channel are detected and this serves to guide the setting of the filter.

Divided Attention

Broadbent's theory had to be revised when Moray (1959) showed that a participant *could* successfully detect his or her name in an unattended auditory stream.

Likewise, Treisman (1960) asked participants to verbally shadow (repeat whilst listening to) a story presented in one ear whilst ignoring a story simultaneously presented to the other ear. If the stories were switched over half way through, participants initially began to shadow the 'unattended' ear before reverting back to the original ear. Therefore, at least some of the semantic content of an unattended input can be processed and later discarded from processing. This suggests that information can be processed to a higher level than first proposed by Broadbent (1958) and *then* filtered so that only relevant information is fully processed. This represents a late model of attentional selection. Treisman (1964) elaborated on this theory when she discovered that the unattended ear could be analysed according to a variety of features, for example pitch. It then became clear that attentional selection occurs further along the processing continuum than was initially proposed by Broadbent (1958).

Deutsch and Deutsch (1963) proposed the 'late-selection' theory of attention. The bottleneck was now proposed to occur nearer the response stage of selection than the identification stage as proposed in early selection accounts. This model supposes that all stimuli are fully analysed and that the activity of competing signals is weighted for task relevance, with the most relevant stimuli being selected for response after full processing. Johnston and Heinz (1979) proposed that the positioning of the bottleneck is flexible and task specific, and occurs as early as is possible. More recently, Lavie (1995) has suggested that it is the perceptual load of a task that determines whether selection occurs early or late. Lavie states that if attentional demands are low then extra resources are available and irrelevant information is being processed (this results in interference effects, which will be discussed in greater detail later). Results of low-load tasks will therefore appear similar to those of a late selection process. In contrast, when the attentional demands of a task are high, there will be no resources remaining for distracter processing and the effects would confirm an early selection account. This conception of the perceptual load led Lavie to conclude that the same attentional mechanism is responsible for both early and late selective processing.

When we divide our attention between two simultaneous tasks it is often at the detriment of performance in one or both tasks (Pashler and Levy, 2001). This is dual-task interference and has been explained by accounts of limited-capacity processing as well as the bottleneck theories outlined above. Kahneman (1973) proposed that the amount of processing that an individual can achieve is subject to an overall limit and interference occurs when the processing demands exceed the capacity of attentional resources.

Whether the information is visual or auditory, there appears to be a limit to the amount that can be maintained or utilised at any one time. An early account of a central, limited-capacity store of attentional resources is that proposed by Atkinson and Shiffrin (1968). Following investigation into short-term memory and decay of information, Atkinson and Shiffrin proposed their 'modal model' of attention. This model involves discrete stages of information processing: Sensory inputs enter the system in parallel and pass to a sensory store where attention is then required to transfer inputs to a short-term store. Active rehearsal then maintains these representations in long-term storage. This early model of short-term memory assumed a unitary limited store for sensory information, regardless of the modality in which the information was presented (i.e visual or auditory). The system of temporary maintenance and manipulation of information was labelled 'working memory' (WM). These two operations were thought to influence each other and as the complexity of information processing increases, the available capacity for storage decreases, and vice versa.

After the early work by Atkinson and Shiffrin (1968), the notion of a unitary store was quickly dismissed in favour of a three-part WM system proposed by Baddeley and Hitch (1974). Baddeley and Hitch considered a unitary store insufficient to account for the processing and maintenance of information over short periods of time. Their model of WM comprises a central executive (CE) which controls two slave systems: the phonological loop and the visuospatial sketchpad (Baddeley and Hitch, 1974). These two subsystems operate on verbal and visuospatial information respectively. The concept of a 'working memory' is central to this thesis and as such the relevant aspects of this model will be discussed in some detail.

Working Memory (WM)

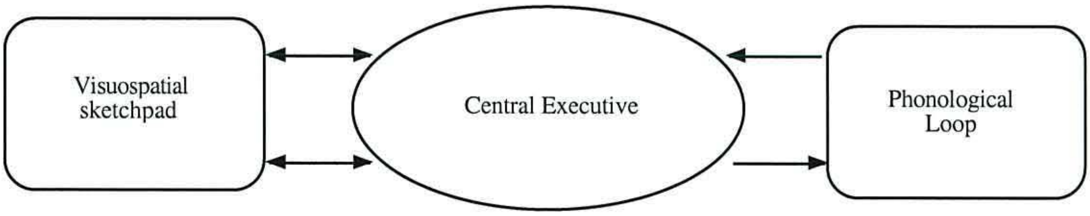

Figure 1: A model of working memory as proposed by Baddeley and Hitch (1974).

Evidence for the division of processing into a verbal and a visual component comes from studies in which little or no interference occurred when verbal memory tasks were run concurrently with visual memory tasks (Baddeley and Hitch, 1974;

Baddeley and Lieberman, 1980). This is in contrast to situations where two memory tasks utilising the same process (verbal or visual) are run together. In such tasks, high levels of interference have been observed (Vogel, Woodman and Luck, 2001). The phonological loop comprises two sub-components: the phonological store and the articulatory loop. Traces of verbal information decay from the store over a period of about two seconds unless refreshed by rehearsal (or subvocalisation) — a process dependent on the articulatory loop. It is often reported that the capacity of verbal WM is approximately 7 items (Miller, 1956) and tests of immediate recall have revealed that rate of decay is affected by phonological similarity and by word length (Conrad and Hull, 1964). The characteristics of the phonological loop slave system have been extensively investigated and modified since the point of their inception but as the focus of this thesis is visual attention, the phonological loop will not be discussed any more in detail here (see Baddeley, 2001 for a review).

The second slave system of Baddeley and Hitch's model, the visuospatial sketchpad, is responsible for the temporary maintenance and manipulation of visual and/or spatial information. There has been much less investigation into this component of WM than the phonological loop, partly because it is difficult to separate the two aspects of visual and spatial information processing. Woodman, Vogel and Luck (2001) have investigated the capacity of visual WM and they reported that only 3-4 objects can be stored at the same time within this system and that complex objects, comprised of 3 or more features, do not require greater WM capacity than simple objects. Wheeler and Treisman (2002) have elaborated on this finding and claimed that competition for capacity within visual WM is related to the dimensions of objects. Features of objects on the same dimension compete for capacity, whilst features on separate dimensions can be stored in parallel.

The CE eluded definition for some time after its proposal. It was considered to be a homunculus that took decisions about the functioning of the two slave systems. Initially, the central executive was defined vaguely as a "limited capacity pool of general processing resources" (Baddeley, 2001, p. 855). Early investigations into working memory deliberately neglected the CE because definition of the two slave systems was deemed more important. The processes involved in even the simplest digit span task such as complex strategy selection, planning and retrieval checking were thrown into the 'ragbag' of the central executive without further explanation (Baddeley, 1996; 2002). However, by the mid-1980's progress had been made. When the time came to revise the model of WM, Baddeley (1986) leaned heavily on the only model at the time that attempted to explain the attentional control of action — the Supervisory Attentional System (SAS) proposed by Norman and Shallice (1980) which was also thought to co-ordinate and plan actions (Gazzaniga et al., 1998). The SAS was developed to account for the problems of attentional control that are seen following frontal lobe damage. The SAS overrides routine behaviour by combining information from long-term memory (LTM) with the current stimuli when novel circumstances require modified actions.

Baddeley (2001), reviewing the progress in the investigation of the CE, outlined four theoretical executive capacities: (1) to focus attention; (2) to divide attention; (3) to switch attention; and (4) to serve as an interface between the two slave systems and LTM (i.e. to be an episodic buffer). The episodic buffer is considered to reflect episodic storage capacities, and the role of a buffer between LTM and the two subsystems that operate on different codes. The new model of WM proposed by Baddeley (2000) is illustrated in Figure 2.

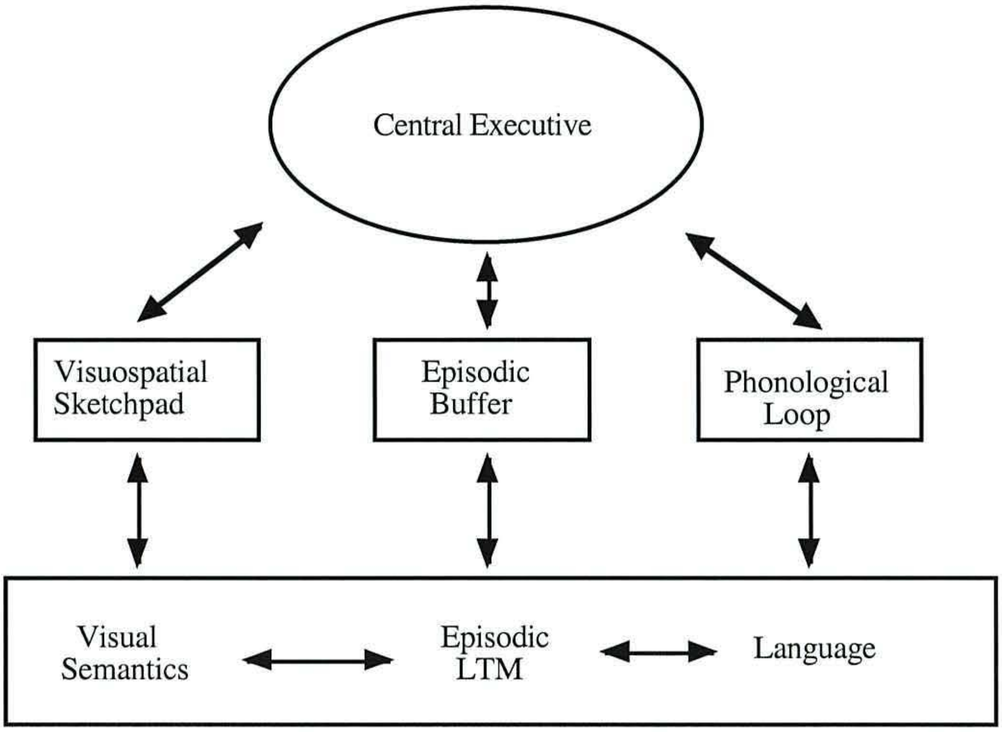

Figure 2: The current model of WM proposed by Baddeley (2000), taken from Baddeley (2001).

De Fockert, Rees, Frith and Lavie (2001) directly investigated the role of working memory in selective attention using fMRI. De Fockert et al. focused on one of the most prominent lines of investigation in the attention literature — the prevention of distracter item processing. In a situation where a target is to be attended or identified, the presence of irrelevant distracting information can cause interference and lead to target processing deficits. De Fockert et al. suggested that when attention is to be directed appropriately, working memory must actively maintain stimulus priorities by specifying which stimuli are relevant to the current task. If there is a high working memory load such as in dual-task situations, there will be less capacity available for discrimination of targets and distracters. Higher working memory load is therefore expected to increase distracter processing. By varying the load in a working memory task which was run concurrently with a selective attention task, de Fockert et al. demonstrated that distracter interference on the selective attention task was significantly greater in situations of high working memory load. Therefore, the extent to which irrelevant distracters interfere in visual selective attention processing is determined by the availability of working memory. Here the role of the central executive component of working memory in attention becomes evident: Functions such as divided attention, selective attention, rule following, and adaptation to novel situations can therefore be considered 'executive functions' (EFs).

Selective attention is required when simultaneous inputs (from either one or many sources requiring a response) compete for attentional resources. As previously mentioned, dividing attention between two simultaneous tasks is often at the detriment of performance in one or both tasks (Pashler and Levy, 2001). Divided attention operates on either multiple simultaneous sources or on sources of information over a very short period of time and as such, dual-task interference can be measured as a constraint on either temporal or spatial processing. Paradigms measuring both temporal and spatial attention are used within this thesis and therefore, although the primary focus is on the developmental aspects of temporal visual attention, a discussion of both temporal *and* spatial attention is included in this introduction.

In the following sections of this thesis, the role of WM and its sub-components in temporal and spatial attention will be discussed in some detail. Where the term 'WM' is used, it refers to the whole system proposed by Baddeley. However, since this thesis primarily investigates visual attention, WM simply refers to *visual* working memory comprising the visuo-spatial sketchpad and the functions of the central executive. In the following descriptions of temporal and spatial divided attention, the term 'visual short-term memory' is synonymous with the visuo-spatial sketch pad and refers to a system of temporary storage. Where a 'function' of WM is discussed, this refers to the operation of the central executive and is described as such.

Temporal Divided Attention

Dual-task interference occurs when the attentional requirements of two events or stimuli outweigh the available attentional capacity. In this situation, processing of one of the events is incomplete or omitted entirely. This can result in confusion between the items or a lack of awareness of one event because resources of attention are limited (Pashler and Levy, 2001). If sufficient time is not available between the events to allow attentional recovery, then task performance will suffer from depleted resources.

Psychological Refractory Period

When two stimuli requiring a speeded response are presented in close temporal proximity, so that the second stimulus appears before a response to the first can be made, the second response becomes delayed. Welford (1952) called this phenomenon the 'Psychological Refractory Period' (PRP). A limited-capacity mechanism is considered to be responsible for the delay since only one response decision appears to be processed at a time and therefore a second response decision becomes delayed until processing of the first is complete. This is a robust finding that is observed whether the response is a manual response, ocular (Pashler, Carrier and Hoffman, 1993), or vocal (Pashler, 1990). The PRP represents a bottleneck at the level of response selection for both tasks in progress. Until the first response selection has been made, the processing demands of the second response cannot be met (Pashler, 1998).

RSVP Methodologies

The temporal limits of the brain's processing ability have been widely studied using Rapid Serial Visual Presentation (RSVP) studies. Weichselgartner and Sperling (1987) investigated the time course of attention using two types of stimulus within a stream of digits that appeared at a single spatial location. Participants were presented with a cue to begin attending to the location and a first stimulus to be attended. Weichselgartner and Sperling reported an inability to encode further targets for a period of 200-400 ms following presentation of the cue. In such tasks the targets differ from other items in the stream by a variation on some feature such as colour or letter case. The terms T1 and T2 are commonly used to denote the first and second targets presented. In contrast to the case of PRP, responses to RSVP streams are not speeded and the entire stream of items is viewed before responses are made. RSVP experiments utilise both single target (where report of T2 only is required) and dual target trials (where T1 *and* T2 require report). Single target trials (T2 only) provide information regarding the temporal characteristics involved in the processing of a single item. This enables an appropriate presentation rate to be established. Classically, RSVP experiments involve briefly presenting visual stimuli (usually letters, words or numbers) at a fixed location in rapid succession, normally between 6-20 items per second (Raymond, Shapiro, and Arnell, 1992). Dual target trials investigate the interference caused by T1 on T2 detection in relation to the time interval separating the two targets. This interval can be manipulated by varying the serial position of T2 in relation to T1 (Broadbent and Broadbent, 1987). Broadbent and Broadbent demonstrated that correct identification of a letter stimulus, T1, interfered with the detection of T2 within 500 ms of T1 presentation.

The Attentional Blink

Raymond, Shapiro and Arnell (1992) replicated and extended the Weichselgartner and Sperling (1987) experiment, and coined the phrase 'The Attentional Blink' (AB). Raymond et al. simplified the task in an attempt to investigate whether this phenomenon could be due to memory-based reporting difficulties. T1 therefore became a white letter, which appeared on all trials and required identification, and T2 (present on 50% of trials) was a black X that required detection. All distracter items in the stream were black letters randomly selected from the alphabet (except X). T1 was the only white letter in the stream and T2 occurred across various serial positions following T1. Each letter in the stream was presented for 15 ms with an ISI of 75 ms., resulting in presentation rates of 11.11 letters per second. This procedure is illustrated in Figure 3.

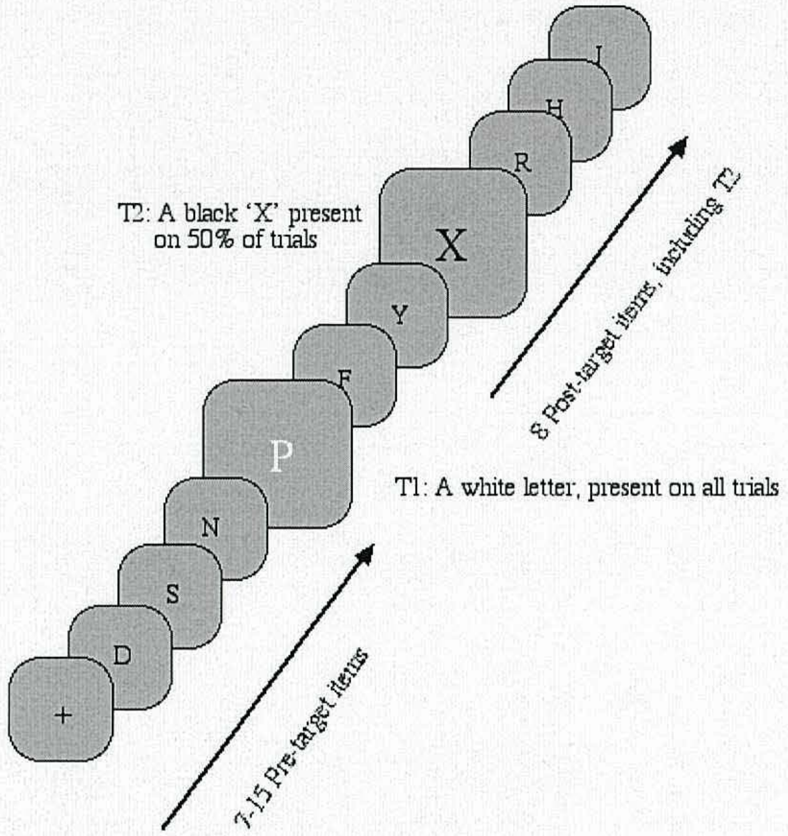

Figure 3: A graphical illustration of the RSVP methodology used by Raymond et al. (1992)

In both trial types (dual and single target), accuracy is measured in terms of T2 detection rates. T1 is presented on all trials and ignored, but T2 is presented on only 50% of trials. For the single target condition, report T2 only, all trials are analysed and a percentage correct T2 detection is calculated. In contrast, for dual target trials, only the trials where T1 is correctly identified are then used to analyse T2 detection rates. Raymond et al. (1992) reported a significant posttarget processing deficit for the interval ranging from 180 to 450 ms following the first target in dual target trials.

More importantly, this deficit was not seen in single target trials indicating that the processing difficulty occurs as a direct result of prior attentional allocation to T1. The AB can be defined as the inability to report a second visual target when it is presented in close temporal proximity (less than 500 ms) to a first visual target, which also requires report. Raymond et al. (1992) proposed the phrase 'Attentional Blink' as a loose analogy to an eye-blink due to the temporal characteristics of the T2 deficit seen in early experiments. An eye-blink results in a suppression of visual processing for approximately 150 ms and the maximal duration of the deficit in T2 processing in Experiment 1 of their report was 90 ms[1]. An eye-blink typically occurs after information has been acquired and the AB is a processing deficit following uptake of information from a stimulus and both processes appear to be ballistic (Raymond et al., 1992).

In dual target conditions, there appears to be an inability to fully process T2 to the level of report. Raymond et al. (1992) proposed that T1, a white letter, is detected preattentively in their dual target condition and that this information initiates an attentional response in order to facilitate target detection. It was first thought that there was a brief but total lack of awareness of the second target during the 500 ms time frame following T1 and Raymond et al. (1992) proposed a 'shut-and-lock' model to explain their data. T1 identification involves the opening of an attentional gate that regulates the input of visual information to the pattern recognition systems in the brain. The gate is then shut and locked behind an item once it has been accepted for processing. The gate is closed for a longer period of time if the item

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[1] However, this rose to 270ms in Experiment 2 and the typical duration of the AB reported in subsequent studies is between 350-500ms.

following T1 is potentially confusable with T1. If T2 is presented whilst the gate is closed, detection will be impaired.

The Interference Model

However, T2 detection rates during the 'blink' period are not at zero, Raymond et al. (1992) reported detection rates only as low as 40% during the 'blink' and therefore the deficit in second target detection rates cannot be considered a *total* lack of awareness. Shapiro, Raymond and Arnell (1994) illustrated the importance of the pattern of information in the generation of an AB and showed an attenuated AB when T1 was a brief temporal gap in the RSVP stream where no pattern information was presented. Shapiro et al. (1994) subsequently proposed the *Interference model* or similarity theory to account for the temporary reduction in T2 detection rates. They suggested that, initially, perceptual descriptions of all presented items are created and that this stage of perceptual processing operates in parallel and occurs early. Then a selection template of the targets is matched against the representations produced by the first stage. Items that match the target templates are passed to the limited capacity visual short-term memory (VSTM). These items are then assigned weights which determine their probability of report.

The similarity between distracter items (especially the T1+1 and T2+1 items) is an important factor in the selection for entry to VSTM. If the target and the item immediately following the target are perceptually similar, confusion will arise. The Interference model predicts that visual similarity between the target and the +1 item causes the attentional blink. In addition, items which enter VSTM first are assigned a higher weight than those entering later, simply because there are more resources available to the first items. It is theorised that the +1 items have a high likelihood of entering VSTM due to temporal limitations in selection speed (also see Maki, Couture, Frigen and Lien, 1997). Items with a sufficiently high enough weight can yield performance detriments in report.

Shapiro et al. (1994) suggest that as the interval between T1 and T2 increases, T1 must either be flushed from VSTM or no longer interferes with T2. This accounts for the improved T2 detection rates over longer inter-target intervals. The AB effect, in the Interference model is considered to occur at the point of VSTM output. Manipulations of targets and post-target items by Raymond, Arnell and Shapiro (1995) support this theory and suggest that it is the type of item immediately following the target that causes a deficit in the ability to report T2. This model suggests that in the presence of confusing distracter stimuli, once T1 has been identified, the 'attentional gate' is shut and locked and that in order to identify or detect T2, the gate must be unlocked and opened. When non-confusing distracter stimuli are present, the gate is just closed, and re-opens for second target detection.

The Attentional Dwell Model

The Interference model has support from N400 event-related potential (ERP) investigations (Luck, Vogel and Shapiro, 1996). ERPs have shown that the meaning of a word presented during the 'blink' is registered but is not processed to a sufficiently high enough level for report. Isaak, Shapiro and Martin (1999) directly demonstrated the intrusion errors of the other three critical items (T1, T1+1, and T2+1) on the report of T2. These items were incorrectly reported as T2 on above-chance proportions of trials, hence supporting the Interference model. Duncan, Ward and Shapiro (1994) and Ward, Duncan and Shapiro (1996) emphasised the role of limited capacity visual processing. In their *Attentional Dwell* model there is competition, according to an item's match to a target template, for a share of the limited capacity in visual processing resources. This competition gradually reduces over time and the winners gain visual processing resources at the expense of the losers.

Raymond et al. (1995) postulated that the interference within a short-term buffer is the cause of the AB. They build on the Interference model and claim that it is the featural and spatial properties of the +1 item that determines the magnitude of the AB: If the target and the +1 item are more similar on these dimensions, the magnitude of the blink is larger. It is the competition for retrieval between the two targets and the two +1 items within this buffer that gives rise to confusion. However, Ghirardelli and colleagues (Ghirardelli and Egerth, 1998; Grandison, Ghirardelli and Egerth, 1997) report significant ABs when the target and post-target item are visually dissimilar. The only situation in which they did not achieve a significant AB pattern is when the +1 item was absent from the RSVP stream. Ghirardelli et al. therefore dispute the Interference model proposed by Shapiro et al. (1994), and their results give support to Chun and Potter's (1995) 'Two-stage' model.

The Two-Stage Model

Chun and Potter (1995) proposed a *Two-stage model* to explain the dual target deficit seen in AB tasks, and suggest that it would be due to limited available capacity for processing and consolidation of items. Chun et al. (1995) theorised that all items in an RSVP stream of about 10 items per second, are processed to the first level (or stage) of their model, where the relevant features for target identification are detected. Stage 1 representations are subject to decay, due to interference from subsequent items, unless they are selected for further processing. Selection from Stage 1 enables the correct item (the target) to be passed on to the next level for additional processing, and the processing of non-target stimuli to stop. The representation of a target must be passed to a more durable stage such as visual short-term memory (VSTM) in order for it to be reported. This second stage of identification and consolidation is considered to be capacity-limited and does not begin until Stage 1 is complete. Once Stage 2 is completed, further items can be processed from Stage 1. This view is shared by Seiffert and Di Lollo (1997) who claim that masking indirectly affects the AB by degrading T1 and therefore increasing the processing time required by T1. T1 processing ability is determined by the discriminability between T1 and the item immediately following it. The role of effective masking is therefore important in AB studies and the presence of a distracter item following T1 is considered essential for obtaining an AB.

Jolicoeur (1998) reviews each of these models and proposes an alternative account that is similar to Chun and Potter's (1995) two-stage model: The *Central interference model.* This model makes comparisons between the interference seen in PRP and that of the AB and suggests that some of the interference seen in the AB has a post-perceptual locus such as response selection in dual target conditions. Subsequent investigation has also revealed the presence of an AB in other modalities and also cross-modally (Arnell and Jolicoeur, 1999). Jolicoeur (1998) gives evidence for a central interference model using cross-modality paradigms (however see Soto-Faraco and Spence (2002) for alternative theories). Shapiro, Arnell and Raymond (1997) present a unified model of the AB which attempts to bring some of the above theories together. Targets that are masked require more attention to reach a level sufficient for report. As with Chun and Potter's (1995) model, less attention is therefore available for T2 consolidation to achieve durable storage and it is therefore subject to decay. Despite an inability to report T2 with a high degree of accuracy, T2 *is* processed to a level of semantic awareness.

Additional evidence for post-perceptual selection, and therefore the processing of a supposedly unattended probe during the 'blink', comes from a study by Shapiro, Driver, Ward, and Sorensen (1997). The authors found positive priming effects of a first probe, P1 on a second probe, P2 when P1 occurred within the blink and P2 occurred outside it. This observation has support from the 'cocktail party phenomenon' where unattended auditory stimuli are perceived and processed so long as they are salient to the listener. For instance, a person's name will be identified from across a room even though the person may already be engaged in a conversation (Shapiro, Caldwell, and Sorensen, 1997). Therefore, items presented during the blink period are processed to some level and the AB does not reflect a total lack of attentional awareness. Instead, there is attentional selection based on a number of items that have been presented and retained in VSTM. Only the appropriate target items are processed to a level sufficient for report and therefore identification and retrieval of the target is dependent, at least to some extent, on competition in VSTM.

Following the hypothesis that attentional selection is important in determining what information is then encoded and consolidated by the central executive in visual working memory, Vogel, Luck and Shapiro (1998) applied the ERP technique to the

AB in an attempt to establish the stage of processing impairment. The WM system can get overloaded, and when it is currently busy with T1, no further items can be selected for consolidation. The AB therefore reflects impairment in VSTM update governed by the central executive operations in WM. Vogel et al. (1998) found a complete suppression of the associated, P3[2], wave (Donchin, 1981; Donchin and Coles, 1998) during the 'blink'. Maki, Frigen and Paulson (1997) and Shapiro, Driver, Ward and Sorenson (1997) have also presented evidence for the operation of attention in WM during the AB. This finding supports the view that the AB operates before or during the stage of the central executive forming a stable representation of the stimulus in VSTM together with a post-perceptual locus of suppression during the AB (Chun and Potter, 1995; Shapiro and Raymond, 1994; and Shapiro, Raymond and Arnell, 1994).

Spatial Divided Attention

Spatial divided attention shares a crucial involvement of WM with temporal divided attention. It is interesting to compare the role of visual WM in temporal and spatial attention. Treisman, Sykes and Gelade (1977) claimed that during visual attention tasks, the individual features of an object are perceived first, before the global composition. If colour, size and orientation are the dimensions of an object, then blue, large and upright are features of those dimensions. An object will typically possess more than one feature and in order to distinguish it from the items in its immediate surroundings, we need to be able to conjoin its features into a meaningful

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[2] P3 wave is generally considered to reflect working memory updating.

representation. Features of items are registered early and in parallel across the visual field. Object recognition occurs later by conjoining these features in a spatial location and requires focussed attention (Treisman and Gelade, 1980). “Focal attention provides the ‘glue’ which integrates the initially separable features into unitary objects” (Treisman and Gelade, 1980, p. 98). Without focussed attention features may be incorrectly joined resulting in 'illusory conjunctions' (Treisman, 1977).

The ‘visual search’ paradigm allows strategies of target detection e.g. using separable features or their conjunction to be investigated. This paradigm requires the detection of a target, which varies from the surrounding distracters either on one dimension (feature search) or on two or more dimensions (conjunction search). Target detection is measured over a variety of display sizes — Treisman and Gelade (1980) used set sizes of 1, 5, 15, or 30 items. A target appeared on 50% of the trials and participants were asked to respond as quickly as possible as to whether the target was present or absent. When simple objects do not require focussed attention, items that differ only by one feature should essentially ‘pop-out’ of a visual array and be detected relatively quickly. According to the pop-out hypothesis, an increase in the number of items in a visual display should not affect the time taken for target detection. Conversely, focal attention *is* required to correctly conjoin the features of a target that shares a feature with each of the surrounding distracters. This would result in a serial scan of the array and search time is then supposed to increase with the number of distracters.

Feature Integration Theory

The 'Feature-Integration Theory' (FIT) of attention proposes that "attention must be directed serially to each stimulus in a display whenever conjunctions of more than one separable feature are needed to characterise or distinguish the possible objects presented" (Treisman and Gelade, 1980, p. 97). This serial deployment of attention is considered to be responsible for the increase in reaction times (RTs) with increasing display sizes. However, there is great debate regarding 'serial' search and this will be discussed briefly later. Treisman and Gelade's theory states that observers become aware of unitary objects in 2 different ways: focal attention, or top-down processing. Focal attention directs attention to a location and features from that location are retrieved to create a temporary representation of an object. Top-down processing predicts likely objects in a familiar context. For example, when looking at a landscape, prior knowledge regarding the colour of the sky and the grass makes it unlikely to combine the colour green with the position of the sky. Distinct features of a predicted object can then be matched to those in the display by checking how they are spatially related.

In a conjunction search the ratio between the RT slopes of target-absent and target-present trials is classically defined as 2:1 — it takes approximately twice as long to report the absence of a target than its presence (Treisman and Gelade, 1980). This reflects the fact that in a target-present trial, an observer has to check an average of half the items in a display before encountering the target, and in a target-absent trial, only when all items have been checked can a response be made. However, this is no longer the commonly accepted explanation and the mechanisms of trial termination remains poorly understood (see Chun and Wolfe, 1996 for a discussion of target absent trials termination).

Guided Search Model

Wolfe, Cave and Franzel (1989) proposed a modification to the Feature-Integration Theory which accounted for searches that were more efficient than would be predicted by FIT (Wolfe, 2003). This new model was termed *'Guided search'*. Evidence from Townsend (1971, 1976) suggests that information from the parallel stage regarding colour can be used to direct attention to items of a single colour in a multicolour array. Therefore, in contrast to that proposed by Treisman and Gelade (1980), serial search is likely not to be random and exhaustive, but rather guided by information from parallel processes. The Guided Search model involves two mechanisms: (a) bottom-up attentional capture by salient items; and (b) top-down mechanisms by matching items to internally held representations (Wolfe, 2003).

Single feature search can sometimes yield results that are inconsistent with FIT. For example a search for T's amongst L's (Bergen and Julesz, 1983) or for an 'L' amongst T's (Duncan and Humphreys, 1989) produces an increase in RT with display sizes as long as the distracters are presented in a variety of orientations. In this example, the target and distracters share features with one another even though their global appearance is different: Each item in the display has a horizontal and a vertical component. In this case, the parallel processes provide no useful information and the task reverts to a serial search.

The Guided Search model proposes that the serial processing stage in conjunction trials takes advantage of parallel maps to divide the items in the display into distracters and potential targets. If the target is a red X then all the red locations and all the X locations become active then the red X location would become doubly excited and attention can be directed to the area of maximum excitement in the array. Wolfe et al. (1989) proposed that conjunction search is serial, but not random since attention is moved to the most likely target. Each time attention moves there is continuous updating of the input from the parallel processes, which makes it more likely that the correct target location will be identified. The same mechanism applies to feature search — attention is guided to the most likely target location. If the salience of targets amongst distracters is high then this is easily achieved. However, if there is great similarity between target and distracters then slight serial slopes of RT can be observed (e.g. when searching for a T amongst L's; Bergen and Julesz, 1983). The serial process would examine more of the distracters before the signal from the correct location exceeds the noise from distracters and guides attention. Interestingly, triple conjunctions yield more efficient searches resulting in flat (Wolfe et al., 1989) or significantly shallower (Quinlan and Humphreys, 1987) functions of RT with display size. This suggests that when more activation is present, on three dimensions, the signal from the target exceeds distracter noise more readily and facilitates fast detection rates. The efficiency of search is a function of the quality of the parallel guidance (Wolfe et al., 1989).

Attentional Engagement Theory

In the same year that Wolfe et al. (1989) proposed their Guided search model, Duncan and Humphreys proposed another theory of visual selection — the 'Attentional

Engagement Theory' (Duncan and Humphreys, 1989). This theory builds on FIT but takes into account the fact that feature search can be serial when the target and the distracter are closely similar (Treisman and Gormican, 1988). With this modification, attention is focussed serially on groups of items. Since visual attention is a limited capacity process, the size of the group directly depends on the discriminability of the target and distracters. If the salience of the target amongst the distracter items is high, then a larger group of items can be attended to. Duncan and Humphreys (1989) proposed a theory where attention is directed to behaviourally relevant information in the visual field. The corresponding model has three components:

1) A parallel stage of perceptual description
2) The process of selection (by the central executive)
3) The entry into visual short-term memory (VSTM).

A parallel representation of input from the visual field is hierarchically structured. A portion of this representation can be selected in response to immediate behavioural requirements. The visual input has a natural part-whole organisation and therefore it must be segmented, or grouped (for example by colour or shape). Duncan and Humphreys suggested that this stage of description and segmentation occurs in parallel across the visual field and does not require attentional resources. Access for potential target items to VSTM is strictly limited, and selection for input is a resource that can be divided in varying proportions among the structural units (or groups of items) defined in the input description. An increase of assignment of resources to any one clump of items increases its speed of processing and its probability of access to VSTM. Selection operates by matching input descriptions to current templates held in the episodic buffer of WM, and weights reflecting the proportion of the total resource available are assigned. Access to VSTM allows one structural unit to become the focus of current behaviour. Once VSTM has been filled, it must be 'flushed' before a further subset of items can enter for analysis. There is therefore both a serial and a parallel component to the limited VSTM access (Duncan and Humphreys, 1989). This view is compatible with the late selection theory of attention as proposed by Duncan (1980) whereby attention operates post-perceptually. The late selection theory of attention is, however, anomalous to the post-perceptual account of the AB.

Duncan and Humphreys' account of visual search mechanisms has support from brain imaging studies. Luck and Hillyard (1990) observed P3 wave activity during visual search (related to working memory update) reflecting a late-stage of processing when items are serially transferred to a decision stage following an initial parallel search. The late stage of processing reflects the fact that the WM central executive operates post-perceptually following the initial parallel stage of processing, however (unlike the AB) the WM central executive operates *before* items are passed to VSTM. A subsequent report of ERP data (Luck and Hillyard, 1994) has shown that single feature search elicit early ERP components suggesting automatic detection. However, Luck and Hillyard concluded that the pre-attentive processes that guide attention to an object are not entirely automatic due to the evidence of top-down influences, which give support to the early involvement of WM. These results are consistent with the Guided Search model of visual search (Wolfe et al., 1989).

Wolfe (2003) commented on the speed of processing of visual items in relation to the entry into VSTM. Wolfe observed that a typical increment in a conjunction search is

20-60 ms per item. This has been considered to reflect the time required for the covert deployment of attention from one item in an array to the next. However, no mechanism can operate that fast. Analysis of N2pc waves in ERP study (Woodman and Luck, 2003) revealed that when a search array is presented it takes time for information to reach the cortex and for pre-attentive processing to make a feature available to higher level systems. Visual information takes 75-100 ms post stimulus to reach the inferotemporal cortex (Woodman and Luck, 2003). Robust measures of attentional dwell time (Duncan et al., 1994; Ward et al., 1996) and the AB (Chun et al., 1995; Raymond et al., 1992) have revealed a typical temporal processing lag of 200-500 ms between items that are successfully processed to a more durable level for report.

Wolfe (2003) builds on the claims of the Guided search model (Wolfe et al., 1989) and of Duncan and Humphreys (1989) to propose that selective attention (a function of the central executive) allows a manageable subset of items to enter VSTM. It is the frequency of entry of items to this limited capacity object recognition system that determines the search slopes. Whilst items are delivered every 25-50 ms, it takes far longer for a bundle of features to be bound together into a recognisable object. Therefore, there are several items being analysed at any one time, giving visual search both parallel and serial qualities. In terms of re-visiting items in an array, prior history is not completely ignored, but neither does the search mechanism keep any record of rejected distracters (Wolfe, 2003). This contributes to the element of re-checking that is thought to occur in target-absent trials. The hybrid parallel and serial model of visual search (i.e Wolfe, et al., 1989) has support from electrophysiological studies (Corbetta and Shulman, 1998). Given the lack of conclusive evidence for either strictly serial or strictly parallel search (Bricolo, Gianesini, Fanini, Bundesden and Chelazzi, 2002; Wolfe, Yu, Stewart, et al., 1990), this thesis will refer to search trials as 'conjunction search' and 'feature search' to avoid confusion.

Working Memory and Divided Attention Tasks

As illustrated by Wolfe (2003), working memory is crucial in visual selective attention and has a role in reducing distraction by maintaining the prioritisation of relevant information for the behavioural task (de Fockert, Rees, Frith and Lavie, 2001). Working memory involvement has been proposed in the third stage of Duncan and Humphrey's (1989) model of visual selection, the buffer stage, which operates prior to VSTM by governing the selection of items. The appropriate direction of attention requires the active maintenance of stimulus priorities in visual WM specifying which stimuli are currently relevant.

Vogel, Luck and Shapiro (1998) illustrate the importance of WM during dual-target tasks such as the AB. They analysed the P3 wave component, and discovered that it was completely suppressed during the blink[3]. They claimed that the post-perceptual processing deficit of the AB is due to an impairment in stimulus identification operating at or before the stage of working memory. This suggests a problem with

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[3] The P3 component has also been associated with visual search (Luck and Hillyard, 1990).

retrieval of the correct target information from VSTM following interference during encoding.

Both the AB and visual search reflect post-perceptual processing deficits, but the point at which WM operates differs between these two paradigms. Since the central executive component of WM has many different functions (see earlier discussion) it is reasonable to suggest that its involvement in visual search and the AB may be different. In visual search, the central executive operates prior to VSTM involvement and in the AB, the central executive operates after VSTM. Visual search efficiency is governed by the size of the groups of items that the central executive transfers to VSTM. Items in the array are processed at a low level and if the search is based on a single feature, this analysis is sufficient to pass the entire array as one group to VSTM for subsequent report. However if the search involves a conjunction of features, smaller groups of items can be passed to VSTM for further analysis. The target item in visual search does not need to be fully identified and consolidated before selection for VSTM, since response requirements are simply present/absent judgements. This is in contrast to the AB where the central executive operates after items have reached VSTM. An identification task in the AB requires correct report of an item's description and therefore potential target items must be fully identified and consolidated for report. In the AB, the central executive is responsible for selection of the correct target from VSTM following processing of all presented items. Deficits in the AB are considered to reflect response competition. The AB requires executive function for efficient organisation and storage of items in VSTM for subsequent response selection, whereas in visual search the maintenance function of central executive serves to continually update VSTM.

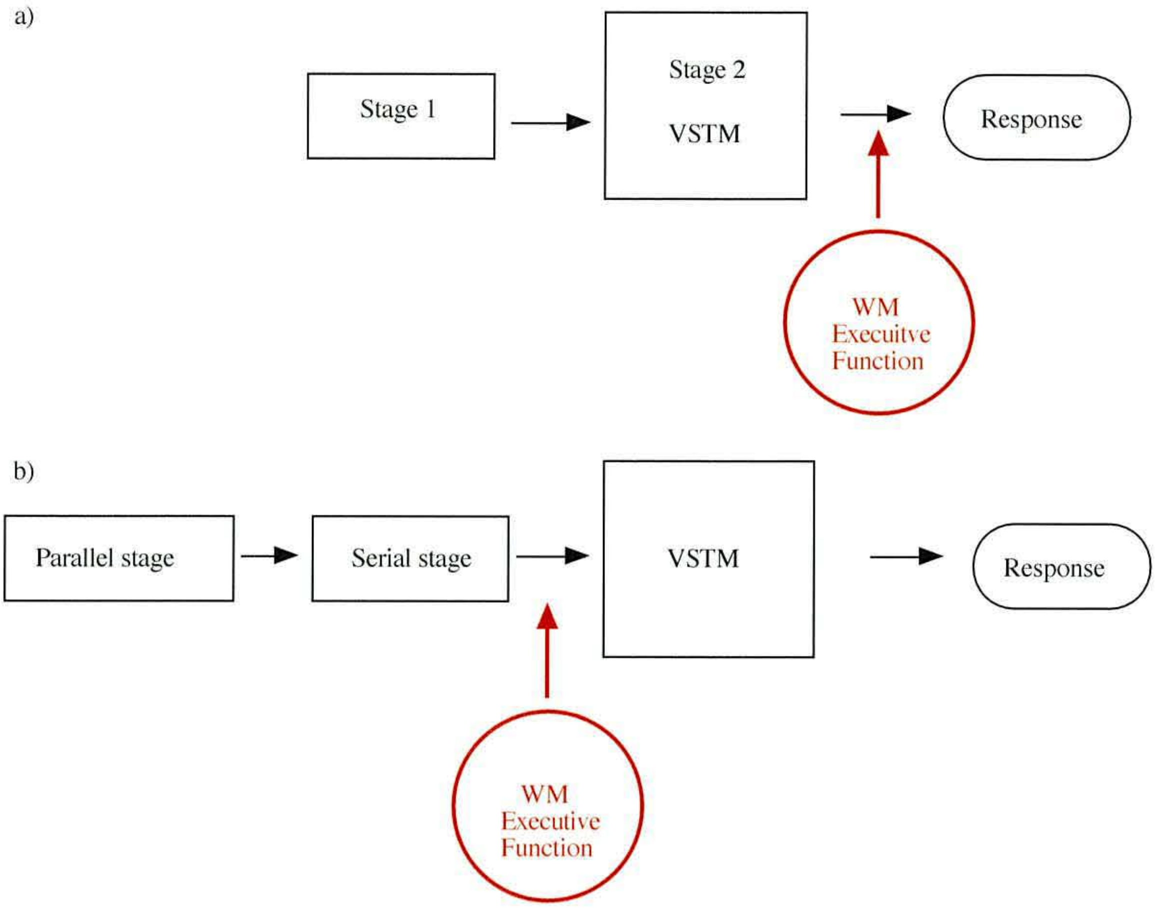

Figure 4: Diagrammatic representation of working memory central executive involvement in a) Attentional Blink and b) Visual Search.

Woodman et al. (2001) do not support a heavy involvement of WM in visual search tasks. They suggested that additional load to working memory does not extensively affect visual search performance. However, if WM can play two separate roles in visual attention perhaps this result is not surprising. The dependent visual search task that Woodman et al. employed required the *maintenance* function of the central executive component in WM for successful target detection. But, the concurrent working memory task required the *storage* aspects of the central executive. Participants were asked to view an array of coloured items prior to a visual search task. Following the visual search task, an array of coloured items was then presented and participants were asked to judge whether the second visual array was identical to the first. The fact that Woodman et al. did not find significant deficits in visual search performance whilst executing a concurrent 'WM' task suggest that load on these tasks may utilise different cortical areas and not, as they suggested, that working memory has little involvement in visual search.

Neural Correlates of Working Memory

There is a large body of research to suggest the involvement of the frontal and, more specifically, the prefrontal cortex (PFC) in visual attention and executive control (see Roberts, Robbins and Weiskrantz, 1998 for a review). Kane and Engle (2002) gave an extensive account of the cortical circuitry associated with WM, and provided evidence that these cortical circuits pass through and engage the PFC. It has been recently suggested that the central executive component of WM is not localised to the frontal lobes however, but instead operates as part of a cortical circuit with more posterior regions (specifically parietal regions) of the brain and this has support from brain imaging studies (Collete, and Van der Linden, 2002). Smith and Jonides (1997) support the role of the PFC in executive processes and list a number of studies that investigate a variety of executive functions: Monitoring WM contents (Paulesu, Frith and Frackowiak, 1993); task-switching (D'Esposito, Detre, Alsop, Shin, Atlas and Grossman, 1996; Rubenstein, Meyer and Evans, 1994); applying a complex rule to be held in WM (Smith, Patalano and Jonides, 1998); and complex problem solving, (Owen, Doyan, Petrides, Evans and Gjedde, 1994). Each of the studies report activation in the PFC and raises the question of how so many functions can involve the same cortical region. Diamond (2002) proposed that the dorsolateral PFC is needed when concentration is required and that both inhibition *and* holding of information on line must be operating concurrently for activation to be seen in this area. However, Smith and Jonides (1999) state that the frontal cortex helps mediate working memory and that the 2 sub-components of the central executive in WM (temporary storage and manipulation of information) can *individually* activate the anterior cingulate gyrus and the dorsolateral prefrontal cortex.

Evidence from functional magnetic resonance imaging (fMRI) studies give support to the dichotomy that Woodman et al.'s (2001) results have suggested. Following a memory organisation hypothesis, Rypma and D'Esposito (2002) investigated the involvement of the dorsolateral and ventrolateral regions of prefrontal cortex (PFC) during specific aspects of a 'working memory' maintenance task. They hypothesised that the ventrolateral PFC is the area associated with the capacity limited short-term buffer of WM and that dorsolateral PFC is associated with organisation and storage function of the central executive in WM. Rypma et al. found that increased activity in dorsolateral PFC during encoding is associated with subsequent retrieval success (and therefore the organisation processes of the central executive) and increased activity in ventrolateral PFC is associated with a limited capacity buffer supporting rehearsal maintenance functions[4].

The organisation of WM maintenance occurs after stimulus identification and subsequently affects retrieval success. This process is analogous to the storage and response selection aspects of the AB. The limited-capacity buffer of the ventrolateral

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[4] This dorsal/ventral division can be compared to the division between 'what' and 'where streams in the visual system proposed by Ungerleider and Mishkin (1982; Milner and Goodale, 1995). The ventral stream projects to the inferior temporal cortex and carries information regarding the object identity and the dorsal stream projects to the posterior parietal cortex carrying information regarding object location in space.

PFC is more closely linked with visual search. Indeed the mechanisms involved in spatial working memory have been shown to be the same mechanisms as those involved in spatial selective attention (Awh and Jonides, 2001). This suggests frontal cortex involvement in both of the visual attention tasks discussed previously. Therefore performance deficits in these tasks may be attributable to different sub-components of PFC.

Frontal Lobes and Attention

The frontal lobe is the area of the cortex that lies anterior to the central sulcus. Examples of behavioural disorders following frontal lobe damage have long been reported, most notably in the case of Phineas Gage in 1848. Following substantial damage to his frontal lobe, it was clear that whilst motor control is controlled by other areas of the cortex, the ability to monitor behaviour and select behaviourally relevant actions crucially involves the frontal lobes (Gazzaniga et al., 1998). This is the control of behaviour associated with the central executive component of working memory. Many researchers (e.g. Stuss and Benson, 1984; Duncan, 1986; Duncan, 1995; Lhermitte, 1983) have since reported disorders of behaviour following frontal damage and the central theme appears to be the control of behaviour and selection of task relevant behaviour. However, the control of task specific behaviour is also known to involve other brain regions such as the parietal, occipital and temporal lobes in as much as task specific components are concerned (Awh and Jonides, 2001).

De Fockert et al. (2001) claim that working memory controls visual selective attention in the normal human brain, and consequently that the frontal lobes play an important part in the control of attention. Different types of frontal lesion may result in different deficits and it is important to note that disorders rarely occur in isolation. The term 'Frontal lobe syndrome' should therefore be used with caution, given the complexity of frontal function and the cortical connections with other brain areas (Duncan, 1986; Stuss, Alexander, Floden et al., 2002). Disorders of the control of attention have been observed following frontal lobe damage varying in degrees of severity (Duncan, 2001). Stuss and Benson (1984) reported case studies of severely impaired directed and selective attention following frontal lobe damage. Sakai and Passingham (2003) specifically linked Brodman's area 46 of the frontal lobe with executive functions. Activity in this area during an fMRI study was increased when participants re-coded online information in a spatial memory task in order to prevent subsequent distraction. Stuss et al. (2002) discussed the difficulty of attributing a 'frontal deficit' to the frontal lobes due to the limited number of focal frontal lesions. However they acknowledged the frontal contribution in the supervisory executive control of working memory. Deficits in both of the attentional paradigms previously discussed in this chapter have been attributed to working memory. The association between the frontal lobes and the central executive component of working memory is then clear. The frontal lobes are therefore primarily implicated in both the AB and visual search.

Frontal Lobe Involvement in Divided Visual Attention Tasks

De Fockert et al. (in press) have found direct evidence for the role of the frontal lobes in the control of selective attention, and the neural correlates of attentional capture during visual search have been localised in the frontoparietal cortex.

Using fMRI techniques Marois, Chun and Gore (2000) have investigated the cortical areas associated with a version of the AB. Due to the temporal limitations of fMRI Marois et al. presented participants with the T1 task only. Behavioural data taken outside the scanner suggested that this task appropriately resulted in perceptual interference on a subsequent T2 task. Marois et al. (2000) associated the right intraparietal sulcus (IPS) with perceptual interference that leads to an AB in both temporal and spatial interference tasks. The IPS is therefore considered to be crucial in the capacity-limited processing of an AB task. Recent studies utilising rapid trans-cranial magnetic stimulation (rTMS) support the role of the IPS in the moderation of temporal aspects of visual attention and have revealed a reduced AB magnitude when concurrent TMS stimulation is applied to this cortical area (Cooper, Humphreys, Hulleman, Praamstra and Georgeson, submitted). The right parietofrontal cortex has previously been implicated in attentional control and enhancement and is considered to be the locus of capacity limited processing of visual attention. Furthermore, activation of the lateral prefrontal cortex was seen in the temporal interference tasks typically employed in AB investigations but not in tasks utilising spatial distracters (Marois et al., 2000). Marois et al. concluded that the right intraparietal sulcus and to a lesser extent the frontal areas of the human cortex are the neural correlates of the capacity limitations underlying the AB[5].

If the AB occurs as a result of response selection competition, as suggested by Shapiro, Raymond and Arnell (1994) then experiments involving the T1 task only (Marois et al., 2000) are not adequate for identifying the cortical areas associated with the AB. Whereas the parietal lobe and intraparietal sulcus are associated with perceptual interference, which intervenes in Marois et al.'s (2000) study, the frontal lobe has been shown to take part in attentional control by reducing susceptibility to interference (Fuster, 1989). Therefore, *greater* frontal activation may be present during the AB than is indicated by Marois et al. (2000). In a later paper, Chun and Marois (2002) acknowledge that the frontal cortex regulates visual processing in posterior visual areas. They claim that the frontoparietal cortex forms the basis of a limited capacity processing system that is required during the AB, a view that supports the role of frontoparietal network in tasks requiring attention (Wojciulik and Kanwisher, 1999).

The involvement of frontal lobes in dual-target interference tasks has support from additional patient studies using RSVP tasks (Richer and Lepage, 1996). Frontal lobe patients appear to be more susceptible to interference in RSVP-based tasks, by showing greater T2 detection difficulties across all serial positions and a later point of attentional recovery. This pattern of results is seen even at relatively slow

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[5] Although a more severe and prolonged AB has been shown in both parietal and basal ganglia stroke patients (Husain, Shapiro, Martin and Kennard, 1997) and also following damage to the inferior parietal lobe and the superior temporal gyrus (Shapiro, Hillstrom and Husain, 2002).

presentation rates of 6 items per second. By 10 items per second frontal patients are even unable to detect T1. This abnormal performance is not simply a reflection of cortical damage, but it is specific to frontal lesions. Richer and Lepage report correctly detected T1 at all presentation rates and a T2 deficit peaking at 300 msec after the first target for patients with temporal lobe damage.

Target discrimination is not rate-dependent in normal adults and recovery is reliably seen within 500 ms of T1 presentation. Richer and Lepage claim that the deficit seen in frontal patients is due to increased susceptibility to interference or may be due to attentional inertia, whereby attentional engagement on one target interferes with attentional engagement requirements of a second target, and that this occurs at rates which do not affect controls or patients with temporal lobe lesions.

Development of the Frontal lobes

The development of the human cortex has been investigated using neuro-imaging by Hashimoto, Tayama, Miyazaki et al. (1995). While the number of neurons in the human cortex does not significantly increase after birth, there appears to be a continued maturation of neurons involving myelination and multiplication of dendrites. Taking into account the latter mechanisms, the human cortex continues to develop into adulthood. Thatcher (1991) identified five rapid phases of growth occuring between birth and age 5, between ages 7 and 9, between ages 11 and 13, between ages 14 and 16 and again between ages 18 and 20. Although the brain has an adult like appearance by age 18 months, complete myelination and maturation is not observed before age 20. The frontal cortex is one of the last areas to be fully developed with cortical development progressing from the posterior area of the brain towards the anterior regions (Hashimoto et al., 1995; Hudspeth, 1987; Stuss, 1992).

The psychological growth of the frontal lobes continues hierarchically past puberty Stuss (1992). The relationship between physiological growth and psychological development of the frontal lobes as indexed by attentional span tasks has been reviewed by Case (1992) who suggests development of attention relies upon the functioning of the frontal lobes and their co-ordination with other cortical systems. As the human cortex develops, the interaction of the frontal lobes with other cortical areas is as important as the actual physical development of the frontal lobes themselves. In particular, various sections of the non-frontal cortex come 'on-line' by establishing a connection with the frontal lobes. Differing areas of the cortex will come on-line at different ages until all the connections are in place (Thatcher, 1991).

Development of Spatial Attention

Since the frontal cortex is implicated in the executive components of visual search and AB and this area of the human cortex continues developing into adulthood, one would expect to observe developmental improvements in performance on these tasks. There have been a limited number of studies investigating the developmental changes of performance in visual search tasks. Although some studies have shown *similar* patterns of performance in both adults and children (Lobaugh, Cole and Rovet, 1998), there is also evidence of developmental improvement. A measure of visual search efficiency in locating a target image amongst an array of distracting items was taken by Klenberg, Korkman and Lahti-Nuuttila (2001) which suggested an increase in search efficiency between 3 and 12 years of age. However, the methodology used in Klenberg et al.'s study was not the feature/conjunction distinctions commonly associated with visual search.

Gerhardstein and Rovee-Collier (2002) designed an ingenious test of visual search efficiency in infants using a touch-screen monitor. Not only was the serial search in conjunction tasks evident (infants systematically moved their index finger across the array before selecting and touching the target), but patterns of search slopes were consistent with adult data. Flat functions of RT with display size were seen in feature search trials, whereas positive slopes of RT with display size were found in conjunction trials. Overall children's RTs were significantly slower than adults RTs as is often seen in speeded tasks (Kail, 1986) and this may be due to developmental improvements in the motor system (Bard, Hay and Fleury, 1990). Motor efficiency is an obvious confound in developmental studies of this kind and therefore it is important to report the *slopes* of reaction times when comparing groups of participants.

Ruskin and Kaye (1990) compared the slopes of reaction time (items per second) of adults and 5- to 10-year old children for both feature and conjunction searches. They have revealed decreasing slopes of RT with increasing age. They suggested that this represents a less efficient search strategy for conjunction trials in children. This view is shared by Thompson and Massaro (1989) who found similar results with children as young as 4- and 5-years old. Slopes were significantly increased in conjunction, but not feature search trials for the children relative to adult performance.

Trick and Enns (1998) have demonstrated developmental differences in performance between children of different ages. They compared the search times of children aged 6-, 8- and 10-years old to young and older adults in conjunction and feature search tasks. They found steeper search slopes for conjunction, but not feature search, in 6-year old participants compared to 8-year olds and older. This builds on previous evidence suggesting shorter search times in adults and reveals a developmental improvement in performance. Casco, Giduli and Grieco (2000) also showed a significant developmental difference, but this difference was evident between 10-year old children and adults, suggesting this attentional ability is acquired later than suggested by Trick and Enns (1998). Casco et al. (2000) claimed that the decrease in search times with increasing age reflects the efficiency of the element-by-element search utilised in conjunction trials. Whereas adults may group distracters for subsequent serial search, in accordance with Wolfe et al.'s (1989) Guided Search Model, children scrutinise the display in an exhaustive element-by-element serial search. However, this experiment did not use computerised tasks (response times to presented arrays were recorded by an observing experimenter).

Taylor and Khan (2000) have used ERPs to assess visual search performance in children independently of behavioural measures such as RTs. They presented search tasks to children aged 7- to 8-, 9-to 10- and 11- to 12-year old children. Significant age and task effects were indexed by decreased latencies of ERP wave components indicating more efficient processing. In particular such modulation of the P1 wave would reveal maturational changes. Results of this study suggested that colour discrimination is more readily achieved than discrimination of shape or size, since colour tasks yielded shorter ERP component latencies. Taylor and Khan also reported a developmental reduction in the latency of the N2 wave reflecting stimulus evaluation and attentional demands. This supports the role of attention in the early stages of visual search and shows that children become more efficient at utilising search strategies as they get older. Furthermore, this view is consistent with Casco et al.'s (2000) theory of developmental improvement. Taylor and Khan concluded that the developmental changes in performance are due either to improved search strategies or to an increase in attentional processing capacity with age. Electrophysiological evidence for this second suggestion comes from their report of decreased anterior positive peaks (P2 waves) with increasing age in target absent trials. This is compatible with increased frontal processing in serial search. In sum, systematic changes with age in anterior attentional functions support developmental theories of increased frontal capacity (Case, 1992; Stuss, 1992; Thatcher, 1991) and the view that deficits in this cortical area may result in poorer attentional performance.

Despite research into the developmental time course of divided attention using spatial tasks, there have been no published articles addressing the developmental pattern of temporal divided attention using tasks such as the AB. It seems sensible to suggest that temporal divided attention may also be subject to developmental evolution since the frontal areas of the cortex have been associated with the AB and these areas develop continually until age 20.

Video Game Playing and its Effect on Visual Attention

Van Selst, Ruthruff and Johnston (1999) have showed that performance in dual task interference paradigms can be improved with practice. Ruthruff, Johnston and Van Selst (2001) provide further support for this by demonstrating that the interference effects seen in dual task paradigms may greatly overstate the real-world dual target interference observed in tasks such as driving, or playing a musical instrument. In particular they showed a dramatic reduction of the interference effect seen in PRP designs over an increasing number of trials.

It is reasonable and ecologically sensible to think that through play children practice skills that they will need in later life. A specific cultural environment can selectively boost some cognitive functions, whilst allowing others to remain relatively undeveloped (Greenfield, Brannon and Lohr, 1994). In our increasingly computerised society, familiarity and expertise in technology from an early age is advantageous. Exposure to video games has become more and more prevalent in recent years as the technology and the market develops. Video games require ‘parallel processing’ such as taking in information from several simultaneous sources (Roe and Muijs, 1998). Children raised in a time where television and video games are commonplace develop parallel processing skills faster than children who are more familiar with the serial processing requirements of reading. Greenfield (1984) claimed that this is the reason why even very young children are often better at video games than many adults. Conversely, Roe and Muijs (1998) reported associations between heavy video game playing and negative, rather than positive, academic achievement. It must be noted however that the heavy video game playing participants in their study also reported being heavy television and VCR users with a preferred action/violent/horror content. Such participants, even at the age of 10 or 11 also report a preference for heavy metal and punk music. The results of Roe and Muijs' study cannot straightforwardly be attributed solely to the heavy use of video games. Greenfield and Cocking (1994) illustrated that with the advent of interactive video gaming and CD-ROM, developmental research should focus on the implications of an ever-decreasing psychological distance between person and medium.

Patricia Greenfield was one of the first researchers to show an interest in the effects of computers on children's cognitive development. She claimed in particular that "From the point of view of development and socialization, video games are particularly important because they affect children during the formative years. ...For most children, the video game is one of the first opportunities they have to interact with computer technology" (Greenfield, Brannon and Lohr, 1994, p 88). Cognitive, as well as social, developmental patterns have been investigated using video games. The interactive visual technology of these games, and their popularity with children and adolescents, makes them an ideal medium for the 'real-world' investigation of cognitive ability. 'Everyday cognition' is a phrase coined by Rogoff and Lave (1984) and represents the cognitive processes that occur in real-world situations rather than in a psychology laboratory. The involvement of complex cognitive skills in video game playing was demonstrated by Rabbit, Banerji and Szymanski (1989) who found that IQ was highly predictive of rate of learning, and of practised performance on an action video game.

Everyday cognition has been investigated by Greenfield, Brannon and Lohr (1994) who looked into the developmental effect of interactive media forms and produced strong evidence that long-term video game playing expertise benefits spatial skills by measuring mental paper folding ability. Spatial skills were also investigated by Subrahmanyam and Greenfield (1994) who assessed the spatial abilities of 11-year old boys and girls using a computerised battery of tasks developed by Pellegino, Hunt, Abete and Farr (1987). Participants then went on to play either a spatial computer game (Marble Madness), which involved guiding a marble along a three-dimensional course, or a word computer game (Conjecture), which involved solving word puzzles. Results showed that participants who had played the Marble Madness computer game had improved performance on dynamic spatial skills tasks compared to those who played Conjecture. Improvement was greatest in participants who had initially shown quite poor spatial ability. Subrahmanyam and Greenfield also demonstrated a strong connection between spatial skills and video games since initial spatial skills ability predicted performance on the video game. In sum, good spatial skills would lead to high levels of competence on subsequent video games and practice with video games would improve spatial skills. However, the experimental game used was specifically spatial in nature and therefore it might not have been video game playing per se that was responsible for improved spatial ability, but the specific requirements of the task used. An interesting control measure would be to use a manual, or pen and paper, spatial game instead of Marble Madness and investigate any differences in initial and final spatial skills scores. Indeed, results from Subrahmaynam and Greenfield stand in contrast to previous attempts to use video game training to improve spatial skills (Dorval and Pepin, 1986; Gagnon, 1985) although previous results were obtained with older subjects than those of

Subrahmaynam and Greenfield. It is possible therefore that 11-years old is an age of development that is sensitive to spatial training. In addition, Roberts, Brown, Wiebke and Haith (1991) showed that 12- and 20-year olds had efficient learning strategies for improved performance on a video game (Asteroids) whereas 4- and 7-year olds did not. This suggests that sensitivity to training is not limited to 11-year olds (Subrahmaynam and Greenfield, 1994) but instead is a developmental process beginning around this age.

Greenfield, Camaioni, Ercolani, Weiss, Lauber and Perucchini (1994) used cross cultural (US and Italy) investigations to demonstrate that experience with a 'non educational' video or computer game can lead to greater skill in acquiring knowledge from a scientific-technical computer program. This finding together with that of Roberts et al. (1991) supports the notion that exposure to recreational video games during childhood may be beneficial for future success in the technological world. Blumberg (1998) claimed that video games provide an ecologically valid setting for the developmental investigation of selective attention. Video games provide an environment in which children can master a complex, rule-governed set of actions in a situation that motivates them. This is an example of incidental learning, which contrasts with the structured learning context of a classroom situation. Blumberg (1998) was interested in the ability of children to discern cues and to incorporate them into a strategy to facilitate performance within a video game. She suggested that this skill is characteristic of selective attention and established that frequent video game players show a better use of attentional strategies than novice players. Furthermore, this effect has its own time course.

Greenfield, DeWinstanley, Kilpatrick and Kaye (1994) have linked video game playing with enhanced ability on a divided attention paradigm. Expert and novice players were tested on a cost-benefit paradigm based on work by Posner, Snyder and Davidson (1980). There were two possible target locations on the computer screen that laid on the horizontal axis in line with the centre of the screen. Two conditions were presented: (a) the target appeared at one location on 80% of the trials, the other location 10% on of the trials and at both locations on 10% of the trials; or (b) the target appeared equally often at either location (45% of trials at each) and at both locations simultaneously on 10% of trials. In line with Posner, et al. (1980), Greenfield, DeWinstanley, Kilpatrick and Kaye (1994) demonstrated that both novice and expert players show a benefit in RTs on correctly cued trials (80% probability of occurrence). However, only novice video game players showed the usual cost to RTs when the target appeared in an unexpected location. This suggests that expert video game players have an improved ability to divide their attention across the visual field when compared to novice game players. A follow up experiment presented the cost-benefit paradigm to participants on two occasions 1 to 1.5 weeks apart. In the interim period participants played a video game for 1.5 hours a day. Results from this experiment established that practice on a video game, which required monitoring of multiple locations, helped develop strategies for dividing attention.

In a more recent study, Green and Bavelier (2003) have investigated the effects of action video game playing on various aspects of visual attention. They based their predictions on the claim that “exposing an organism to an altered visual environment often results in modification of the organisms visual system” (p 534). Green and Bavelier tested frequent video game players (VGPs) and non-video game players

(NVGPs) on a flanker compatibility effect task, which measures the interference effect of distracter items. Typically, distracters interfere more when the target task is easy compared to when it is hard. In accordance with the hypothesis that VGPs have an increased visual attention capacity, Green and Bavelier demonstrated no reduction in the distracter effect of these participants even when the task was difficult, whereas the distracter effect disappeared for NVGPs at low levels of difficulty. A second experiment supported this claim using an enumeration task, which revealed a significant improvement in video game trained participants and no improvement in a control group. The third experiment of Green and Bavelier demonstrated that VGPs have an enhanced allocation of spatial attention across the visual field and not simply within the usual video game playing visual field of 0° to 5° from fixation. Overall, these results support the claims of Greenfield and colleagues (Greenfield, Brannon and Lohr, 1994; Subrahmanyam and Greenfield, 1994) that video game playing improves spatial attentional ability. All the video game experiments described until now have focused on the spatial aspects of attention.

Green and Bavelier have also made a significant and novel contribution to the literature, by investigating the effects of video game playing on temporal attention. They used a version of the AB that required dual target detection and a task-switch (T1 was an identification task and T2 was a detection task) and reported significantly higher second target detection rates from T2 lag 1 to lag 5 in VGPs than in NVGPs. This is taken as evidence that video game playing enhances task-switch ability and reduces the AB. Since correlation does not infer causality, the results from Green and Bavelier may have occurred due to a greater natural ability in VGPs rather than as a result of their game playing. Therefore a sample of NVGPs were trained on a video game and tested on the AB before and after training. Training comprised a one-hour session playing Medal of Honour, an action video game, for ten consecutive days. A control group of NVGPs played Tetris for ten consecutive days and were also tested before and after training on the two visual temporal divided attention tasks. The difference in the two games is that an action video game requires attention to be distributed and divided across the visual field, whereas Tetris requires focus on a single item at a time. Both games require visuo-motor control, but only Medal of Honour would be expected to change aspects of visual attention. Results demonstrated that training on an action video game lead to faster recovery of the AB and therefore ten days of training were enough to improve the temporal resolution significantly.

Summary and Hypotheses

To date there has been no investigation into the developmental aspects of the AB even though some studies have addressed the developmental time course of spatial attention. This is an important field of investigation because studies of clinical populations will need fundamental references to normal development of attention. For instance, Shepperd, Bradshaw and Shapiro (in progress) have showed a prolonged AB in ADHD children compared to a normal pattern of attentional recovery (approximately 500ms) in controls. However, this study used a sample of children with an average age of 9.5 years old and performance at any one age was not calculated, nor was the performance of these children compared specifically to adults on the same task.

The frontal lobes are clearly implicated in the control of visual attention (de Fockert et al., 2001) as lesions in this cortical area have resulted in poorer performance on RSVP tasks (Richer and Lepage, 1996). Therefore, it seems appropriate to investigate dual task performance in children at a range of ages prior to complete cortical development and to make a comparison with adult performance. This thesis intends to plot the development of performance in temporal divided attention tasks such as the AB in 7-, 12- and 15-year old children and compare their performance with that of an adult control group.

Aims and Objectives of this Thesis

This thesis primarily investigates developmental differences in the severity and duration of the AB in children across three age groups (7-, 12- and 15-year olds) and compares this performance to that of adults completing the same task. The measure of temporal attention contributes to current research into the development of visual attention processes. If a delay in the ability to recover attention is related to the frontal lobes, then this should be observed over the age range during which the frontal lobes are known to develop. The AB effect has been attributed to a limited capacity of the central executive functions of WM to control efficient organisation and storage in VSTM. Second target detection rates fall when there is response competition in VSTM due to insufficient attentional processing capacity. With increased temporal distance between two targets, effective identification and consolidation can be achieved for both the targets and T2 detection rates return to baseline. This duration is typically 350-500 ms after T1 presentation in normal adults and it is expected that this duration will be significantly longer in younger participants.

To provide support for the developmental progression of working memory and frontal functions and their impact on the time course of the AB, tests of visuo-spatial sketchpad capacity and executive control (inhibition) are administered. Developmental differences in these aspects of executive WM function would further the understanding of frontal lobe development connections with other cortical areas. It may then be argued that the development in frontal function is responsible for the reduction in AB magnitude with age giving support for the role of WM in dual-target tasks.

The current literature has provided evidence of developmental differences in spatial attention using the visual search paradigm. Developmental patterns of performance in this paradigm have been attributed to a relatively inefficient use of strategies in the early stages of processing which again rely on WM function. Here, successful replication of a developmental improvement in performance would suggest that both temporal and spatial attention, each governed by executive control in WM, are underdeveloped at the age of 7-years old. However if non-significant differences are found then greater understanding will gained regarding which executive functions in WM appear to be associated with underdeveloped frontal lobes at age 7.

The external validity of the claim made is then tested using video games. Such games rely on the executive functions assessed in the paradigms used in the present line of investigation. It is hoped that the link between video game playing ability and visual attentional performance (particularly temporal) will contribute to the literature in the field. Recent publications have shown an improvement in temporal attentional performance following training with video games in adults and the same may be true for children. This has implication for the clinical application of video game playing both for children suffering from attentional disorders and for patients following frontal lobe damage/surgery.

Chapter 2 develops an appropriate set of stimuli for participants aged as young as 7-years old and reports the performance in the corresponding task of 7-, 12- and 15-year old participants alongside adults. Further investigation into the underlying developmental differences is then carried out through a critical items RSVP stream and an extended RSVP stream.

Chapter 3 aims to support the claim that the developmental improvement seen in the AB (in terms of reduced magnitude) is due to underdeveloped working memory capacity as a consequence of frontal lobe maturity. The same participants as those used in Experiment 3 of Chapter 2 are involved to enable a comparison of performance in a later chapter. Measures thought to reflect two of the central executive components of working memory involved in temporal and spatial attention are analysed.

Chapter 4 disputes current literature regarding developmental performance in visual search tasks and illustrates that performance does not differ between the youngest age range in the AB task and adults. Stimuli in the first experiment remain the same as target items in the AB for cohesion. Then a second visual search task uses alternative stimuli to consolidate the claim.

Chapter 5 addresses the issue of ecological validity of this research. Video game playing ability is measured using two novel video games. Game playing ability is then correlated with performance on both the AB and the WM tasks.

Chapter 6 discusses and summarises the experimental findings from Chapters 2-5 and how they relate to working memory performance and the developing frontal cortex.

Chapter 2 – Temporal Attention

Abstract

Chapter 2 investigates developmental changes in the Attentional Blink (AB). The first experiment replicates the procedure used by Raymond et al. (1992) but, due to the very young participants to be studied, replaces letter stimuli with more easily recognised shape stimuli. Attentional recovery in dual target trials was found, but the deficit could not be attributed to prior allocation of attentional resources since the target requirements were different — T1 was an identification task and T2 was a detection task. Experiment 2 presents identification tasks for each target and successfully yields an AB. Experiment 3 presents a modified RSVP stream to children, aged 7-, 12-, and 15-years old, and to adults. Experiment 3 reveals a developmental improvement in temporal recovery of selective attention, but fails to show attentional recovery in 7-year olds. Experiment 4 investigates whether the complete lack of attentional recovery seen in 7-year olds is due to an inability to inhibit distracter items in the stream, and as such presents a critical item RSVP stream. This failed to yield an attentional recovery and therefore Experiment 5 attempts to establish at what point, if any, 7-year olds would recover their attentional abilities. T2 detection rates in dual target tasks for these participants returned to baseline when the T2 lag was 1166ms. Results from Experiments 3-5 show a developmental improvement in temporal attention and are discussed in relation to current theories of the AB.

The Development of Temporal Selective Attention.

The Attentional Blink (AB) paradigm investigates the temporary deficit in attentional resources for second target detection following allocation to a first target using RSVP streams. The time frame for attentional recovery in a dual-target task of this type is typically 350-500 ms in normal adults. Imaging studies (fMRI) revealed the right parieto-frontal network, previously associated with attentional control, to be a centre of capacity-limited processing required during the AB (Marois, Chun and Gore, 2000). The involvement of the frontal cortex represents the capacity-limited processing deficits that are associated with the working memory component of the AB. Poorer performance of frontal lobe patients has also been reported by Richer and Lepage (1996) who show that these patients are subject to more interference in lower rate presentation dual target tasks than were temporal patients or normal controls. Moreover, at higher presentation rates (10 items per second), frontal patients are unable even to detect the first target. Richer and Lepage attributed this poor performance to an increased susceptibility to interference suffered by frontal patients. This effect of this increased interference is to heighten the inertia of target discrimination. Husain, Shapiro, Martin and Kennard (1997) revealed AB durations of 1440ms in participants suffering visual neglect following right hemisphere damage to the parietal or frontal lobes, or to the basal ganglia. Clearly the frontal lobes are heavily implicated in the successful target discrimination required for the AB.

Previous research into the temporal deficits revealed by the AB has been limited to an adult population, both patients and healthy adults. Despite literature on developmental aspects of spatial attention, investigations into the performance of children in temporal attention tasks (AB) are limited —although Sheppard, Bradshaw and Shapiro (in progress) have compared the performance of ADHD children to control children. The human cortex develops progressively from the posterior to the anterior (Hashimoto et al., 1995; Hudspeth, 1987; Stuss, 1992), and as such the frontal lobes are one of the final areas to become fully developed (Case, 1992; Stuss, 1992; Thatcher, 1991). This area is known to continue developing past puberty and is not fully developed until the age of 20. This chapter attempts to extend current AB research to a younger population and investigate any developmental differences in the pattern of the AB due to the progressive stages of frontal lobe growth.

The first two experiments in this chapter address methodological issues of presenting RSVP streams to children as young as 7-years old. Previous research into the AB (e.g. Raymond et al., 1992) has mostly used letter stimuli in this paradigm to reveal the dual-target deficit in attention which is seen when two targets are presented in close temporal proximity. Using letter stimuli with very young children may be problematic since their grasp of the alphabet graphemes may not yet be fully developed. Experiment 1 uses a similar experimental procedure and timing parameters as those used in Raymond et al. (1992) but replaces the letter stimuli with coloured shapes. Therefore, in Experiment 1 the T1 task is to identify the direction of an isosceles triangle and the T2 task is to detect the presence or absence of a red circle. The success of this experiment suggests that coloured shape stimuli can yield an AB. however, it cannot be reliably concluded that this deficit is due to a temporal deficiency in attentional resources because T1 is an identification task and T2 is a detection task (a task switch). In order to attribute second target deficits to a depleted attentional pool of resources both targets must utilise the same cognitive mechanisms and therefore the experiment was modified so that T1 and T2 are both identification tasks.

Experiment 2 reveals a significant T2 deficit at early serial positions followed by attentional recovery. Experiment 2 was then presented to participants of four age groups; adults, 15-, 12- and 7-year olds.

Experiment 3 reveals an increase in AB magnitude at younger ages represented by a protracted AB in younger participants. A developmental trend appears to show a progressive increase in AB duration with decreasing age. A novel finding is that 7-year old participants fail to show any attentional recovery over the 1-second time frame presented.

This anomalous result is investigated further in Experiment 4, which explores the effect of interference from distracter items in the stream by presenting only the critical items. This variation of the RSVP stream does not appear to significantly affect the performance of 7-year old participants from that observed during the full stream RSVP of Experiment 3.

Experiment 5 ensures that these younger participants are in fact able to detect T2 and does so by presenting an RSVP stream that extends the T2 lag to an interval of 1802ms. Results of this experiment extend the pattern seen in Experiment 2: that temporal recovery of attention is subject to developmental delay. 7-year olds show attentional recovery only when T2 is presented 1166 ms after T1. This result is discussed in relation to cortical growth and the involvement of the frontal lobes in the AB process.

General methods

Participants

Participants in all experiments had normal or corrected to normal vision and due to the flickering appearance of an RSVP stream, must not suffer from epilepsy. ADHD participants were also excluded. Informed consent was obtained from all participants prior to participation in an experiment. Where participants were under the age of 15 parental consent was also obtained. All children in the developmental studies were recruited from schools or through employees of the University of Wales, Bangor and were paid for their time. Adult participants were either students at the university participating for course credit or were recruited from the community panel of volunteers and were paid for their time.

Apparatus

The stimulus streams for this experiment were generated using a Pentium Pro(r) PC (32MB RAM) on a 24 x 32.5 cm colour monitor (99.5 Hz refresh rate). The software used was E-Prime beta 5.0 (Psychology Software Tools). Stimuli appeared at fixation, had 72ppi resolution and were created using Graphics Converter 4.0. Responses to RSVP steams were recorded via the computer's keyboard, using central buttons allocated to each response. For each experiment the participant was sat approximately 50cm from the computer screen. A chin rest was not used since this was deemed to be too intimidating for younger participants.

Design

Each of the AB experiments in this chapter comprised single and dual target trials. Single target trials (control trials) illustrated high levels accuracy of single target detection at the presentation rates and required the detection and /or identification of just the second target in the stream (T2). Experimental trials required detection of both T1 and T2. Reduced accuracy in T2 detection at early serial positions in these trials represents the depleted attentional resources for VSTM update following correct T1 detection (only trials where T1 was correctly reported were used). There were always 7-15 pre target items (or blank temporal intervals in place of targets) prior to T1 presentation. Serial position of T2 varied within and between experiments.

Procedure

A block of 30 practise trials preceded both single and dual target trials and participants undertook each trial type. Participant number counterbalanced allocation to initial condition. All items in the stream were presented on a uniform grey background and each RSVP stream began with a fixation '+' which was presented for 500 ms. Trials were self-initiated using the space bar except in the case of 7- and 12-year old participants when the experimenter made a manual input of participants' verbal responses.

Experiment 1 —The AB with coloured shapes

This experiment closely resembles the experimental structure of Raymond et al. (1992) but uses coloured shape stimuli in place of letters. This first experiment is designed to assess the appropriateness of using these novel stimuli in the generation of an AB. The present experiment uses coloured shapes requiring pattern information responses to obtain an AB. If the stimuli are successful a temporary deficit in the ability to detect T2 will be seen when it is presented in a temporal window of 350-500 ms following presentation of T1. T2 detection rates are then expected to return to baseline.

Method

Participants.

Data was collected from eight adult participants (5 female, 3 male: age range 18 – 25). One male participant was subsequently removed because of poor single-target trial performance.

Design and Stimuli

Each distracter stimulus was of dimensions 119 x 119 pixels (4.2 x 4.2 cm) and had 72ppi resolution. The black isosceles triangle used for T1 was of dimensions 61 x 118 pixels (2.15 x 4.16 cm). T2 was always a red circle that appeared on 50% of the trials (Figure 5). Each RSVP stream contained 24 items. Each stimulus was presented for 58.3 ms with an interstimulus interval (ISI) of 33.3 ms. This gave a Stimulus Onset Asynchronny (SOA) of approximately 90 ms (11.1 items/sec). T2 occurred on 50% of the trials at serial position 2, 3, 4, 5, 6 or 8. T2 therefore could occur at an SOA of 180, 270, 360, 450, 540 and 720ms.

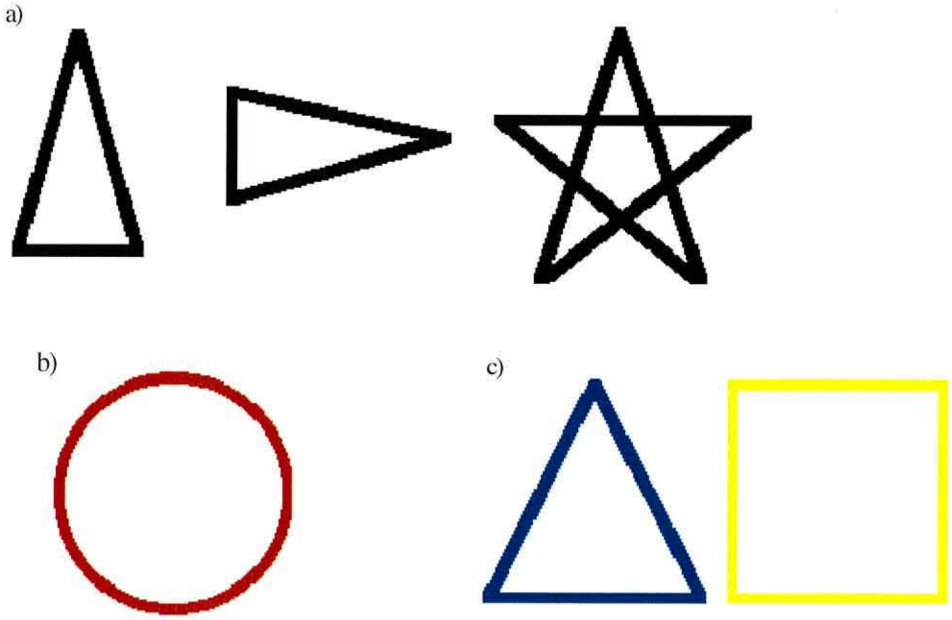

Figure 5a) Examples of T1, a black isosceles triangle, which could face up, left or right and was followed by a five-pointed star mask. b) T2 was a red circle, which was embedded in the stream of coloured shape distracters, e.g c).

Procedure.

Each participant undertook one experimental session comprising 180 single target RSVP trials and 180 dual target trials. T1 was always present, and its direction (left, right or up) varied and could appear equally as often in each direction. T2, the red circle, was present on only half the trials, giving a chance performance rate of 50%. When T2 was not presented a distracter replaced it. For T2 alone (single task) trials participants were asked to ignore T1 and to report whether or not there was a red circle. Responses were recorded by pressing 'y' or 'n' on the keyboard. In the dual task trials, participants were also asked which direction T1 faced and they responded 'up', ‘left’ or ‘right’.

Results.

Performance is calculated in terms of the percentage of trials where the T2 response was correct. In the T2 alone (single task) condition all trials are included and the percentage correct at each position is calculated, but in the dual condition only the trials where T1 is correctly identified are included in analysis of T2 performance. Only in this way can a deficit seen to T2 be attributed to the allocation of attentional resources to T1 processing. The percent correct T2 response for each block of trials was then plotted against T2 lag (Figure 6).

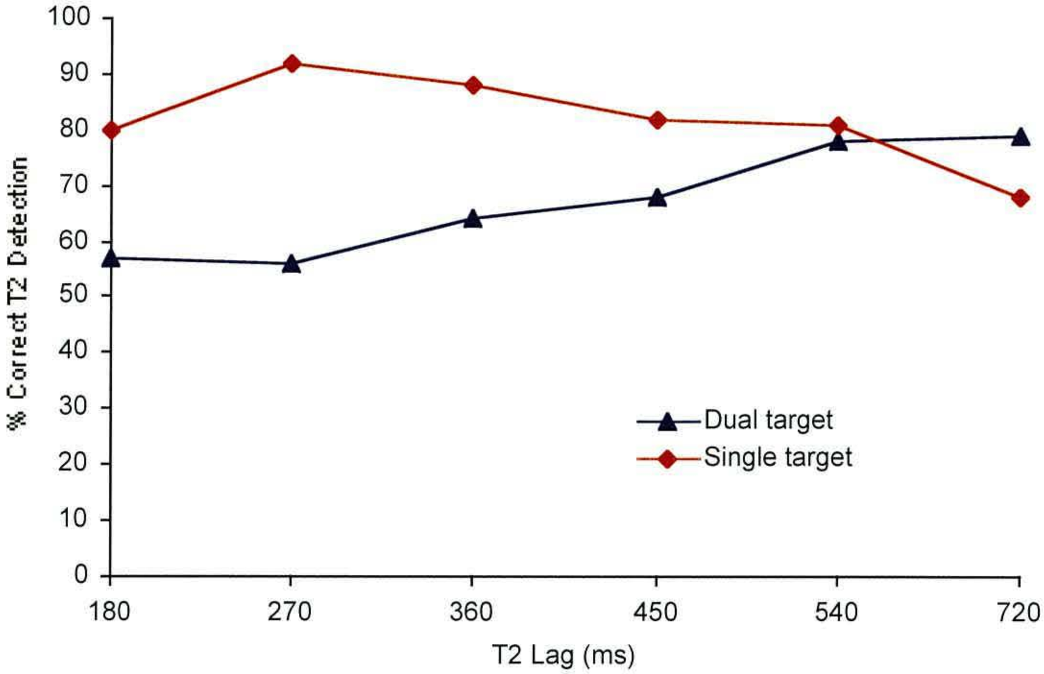

Figure 6: Temporary depletion of T2 detection rates with subsequent recovery over a typical temporal window of 350-500 ms.

Figure 6 presents percent correct detection of T2 over lag positions 2 - 8 (180-720 ms) in both dual and single target trials. A two-way repeated measure ANOVA reveals a main effect of condition (F (1, 6) = 6.04, $p<0.05$) and a significant interaction (F (5,30) = 4.20, $p< 0.05$). Figure 6 shows that there are some differences between both the task conditions and the serial positions that would indicate an AB. Planned comparisons of dual and single target performance at each serial position are conducted in order to find out where the interaction takes place and therefore the temporal interval of attentional recovery.

Paired sample t-tests on serial positions 2, 3, 4, 5 and 6 show that only lag 2 and 3 exhibit significant differences between conditions, t (6) = -2.75, $p <0.05$ and t (6) = -3.85, $p<0.01$ respectively. All other lags show no significant differences between T2 detection rates in dual and single target trials. T2 detection rates return to baseline when T2 is presented 360ms after T1.

Experiment 1 – Discussion

The baseline measure of T2 detection rates is over 80% at all lags which suggests that detection rates of T2 are unaffected by lag in single target trials. In the dual task trials, detection of T2 varies as a function of lag. When T2 occurs in close temporal proximity to T1, detection rates are low (positions 2 and 3) suggesting that attentional resources required for T2 processing are still involved in processing of T1. At later T2 lags, detection rates approach the baseline performance level that is seen in single task condition representing the time required for the recovery of sufficient attentional resources.

The effect of reduced second target detection rates at early serial positions indicates that dual target interference is occuring. There are insufficient attentional resources available for accurate processing and report of two stimulus events when they occur in close temporal proximity. However, the duration of the interference is not very long (360 ms) and this is possibly an indication of an ineffective mask following T1. An important factor in AB experiments is the masking of the targets requiring report. If the T1+1 item does not effectively mask T1, the magnitude of the AB may be reduced (Ross and Jolicoeur, 1999) as appears to be the case in this experiment. Giesbrecht and DiLollo (1998) investigate T2 masking and report that when T2 is the last item in the stream, the AB is completely eliminated. Therefore effective masking of both T1 and T2 is important when measuring the duration of the AB. In the present experiment a 5-pointed star, the same colour as the target, follows T1. Since T1 is an isosceles triangle that could point up, left or right the 5-pointed star is thought to act as an integration mask and the stream following T2 acts as an interruption mask. However, on closer visual examination it appears that the left and right arrows of T1 are not masked as well as the upright arrow (see Figure 5). The masking types are different for each target a new RSVP task must be created, based on Experiment 1, but replacing the current targets with revised ones.

It is important to establish that the divided attention interference is not due to task-switching, for example when the target tasks within an RSVP stream are not the same. This is the case in Experiment 1: the T1 task is to report the identity of the target and therefore fully encode its description, whereas the T2 task is simply to detect the presence or absence of a stimulus. T2 detection rates may be falsely high and the blink duration deceptively short in these situations since less attention is required to detect an item than to report its identity. There may be an element of attentional capture by T1 since it was the only black item in the stream and therefore highly salient. Attentional capture may also occur for T2 since it is not followed by an integration mask and instead is ‘masked’ solely by the following item in the stream.

The Effects of Task-Switching

The intention in Experiment 1 was to adhere as closely as possible to the methodology used by Raymond et al. (1992), but to do so by using coloured shapes. However, the target tasks were different from each other: one was an identification task and one was a detection task. This represents an attentional switch between targets. T1 is an identification task and T2 is a detection task — this represents a task-switch. These two tasks may rely on slightly different cortical functions and the T2 deficit seen cannot solely be attributed to the attentional demands of the same processes following T1 detection. Therefore, the T2 deficits seen in Experiment 1 could be due to the costs of attentional switching from one target to another rather than a reduced capacity for attentional processing (Visser, Bischof and DiLollo, 1999). For the RSVP stream to effectively measure divided attention, both tasks must be of the same type (i.e detection *or* discrimination).

To overcome the issues raised in Experiment 1 a new RSVP stream is devised, which utilises the same attentional mechanisms for each target task, and presents effective integration masks for each target.

Experiment 2 — The AB without task switching

In Experiment 2 the targets are a red isosceles triangle that can face either left or right, and a blue isosceles triangle that can face either up or down and an integration mask followed each item. The masks are composite masks comprising four isosceles triangles of the same colour as the preceding target pointing up, down, left and right (see Figure 7). T1 and T2 tasks are now both discrimination tasks with a chance performance level of 50%.

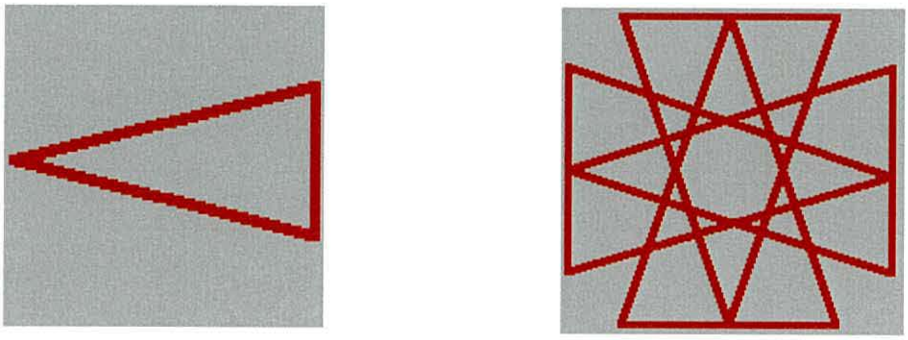

Figure 7: An example of the target and mask used in Experiment 2.

Method

Participants.

Sixteen participants aged 18-25 took part in Experiment 2. Participants were selected from the undergraduate participation panel at University of Wales, Bangor.

Design and Stimuli.

As in Experiment 1, each stream contained 24 items and T2 appeared at serial position 2, 3, 4, 5, 6 or 8. Each stimulus was presented for 58.3 ms and the ISI was 33.3 ms. Each SOA was therefore approximately 90 ms (items were presented at rate of 11.1 per second).

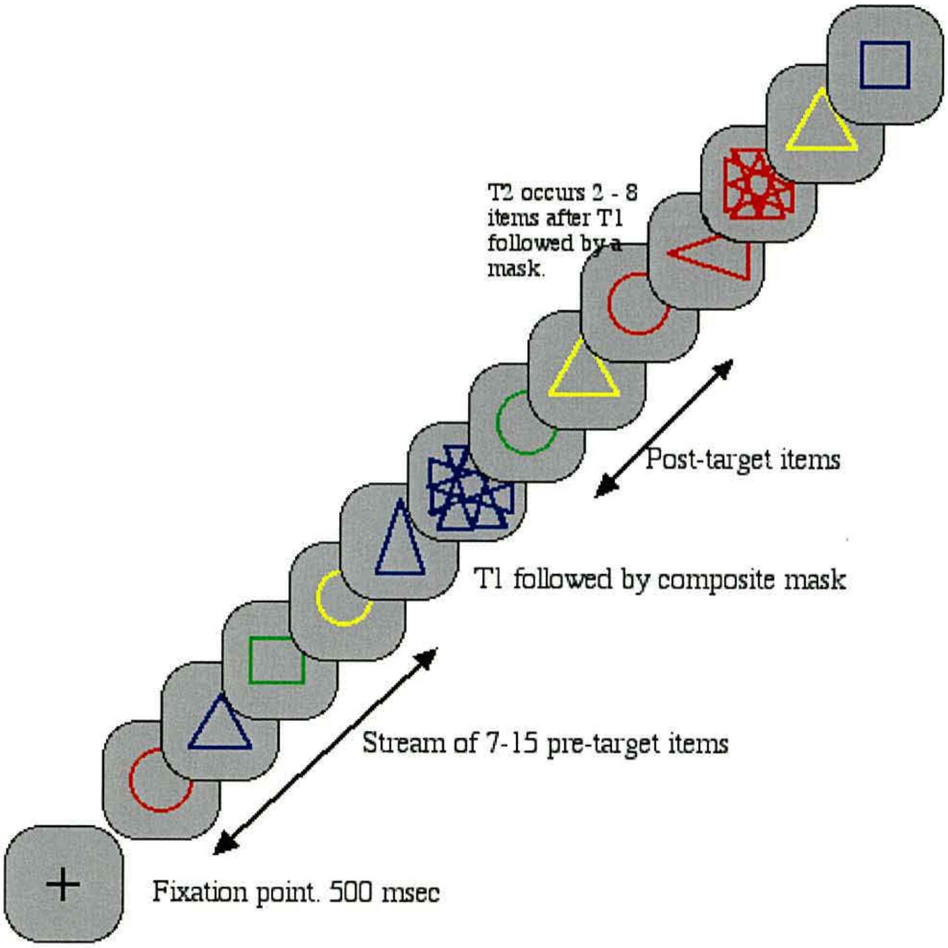

Figure 8: Diagrammatic representation of the RSVP stream used in Experiment 2.

The targets were of dimensions 61 x 118 pixels (2.15 x 4.16 cm) and the target masks were of dimensions 180 x 180 pixels (6.35 x 6.35 cm). The distracter items remained the same as in Experiment 1 and were of dimensions 119 x 199 pixels (4.2 x 4.2 cm). Allocation of the target types to T1 and T2 was counterbalanced.

Procedure.

Each participant took part in one session comprising 120 dual target experimental trials and 120 single target experimental trials. Each participant received practise trials for the first condition (dual or single) followed by 60 experimental trials. This was repeated for the second condition. Participants then received a further 60 trials for each condition following the original order of presentation. For example: 30 practise dual, 60 experimental dual, 30 practise single, 60 experimental single, 60 experimental dual, 60 experimental single. This was done to reduce any order effects that may occur by using two larger blocks of trials.

Results.

Performance is calculated as in Experiment1 and plotted against T2 serial position (Figure 9).

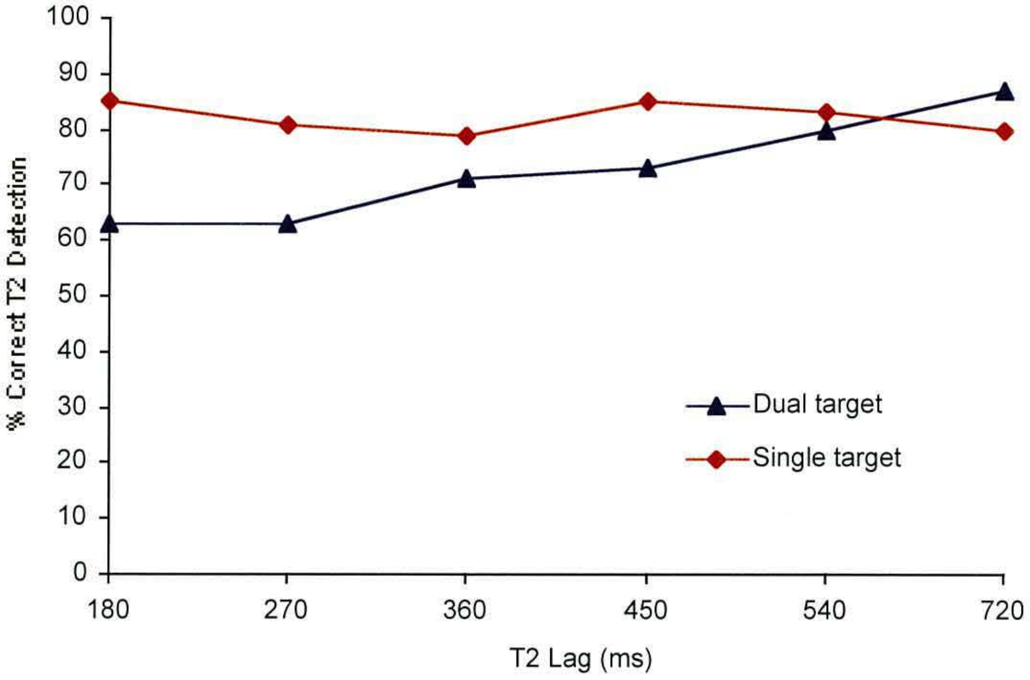

Figure 9: Dual and single target performance in Experiment 2

Figure 9 shows that T2 performance in dual task trials improves over T2 lag, and that T2 percent correct appears to reach baseline at position 6 (540 ms after T1 presentation). A repeated measures ANOVA shows that there is main effect of both condition and lag *F* (1,15) = 7.84, $p < 0.05$ and *F* (5,75) = 5.12, $p<0.01$ respectively. The interaction is also significant: *F* (5,75) = 5.14, $p < 0.01$.

Planned comparisons are conducted to investigate the point of temporal recovery indicated by the significant interaction. Paired sample t-tests show significant differences between T2 detection rates in dual and single target trials at lags 2, 3 and 5 (t (15) = -3.32, $p<0.01$; t (15) = -3.71, $p < 0.01$ and t (15) = -2.44, $p<0.05$ respectively). There is no significant difference between dual and single target performance at lag 4. However, since single target detection rates are lower at this lag than those flanking it, and there is a significant difference at lag 5, dual target performance is still affected by T1 requirements until position 6, representing 540 ms following T1presentation.

Experiment 2 – Discussion

This experiment successfully generates a significant T2 deficit at early T2 lag positions. The recovery of T2 detection rates over subsequent lags indicates an AB. The duration of the AB is slightly longer in this experiment that in experiment 1. This suggests that the masks are interfering with the processing of the targets and, as suggested by Raymond et al. (1995), the similarity between the targets and their +1 items makes them difficult to distinguish. In Raymond et al.'s model this would result in the attentional gate being shut and locked following target detection resulting in a longer 'blink' period before a subsequent item could be accurately reported. Shapiro et al. (1997) explained the same effect by saying that masked targets require more attention to reach a level sufficient for report and Chun and Potter (1995) stated that less attention is therefore available for T2 consolidation during Stage 2 of their model and it becomes subject to decay. The presence of an effective mask in this experiment has lengthened the blink slightly but the duration, 540 ms, is still typical of current AB literature. This experiment is therefore successful in creating a RSVP stream with two target tasks utilising the same attentional resource. The issue of task switching has been eliminated and the stream can now be presented to a range of ages for comparative analysis.

Experiment 3 – Is there a developmental difference in Temporal Attention?

The deficit seen in the attentional blink tasks reflects the time that is required for target discrimination and consolidation, before attentional processing capacity is made available for a subsequent target. The deficit reflects impairments in VSTM organisation, governed by WM. Experiment 2 demonstrated that coloured shapes successfully yield T2 deficits at short temporal lags followed by an increase in T2 detection rates as the temporal distance between T1 and T2 increases.

Experiment 3 presents a slightly modified version Experiment 2: the SOA of each item in the stream has been increased by 1 refresh rate to 106 ms[6] and the steam has been extended so that T2 can now occur at serial position 10 (SOA 1060 ms).

Method

Participants

Sixty-four participants took part in this experiment. All adult participants were between the age of 20- and 45-years of age and the mean ages and age ranges of the children are presented below in Table 1

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[6] Pilot studies with 6-year old and 12-year old participants suggested that a slightly slower presentation rate of 106 msec SOA and a longer stream would be more appropriate for child participants.

Table 1: Mean ages and age ranges of children who took part in Experiment 3.

	Age 7	 12	 15
Mean	7y 7m	12y 5m	15y 5m
Age Range	7y 0m —8y 3m	12y 0m – 13y 0m	15y 1m – 15y 11m
n	16	16	16

Design and Stimuli

The experiment is a mixed design whereby age is a between-subjects aspect and the AB task serves as a within-subjects design. Each participant completes both dual and single target trials.

Procedure

The presentation of practise and experimental blocks remains the same as in Experiment 2 with the exception that in the current experiment T2 could occur at one of serial positions 2, 3, 5, 6, 8 or 10. Each RSVP stream therefore contains 26 items. Each stimulus is presented for 66.7 msec with an interstimulus interval (ISI) of 39.9 msec. This gives an SOA of approximately 106 msec.

Results

Experiment 3 presents the attentional recovery patterns of four age groups. Illustrating both the dual and single target trial performances at each of 6 serial positions for 4 age groups would be difficult on one graph, and therefore Experiment 3 uses the *magnitude* of the AB at each T2 lag position for each age group. Magnitude of the AB is calculated by subtracting the dual target performance from the single target performance at each serial position.

Magnitudes however do not represent the information on the y-axis of an AB graph, i.e the single target detection rates. It is important to establish that any developmental differences seen in the AB are due to variations in a dual target performance and not, instead, to a reduced single target performance. Therefore the dual and single target performances (standard AB) of each age group are presented graphically for reference before the magnitude data is presented and analysed.

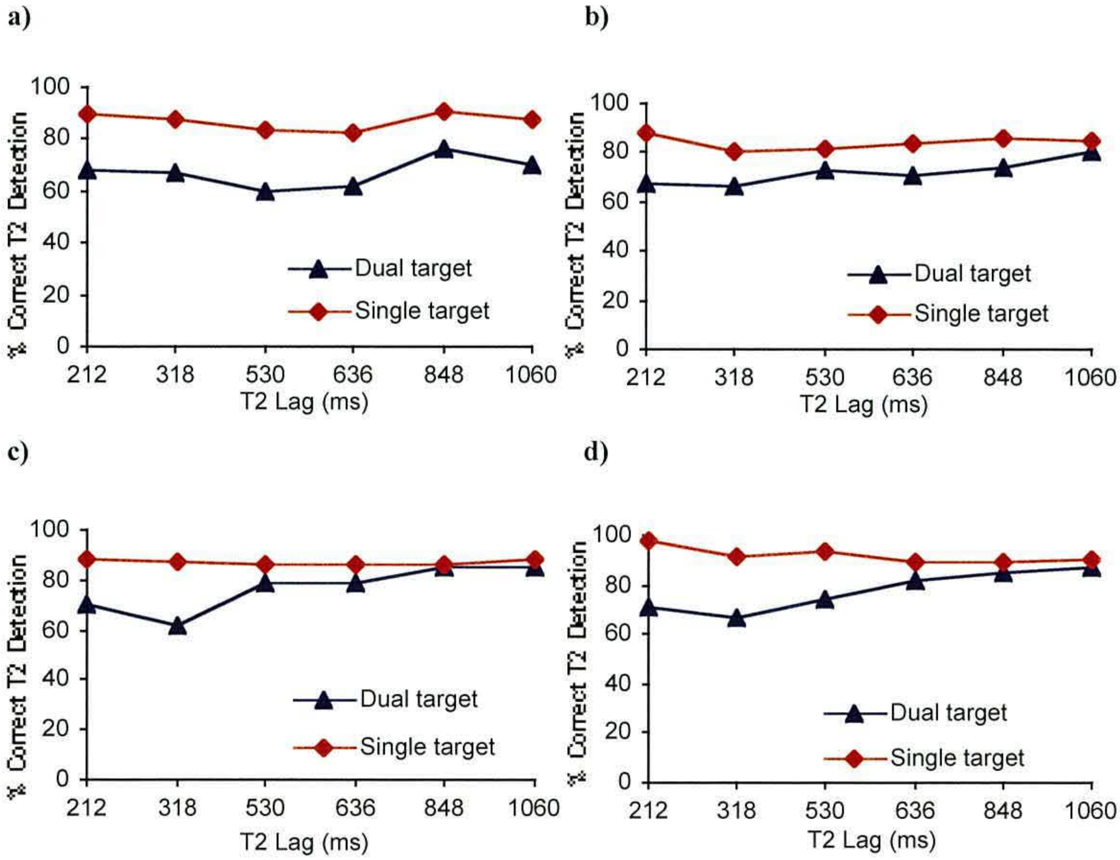

Figure 10: Dual and Single target performances over T2 Lag positions for a) 7 year olds, b) 12 year olds, c) 15 year olds and d) adults.

Figure 10 shows that the single target detection rates for all age groups remains high – over 80% across all serial positions for all ages. A mixed ANOVA shows no main effect of age in single target trials. Figure 10 also shows that the patterns of T2 detection rates in the dual target conditions are different. This is further examined through the use of magnitudes in the following section.

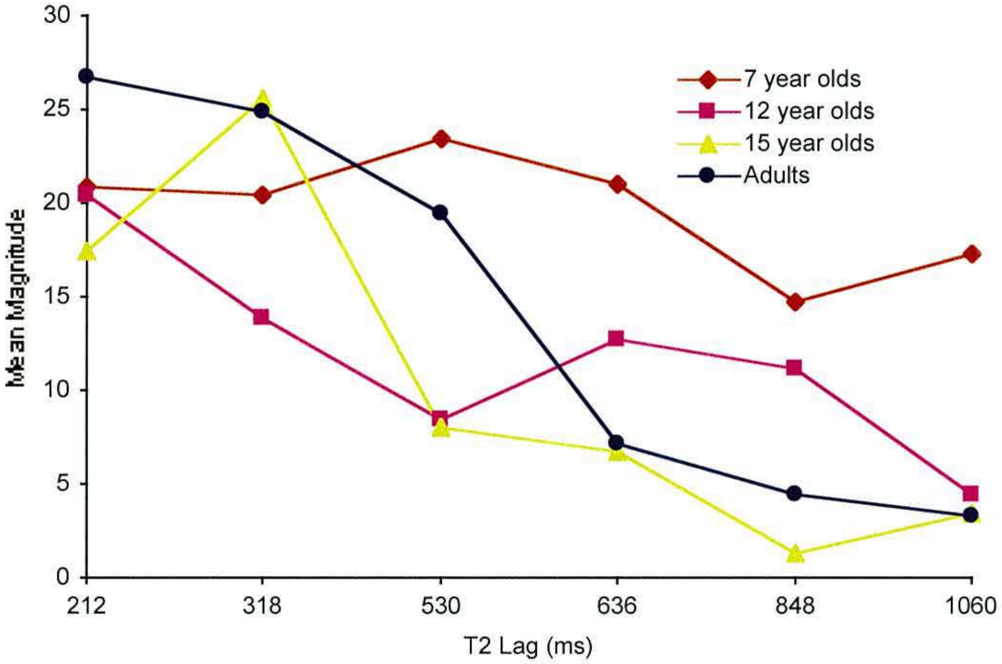

Figure 11: Magnitudes of the Attentional Blink for 7-, 12-, 15-year olds and adults.

A mixed measure ANOVA on the above data reveals a significant main effect of age (F (3, 60) = 2.98, $p<0.05$) and T2 lag position (F (5, 300) = 14.10, $p<0.01$). There is also a significant interaction between age and T2 lag position (F (15, 300) = 2.44, $p<0.01$)[7].

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[7] When the ANOVA is run using data from both conditions, the interaction Age x Condition x Position is also significant (F (15, 300) = 2.44, $p<0.03$).

Figure 11 illustrates the magnitudes of the AB across serial positions for each of the four age groups tested. The 12- and 15- year olds, as well as the adults, appear to show an attentional recovery – the magnitudes approach zero over increasing T2 lag, but the magnitude of the AB for 7-year old participants is hardly affected at all over serial position. Polynomial contrasts in the form of trend analysis confirm this developmental difference since the linear trend of the magnitudes over serial position is different for each age group (F (5, 300) = 44.54, $p<0.01$).

Planned comparison in the form of paired t-tests at each of the T2 lag positions for the four age groups will illustrate the temporal deficit in VSTM update (AB duration) for each age group. The adult data reveals significant differences between dual and single target performance up to and including lag 5, 530ms (t (15) = -4.50, $p<0.01$). The same comparison with data from 15-year olds reveals a significant differences up to and including lag 6, 636ms (t (15) = -2.41, $p<0.05$). 12 year olds reveals a significant differences up to and including lag 8, 848ms (t (15) = -3.07, $p<0.01$). The final age group, 7-year olds, do not appear to show any attentional recovery at all over the time frame presented. Indeed, all T2 lag positions reveal a significant difference between single and dual target detection rates: position 10 (1060ms) reveal significant differences between dual and single target performance (t (15) = -3.21, $p<0.01$). The duration of the AB therefore appears to be different for each of the age groups tested and a developmental trend is suggested: that the duration of the AB will decrease over increasing age.

Table 2: Summary of Attentional recovery as revealed by Experiment 3

Age			
7	12	15	Adult
N/A	1060 ms	848 ms	636 ms

Experiment 3 — Discussion

Experiment 3 reveals a developmental difference in the duration of the AB. AB duration reflects the time required for sufficient attentional capacity to become available following allocation to a first target (Chun and Potter, 1995; Raymond, Shapiro and Arnell, 1992; Shapiro Raymond and Arnell, 1997). This is considered to be a representation of the time course required for VSTM to efficiently consolidate and store a target representation and this is governed by WM (Shapiro, Driver, Ward and Sorenson, 1997; Vogel, Luck and Shapiro, 1998). Experiment 3 has shown the duration of the AB to be 636 ms in adult participants. This is slightly longer than has been previously reported, but this may be due to the identification-identification requirements of this experiment in contrast to the identification-detection requirements previously assessed, or the slightly longer SOA. The duration of the second target deficit was extended to 848 ms in 15-year olds, and to as long as 1060 ms in 12-year old participants. More interesting was the 7-year old participants' failure to recover their attentional resources at all within the time frame presented. At T2 lag position 10, representing 1060msec, the deficit in dual target identification rates following correct T1 identification were as great as at T2 lag position 2. An AB duration longer than 1 second is unusual in normal participants in the existing AB literature, although Husain et al. (1997) revealed an AB as long as 1440ms in participants suffering visual neglect following right hemisphere damage to the parietal or frontal lobes, or to the basal ganglia. The AB effect appears to be greater for adults at early serial positions than for children, however this is not due to poorer dual target detection rates of adults and instead is attributed to higher T2 detection rates in single target trials for these participants (Figure 10).

The increased AB duration in the younger participants of this experiment may reflect an increased susceptibility to interference (Raymond et al., 1995). Rather than the blink duration representing the time required for attentional resources to become available for a second target, it might instead represent the length of time that subsequent items interfere with T1 processing. In this situation, it would not be just the +1 item that creating confusion for target identification, but further objects in the stream may be intruding. This would support the Interference theory (Shapiro et al., 1994) suggesting that perceptual representations are initially created for all items prior to target selection. Increased susceptibility to interference in dual target tasks has also been shown with frontal lobe patients (Richer and Lepage, 1996). The effect of this increased interference is to heighten the inertia of target discrimination. The frontal lobes are implicated in the successful target discrimination required for the AB (Fuster, 1989). Imaging studies (fMRI) have provided support for this and as such have revealed the right parieto-frontal network to be a centre of capacity-limited processing required during the AB (Marois, Chun and Gore, 2000).

The frontal lobes of 7-year olds are under developed since this cortical area continues to develop until the age of 20 years old (Case, 1992) and the frontal lobes are considered to be important for working memory and executive functions (this is discussed in detail in the introduction). The AB task requires that distracting information in the form of non-target items, be ignored. The ability to suppress these stimuli and facilitate processing of target items is considered an executive function. In addition to this inhibition, participants also have to hold a template of the target image in working memory along with the detected shape for report. For these processes to be successfully executed at rapid presentation rates, items in VSTM must be quickly consolidated and stored. This process is controlled by the central executive component of WM, the networks of which pass through the frontal lobes. It may be the case that the developmental difference in AB is a reflection of poorer frontal lobe performance in these participants. The results of Experiment 3 therefore initially suggest investigation into distracter inhibition.

Duncan, Ward and Shapiro (1994) investigated the attentional dwell time in human visual attention using two spatially separate targets followed by pattern masks. This experiment demonstrated that the processing of a single visual item takes several 100 ms and the results were directly comparable to a full stream AB experiment. This finding has since been replicated by a number of researchers (Moore, Egeth, Berglan and Luck, 1996; Ward Duncan and Shapiro, 1996). Given the similarities in the interference patterns of AB experiments and the simple two-target attentional dwell time paradigm, Ward et al. (1996) have suggested that the target objects compete in parallel within the limited capacity of the visual attention system. However the interference in the RSVP paradigm could be due to the selective processing mechanisms required for discrimination of targets from distracter items in the stream. This could mean that the similar interference patterns in the two paradigms is in fact due to different processes. Ward, Duncan and Shapiro (1997) attempted to resolve this issue by using the two-target paradigm of Duncan et al. (1994) but with the targets presented in the same spatial location. Their skeletal RSVP streams therefore comprise T1, T1 mask, and T2, T2 mask — separated by a variable blank interval. It was discovered that interference on this modified task is sustained for approximately the same length of time as in a standard AB task.

A normal 'blink' pattern can therefore be obtained in adults using just the 'critical items' of a stream and therefore subsequent investigation presenting this type of stream is required. Distracter items do not normally affect the pattern of the AB in adults, but perhaps the inability to inhibit distracting information will cause increased interference in the full stream AB in 7-year olds due to underdeveloped frontal lobes. Therefore removing the distracter items will remove the possibility of interference from further items in the stream. If the lack of recovery represents a prolonged AB in the 7-year olds of Experiment 3, and this is due to increased susceptibility to interference, then RSVP streams presenting just the critical items should yield a return to baseline of T2 detection rates in younger participants.

Experiment 4 – A critical items AB

Experiment 4 is a follow-up to Experiment 3 and attempts to explain why 7 year olds show such an unusual pattern of results in an AB task. In Experiment 3, 7 year olds are the only age group that do not show an attentional recovery on the AB task. Following hypotheses regarding the inhibitory functions of the frontal lobes and the underdevelopment of this cortical area in the youngest participants of Experiment 3, Experiment 4 is therefore an investigation into the interference of distracter items in the RSVP stream.

The presentation rates of Experiment 4 remain the same as in Experiment 3, but the random stream of distracters is now replaced with a variable blank interval. The following experiment investigates the AB with critical items for both adults and 7 year olds.

Method

Participants

8 children mean age 7 years 8.5 months (age range 7y 1m – 8y 2m) and 8 adults (all over the age of 20) took part in this experiment.

Design and stimuli

The target stimuli and experimental design are those used in Experiments 2 and 3. In the current experiment, only T1 and T2 followed by their respective masks are presented and distracter items in the stream are replaced by a uniform grey background, which appears as a variable length gap.

Procedure

The procedure remained the same as in Experiment 3.

Results

T2 performance for each condition is calculated as in previous experiments in this chapter.

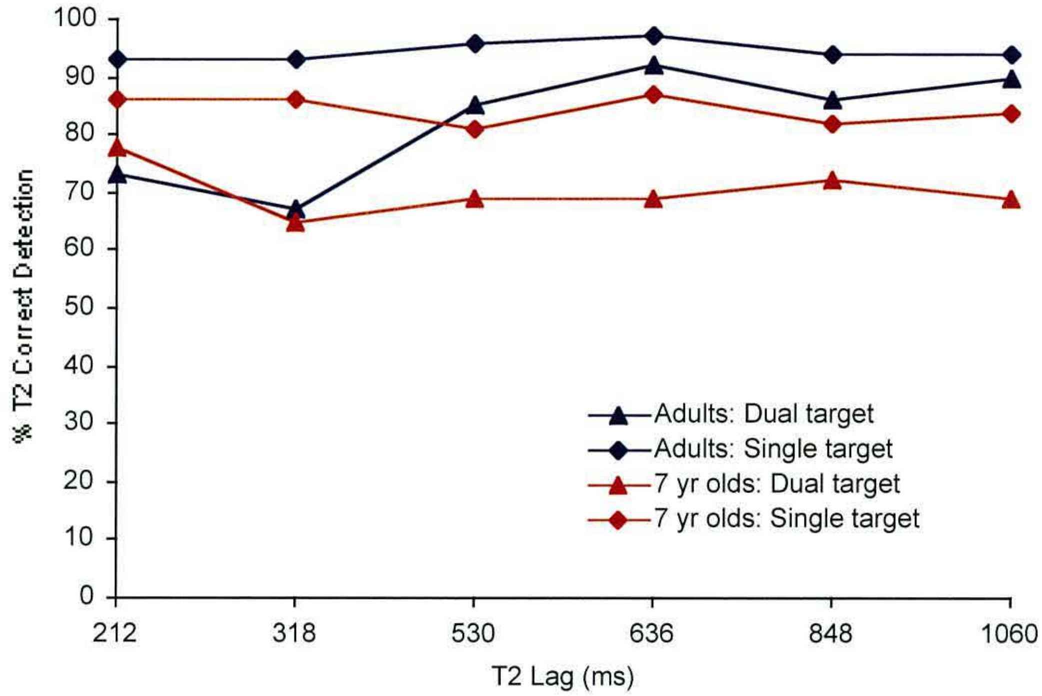

Figure 12: Dual and single target performance of adult and 7-year old participants in a critical items RSVP stream.

A mixed measures ANOVA conducted on the above data reveals a marginally significant main effect of age (*F* (1,14) = 3.90, $p = 0.068$), and highly significant main effects of T2 lag position and condition (dual or single target trials, *F* (5,70) = 33.13, $p<0.05$ and *F* (1,14) = 33.13, $p<0.01$ respectively). The interaction between age x T2 lag position x condition is marginally significant (*F* (5,70) = 2.23, $p = 0.06$). The difference between the patterns of the blink of these two age groups can be determined from the two-way interaction of age x T2 lag position. This is indeed significant (*F* (5,70) = 3.85, $p<0.05$) and the polynomial contrasts reveal that the linear trend of each age group is significantly different (*F* (5,70) = 12.38, $p<0.01$) as is the quadratic trend for each group (*F* (5,70) = 9.79, $p<0.01$). This suggests that the overall pattern of recovery is different for these two age groups and that the direction of the data with regard to the quadratic trend is also different. This is illustrated in Figure 13 where the adult magnitude follows an expected pattern — a gradual decrease over serial position, and the 7-year olds (although the magnitude fluctuated slightly) showed no overall decrease over serial position.

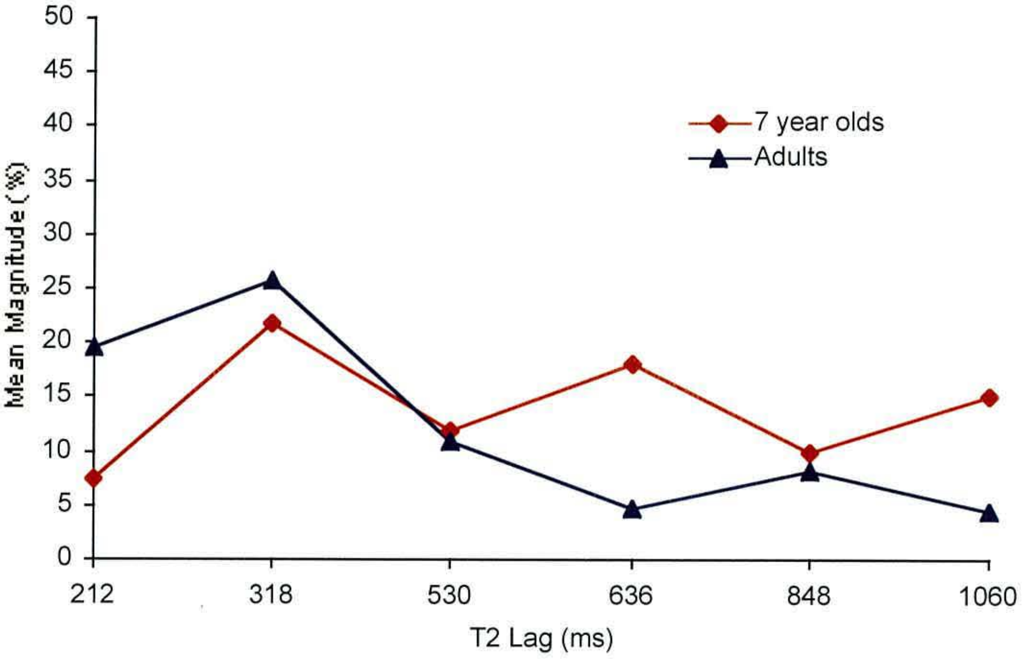

Figure 13: Magnitudes of the Critical items AB for adults and 7 year olds.

The adults in this experiment show a normal attentional recovery which is revealed in a repeated measures ANOVA as a main effect of condition (F (1, 7) = 17.48, $p<0.01$), a main effect of position (F (5, 35) = 8.80, $p<0.01$) and highly significant interaction (F (5,35) = 8.79, $p<0.01$). Planned comparisons reveal significant differences between dual and single target performance at T2 lag positions 2 (212ms) and 3 (318ms) (t (7) = 5.20, $p<0.01$ and t (7) = 5.79, $p<0.01$ respectively). T2 detection rates appear to have recovered to baseline by position 5 (530 ms) in the adult participants. This is slightly earlier than was seen in the full stream experiment, but as the following comparison illustrates, the pattern of performance is not significantly different between these two experiments for the adult participants.

A repeated measures ANOVA run on the 7-year olds data showed only a main effect of condition (*F* (1, 7) = 16.05, *p*<0.01) and no significant interaction between condition and T2 lag position. This suggested that the function of T2 detection rates across serial position was approximately flat for these participants and further analysis would not normally be required. However, Figure 12 seems to depict a smaller AB magnitude at lag 2 for these participants. Paired t-tests were therefore run on the above data and revealed that the difference in dual and single target performance at lag 2 (212 ms) is only marginally significantly different (*t* (7) = 2.16, *p* = 0.068), but at lag 3 (318 ms) it is significantly different (*t* (7) = 2.74, *p* <0.05). The main effect of condition was significant suggesting that over the 6 serial positions dual target performance is significantly lower than single target performance. This issue is discussed further in the summary of this chapter.

Comparison between critical items and full stream

Adults

A mixed ANOVA comparing critical items data with the full stream data from Experiment 3, with a between subjects factor of experiment shows main effects of condition and T2 lag position (*F* (1,22) = 23.98, *p*<0.01 and *F* (5, 110) = 9.78, *p*<0.01 respectively). The two-way interaction between condition and T2 lag position is significant across experiments (*F* (5, 110) = 12.54, *p*<0.01). There is no significant main effect of experiment or significant interaction between condition x T2 lag position x experiment for adult participants. Despite the unequal participant numbers in these experiments (n=8 for the critical items, and n=16 for the full stream), Mauchly's test for sphericity shows there is no evidence of unequal variance between the two populations.

7-year olds

The same analysis conducted on 7-year old participants also shows a main effect of condition and of T2 lag position (F (1,22) = 51.93, $p<0.01$ and F (5, 110) = 3.35, $p<0.01$ respectively). There is no main effect of experiment or any significant interaction between condition x T2 lag position x experiment. Again, Mauchly's test of sphericity gives no cause for concern regarding variance between populations due to unequal sample sizes.

Experiment 4 —Discussion

The performance on the critical items AB is the same as that of the full stream AB of Experiment 3 for each age group. Whilst adult participants recover attention during the time frame presented, 7-year olds do not. The lack of attentional recovery in 7 year olds is analogous to the result from the full stream AB experiment (Experiment 3) and this is supported by cross-experiment analysis. The removal of distracter items from the stream does not affect the performance of the 7-year olds.

There are two main findings in Experiment 4: (1) that a normal pattern of temporal attention performance is attainable in adult participants using just the critical items (Ward et al. 1997); and (2) that the removal of distracter items in the current experiment does not improve dual target detection rates in 7-year olds. This therefore suggests that distracter items that are not affecting the younger participants' performance. Experiment 4 suggests that the lack of attentional recovery in Experiment 3 is not due to the presence of distracter items and the results do not support the Interference model proposed by Shapiro et al. (1994). Instead results are inline with the suggestions made in the introduction (p. 19-21): targets which are masked require attention for them to be passed to a more durable stage (VSTM) for consolidation and storage. WM is required for the efficient storage of items and when insufficient processing capacity remains following T1processing and consolidation, retrieval competition occurs and T2 is not accurately reported. If the temporal duration of this process is subject to developmental delay, as would be suggested from the pattern of performance in the 12- and 15-year old participants, perhaps 7-year olds require an even longer inter-target interval for efficient consolidation of both T1 and T2. It therefore seems appropriate to test 7-year old participants on an AB stream extending beyond 1 second in order to establish the point of attentional recovery that may exist for these participants.

Experiment 5 — An extended RSVP stream.

Removing the distracter items fails to produce attentional recovery in 7-year old participants over a 1-second time frame. Experiment 3 shows a progressive reduction in duration of the AB time over the age range of 12-years old to adult. The flat function of the 7-year olds suggests an inability to discriminate two targets in an RSVP stream and Experiment 4 investigated the possibility that it was due to poor inhibitory functioning. Since performance in an AB task presenting just the critical items of an RSVP stream does not significantly vary from performance in a full RSVP stream it seems appropriate to investigate whether 7-year olds do in fact show a delayed attentional recovery over a longer time frame.

Therefore Experiment 5 presents an extended AB stream which presents T2 up to a maximum of Lag 17 (1802 ms) after presentation of T1. This almost doubles the stream length of Experiment 4 and should reveal any late recovery in attentional ability that may be present. This experiment is only run on 7-year olds since no age comparison is required for this investigation.

Method

Participants

The same 7-year old participants as in Experiment 4 were tested on this extended RSVP stream. They were not tested on the same day and initial allocation to

Experiment 4 or Experiment 5 was counterbalanced. At the time of testing for Experiment 5 the mean age was 7 year 8.9 months (age range 7y 3m to 8y 1m)

Design and Stimuli

The target stimuli are those used in Experiments 2 and 3. There are two blocks each containing 60 trials for each experimental condition that were presented in an ABAB fashion[8]. The RSVP stream is extended in Experiment 5 such that there are now 33 items in the stream and T2 can appear at serial position 2, 5, 8, 11, 14, and 17 (212, 530, 848, 1166, 1484, and 1802 ms). T1 occurs at position 7 –15. All other aspects of the stream remain the same as Experiments 3 and 4.

Procedure

The procedure remains the same as in Experiments 3 and 4.

Results

Performance on single and dual target trials is plotted as a function of T2 lag position and is presented in Figure 14

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[8] Dividing the trials up in this way helps to reduce carry over effects to the second trial type, and provided convenient rest points for the children during the slightly longer session of Experiment 5.

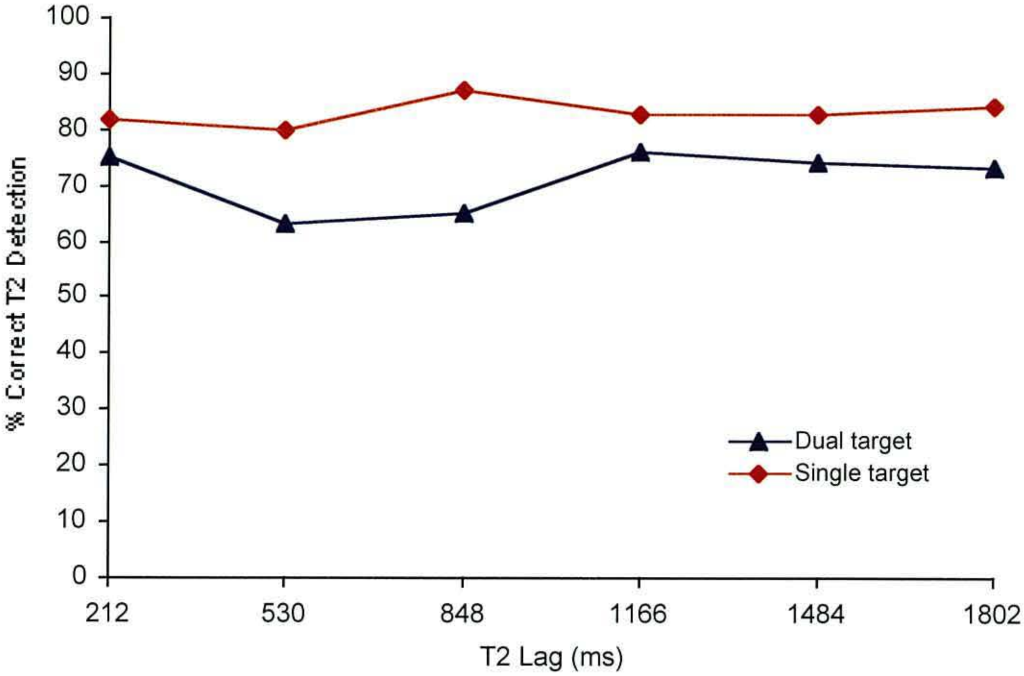

Figure 14: 7-year olds performance on an extended RSVP stream

A repeated measures ANOVA on the above data reveals a significant main effect of condition (*F* (1,7) = 12.0, $p< 0.01$), and a marginally significant interaction between T2 lag position and condition (*F* (3,35)= 2.41, $p = 0.056$). Analysis in the form of paired t-tests reveals that there is a significant difference between dual and single target performance for T2 lag 530ms and T2 lag 848ms (t (7) = -5.29, p <0.01 and t (7) = -4.11, $p < 0.01$ respectively). Position 11 (1166 ms) was not significant, suggesting that the ability to detect T2 had returned to the level of single target performance by this point. Position 2 (T2 lag 212ms) did not show a significant difference between dual and single target performance. This pattern of performance was also suggested in Experiment 4 and the issues of high detection rates at early serial positions are discussed in the summary of this chapter.

Experiment 5 – Discussion.

Experiment 5 is a follow-up experiment to Experiment 3 and as such attempts to discover the point of recovery of temporal attention in 7-year olds. ANOVA reveal that there is an interaction between trial type and serial position of T2, which suggests that the T2 detection rates across serial position are not parallel as in Experiments 3 and 4. Planned comparisons showed that the point of interaction is at 1166msec T2 Lag. This is the point at which the dual target performance no longer significantly differs from the single target performance.

Results indicate that the attentional processing capacities of 7-year olds do recover and that the children were not simply giving up in previous experiments. The unusually long duration of the AB extends the findings of Experiment 3 and suggests a developmental improvement in this ability. The accepted view of dual target interference in RSVP streams is that targets must be identified and then consolidated and organised in a durable store (VSTM) and that this process is governed by WM (Shaprio, Driver, Ward and Sorenson, 1997). Identification of a second target cannot begin until the representation of the first target has been passed to the durable store for consolidation (Chun and Potter, 1995). Since WM functions operate in networks that pass through the prefrontal cortex (Kane and Engle, 2002), and the frontal lobes continue developing over the first 20 years of life (Case, 1992), it seems appropriate to suggest that this underdevelopment is the cause of the extended blink in children. This suggestion has support from patient data showing a prolonged AB in frontal lobe patients (Richer and Lepage, 1996) and from imaging studies illustrating the involvement of WM update during the AB (Vogel, Luck and Shapiro, 1998)

Experiments 1-5 — Summary and Discussion

Chapter 2 attempted to expand the current literature on the Attentional Blink by investigating the developmental differences in temporal attention performance of children. Motivation for this investigation came from the literature implicating the frontal lobes during an AB task (Husain et al. 1997; Marois et al., 2000; Richer and Lepage, 1996). Dual target deficits in AB performance have been attributed to an impairment in VSTM update which is controlled by WM. Although working memory functions utilise various cortical areas, depending on the task, the central executive component considered to be important on the AB (efficient organisation and storage) generally activates areas of the prefrontal cortex in imaging studies (Roberts, Robbins and Weiskrantz, 1998).

The frontal lobes of humans are known to continue developing until the age of 20-years old and therefore a detriment in dual target performance of the AB was hypothesised for participants with underdeveloped frontal lobes. In order to conduct research in this area with young children, alternatives to the widely used letter stimuli needed to be established. It was considered that identification and report of letters would be problematic for very young children and therefore alternative stimuli were developed. Experiment 1 was successful in generating an AB pattern in adults using coloured shapes, but the dual target deficit could not be attributed to prior processing requirements since T1 and T2 were different tasks: T1 was a detection task and T2 was a discrimination task[9]. Experiment 2, therefore moderated the target tasks, so that both targets required an identification judgement and differed only in their colour. Adult participants again yielded a typical AB pattern in this task and

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[9] This issue is discussed following Experiment 1.

therefore Experiment 3 extended the investigation to children aged 7-, 12- and 15-years old. The parameters of the experiment were adjusted slightly following pilots with 6- and 12-year old children and the new version of the stream was presented to all four age groups.

Experiment 3 produced two interesting findings. The first of which was a developmental reduction in attentional dwell time as measured by an RSVP task over the ages 12, 15 and adult. Whilst adults yielded a typical attentional recovery period of 636 ms, 15-year olds required 848 ms and attentional recovery was not seen in 12-year olds until 1060 ms following presentation of T1. Secondly, this incredibly long AB, is made all the more interesting by complete lack of attentional recovery in 7-year olds. Experiments 3 and 4 suggested that the attentional abilities of 7-year old children do not recover in a dual target paradigm. This finding could mean that the youngest participants have trouble inhibiting visual information from distracter items in the stream or that the period of time required for their attentional systems to recover capacity is longer than the time frame presented in Experiment 3. Therefore Experiment 4 and 5 served as follow-ups to Experiment 3 in an attempt to resolve this question.

Experiment 4 presented an RSVP stream of the same parameters as Experiment 3, but the distracter items were removed. If these were responsible for the lack of recovery in Experiment 3, then removal of these items would enable attentional recovery to take place. However, this was not the case and attentional recovery was still not present in the youngest participants. Cross-experiment comparisons revealed no significant differences between the experimental outcomes of Experiment 3 and 4 for either adults or 7-year olds. Results of this experiment do not support the attentional gating hypothesis put forward by Raymond et al. (1992) and instead results are discussed in relation to the two-stage hypothesis (Chun and Potter, 1995) suggesting that first target consolidation in VSTM must be completed before subsequent items can enter VSTM. Attentional capacity (WM) is required for this consolidation and the temporal delay in accurate second target detection reflects the duration of this process. It would seem as though when less attentional capacity is available the temporal delay is increased. The under developed frontal lobes of participants under the age of 20 would possess a reduced attentional capacity and this is considered to be responsible for the developmental pattern.

Given the developmental reduction in attentional dwell time illustrated in Experiment 3, it seems sensible to hypothesise that the attentional abilities of 7-year olds would recover, but at a later point than was measured by the stream length presented in Experiment 3. The final experiment in this chapter, Experiment 5 successfully generated an AB pattern and showed that the T2 detection rates in dual target tasks return to baseline levels, but not until 1166 ms after presentation of T1. This represented an exceptionally long attentional blink, but followed the developmental trend set in Experiment 3.

A recurring issue in this chapter is that of high T2 detection rates at early serial positions for 7-year olds. The effect was marginal, although present in Experiment 4 and was repeated in Experiment 5. This pattern of performance has been previously been seen and investigated (Visser, Bichof and DiLollo, 1999) and is usually referred to as 'Lag 1 sparing'. This typically produces a U-shaped function of T2 detection rates over serial position and is defined by Lag 1 exhibiting detection rates exceeding the lowest performance by 5%. Lag 1 sparing is typically seen when a task-switch is required between the targets on only one dimension (as in Raymond et al. (1992) where T1 is an identification task and T2 is a detection task) or when no switch is required (as in the current experiment). Task switches can be by modality, task (e.g. identification or detection), or by category (e.g. letters or digits). Shapiro and Raymond (1994) suggest that Lag 1 sparing occur due to slow closing of an attentional gate. In this situation both targets are processed during the same attentional window. The pattern of performance seen in the current investigation demonstrates high T2 detection rates at Lag 2 and may indicate that the speed at which the attentional gate can be closed is slower in 7-year olds compared to adults. This point could be further investigated, using a task-switch RSVP stream, whereby T2 is an identification task. A measure of the intrusion errors on T2 report would indicate whether targets at subsequent lags were being processed. Regardless of the presence or absence of Lag1 (or 2) sparing, the AB is consistently measured by the point at which dual and single target performance is not significantly different following a phase where the detection rates were significantly different. The experiments in this chapter have reliably shown that this point of attentional recovery is subject to developmental delay, whereby younger participants show a prolonged AB.

The question is why should younger participants require longer to process information from items in an RSVP stream? The developmental pattern, together with the knowledge that the frontal lobes are not only implicated in the AB but also continue developing until the age of 20, reflects the working memory aspect of frontal lobe involvement. This may well be the cause of the prolonged AB at ages when the frontal cortex is not fully mature. Before this theory can be accepted, some investigation is needed into the development of the executive functions of working memory for the participants in Experiment 3. Although frontal lobes are known to continue developing, it is important to establish that this is reflected in the working memory performance amongst these specific participants. The development of working memory is not purely structural, but also reflects the improving connections made between the frontal lobes and other areas of the cortex for example the parietal lobe. The following chapter intends to support this point by employing two working memory tasks for each participant who completed the AB experiment in Experiment 3, each task utilises a different aspect of working memory and as such should reveal developmental differences in this ability.

Chapter 3 —The Development of Frontal Lobe Function

Abstract

Executive functions of WM operate during the AB for the efficient consolidation and storage of target responses (Shapiro, Driver, Ward and Sorenson, 1997; Vogel, Luck and Shapiro, 1998). Chapter 2 revealed a developmental delay in the recovery speed of attentional resources required for this task. The prefrontal cortex is active during organisation and storage of WM tasks (Rypma and D'Esposito, 2002), and this cortical area continues developing until approximately age 20 (Case, 1992). It is therefore hypothesised that the poorer performance of younger participants in Chapter 2 is as a result of developmentally inferior frontal functioning. Chapter 3 assesses frontal functioning in the participants from Experiment 3 using 2 tasks adapted from Diamond (2002). The first task assesses the storage capacity of the visuo-spatial sketchpad of WM, which is used during the AB. The second is a test of inhibition – a function which is deficient in frontal lobe patients (Lhermitte, 1983). Results from these experiments reveal slight developmental differences in these measures of frontal function. The results of the experiments in Chapter 3 therefore support the developmental hypothesis outlined in Chapter 2 and the results are discussed in relation to the working memory operations during the AB.

Working Memory (WM) and Executive Function.

A measure of the Attentional Blink (AB) was taken from participants aged 7-, 12-, 15-years old as well as adults (Chapter 2) and revealed a developmental improvement in the temporal recovery of attention: the duration of the AB reduced with increasing age. The AB deficit is thought to occur as a result of central executive impairments in Visual Short-Term Memory (VSTM) update and storage (Vogel et al., 1998). Due to the limited capacity of VSTM, the central executive is required to ensure accurate stimulus consolidation and the correct retrieval of target responses (Chun and Potter, 1995).

WM has a major role in the control of attention and WM functions operate in cortical networks which pass through the pre-frontal cortex (de Fockert et al., 2001). The frontal lobes continue to develop for the first 20 years of life (Case, 1992) and are the one of the last areas of the human cortex to mature (Hashimoto et al., 1995). These anterior portions of the brain are under developed in the children tested in Chapter 2. The frontal lobes operate during the AB to govern the update of information in VSTM and in this instance, the frontal lobes play a role in the organisation and storage functions of WM. These functions have been specifically linked to the dorsolateral prefrontal cortex (Rypma and D'Esposito, 2002). The fact that the youngest age group (7-year olds) showed the poorest AB performance, in addition to patient data showing poorer performance following frontal lobe damage (Richer and Lepage, 1996), suggests that underdeveloped frontal lobes may be the cause of this developmental delay in WM functioning.

Baddeley (1992) described WM as temporarily holding information online, whilst concurrently manipulating that information and indeed, greater dorsolateral PFC activation has been shown when these two executive operations occur concurrently than when they occur separately (e.g. D'Esposito, Detre, Aslop, Shin, Atlas and Grossman, 1995). But, activation of this cortical area also has been shown whilst *either* of the two executive functions (temporary storage or manipulation of information) is in operation (Smith and Jonides, 1999). Therefore dorsolateral PFC activity can be assessed to some extent through tests of either function.

The first experiment in this chapter investigates the visuo-spatial sketchpad aspect of WM. This reflects the temporary storage aspect of WM that is utilised during the AB. The second experiment assesses the function of inhibition, poor performance of which has been observed for patients suffering frontal lobe damage (e.g. Lhermitte, 1983). The two tasks used in this chapter are adapted from those reported by Diamond (2002; and personal communication). Measures of reaction time (RT) and accuracy are taken for both experiments. The first experiment requires that participants learn and remember the appropriate responses to a number of abstract shapes. There are two conditions to this experiment: 2-shapes (control condition), and 6-shapes (experimental condition). This task does not require any response inhibition since all stimuli are presented to the centre of the screen and are abstract shapes. Inhibition, as a central executive and frontal lobe function, is tested in the second experiment presented here. In this experiment participants are presented with dot stimuli, which appear either on the same side as the required response (control condition) or on the opposite side (experimental condition[10]. Operations of inhibition are tested during the incongruent trials.

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[10] The effect of slower RTs to the opposite side reflects spatial incompatibility and is called the Simon effect. (Diamond, 2002; Simon, 1969)

General Methods

Participants.

All participants from Experiment 3 were tested on both of the experiments in this chapter. As such there were 16 participants at each of four ages: 7-year olds, 12-year olds, 15-year olds and adults. Participants returned to the university for Experiments 6 and 7 no longer than 2 months following Experiment 3 testing.

Design.

Each experiment in this chapter was a mixed design whereby age was the between subjects variable and condition was the within subjects variable. Dependent measures of percent accuracy, mean response time and anticipatory responses were taken. Experiments 6 and 7 were two-part experiments with participants first completing the baseline measure, followed by experimental trials. Participant number in each age group counter balanced the allocation of a left or right response to each stimulus.

Apparatus.

The stimuli for both experiments were generated using a Centerprise Pentium 650Hz third generation processor PC (128 MB RAM) on a 24 x 32.5 cm Iiyama vision master pro 410 colour monitor (13.3 msec refresh rate). The software used was E-Prime beta 5.0 (Psychology Software Tools). Stimuli had 72 x 72ppi resolution and appeared at fixation, surrounded by a black rectangle of dimensions 345 x 175 pixels (12.17 x 6.17 cm) on a white background and were created using Graphics Converter 4.0. Responses to stimuli were recorded via the computer keyboard, using buttons allocated to each response (left or right).

Procedure

The participant was initially shown the stimuli and their appropriate response assignments. Each participant then proceeded to under take practise trials followed by the experimental trials in each condition of the experiment. Participants were asked to respond as quickly and accurately as possible. Each trial began with a '+' which would appear at fixation for 1000 msecs followed by the stimulus, which was presented for 747 msec. After this time the screen was blank and if the participant did not respond within 5000 ms, the next trial began. The ISI between a response and the next trial was always 500ms. Responses given after 5000 ms were not included in the reaction time (RT) analysis. A trial was considered correct if the correct response button was pressed and if the response time was greater than 200 ms. A response given before that time was considered an anticipatory response – such responses are reported as a percentage of all possible responses. The percentage of correct responses is calculated by dividing the number of correct responses by the sum of correct plus incorrect responses.

Experiment 6 – A measure of visual working memory capacity.

The first task presented here involves utilisation of on-line working memory for responses to first 2, and then 6 abstract shapes. The 2 shapes condition requires very little visuo spatial capacity and therefore serves as the baseline measure. The 6 shapes task is designed to utilise a larger capacity of working memory and hence is more difficult and will result in slower RTs and lower accuracy rates in all groups. If the frontal lobe functioning of younger participants is underdeveloped, then the additional working memory load in the experimental condition will have a more adverse effect on these participants than on older ones.

Method

Design

The baseline task for Experiment 6 was to remember and hold on line the appropriate responses to 2 abstract shapes. The experimental trials utilised an increased working memory load and as such required responses to 6 abstract shapes.

Stimuli

Within the presented rectangle, each stimulus appeared at fixation and comprised an abstract shape (approximately 55-60 x 55-60 pixels).

Procedure

Participants undertook 4 practise trials (2 for each shape) followed by two blocks of 16 experimental trials. Once this session was complete, the experimenter showed the participant the remaining four abstract shapes. There were now three shapes allocated to a right response and three allocated to a left response (all shapes are shown in Figure 15). For this part of the experiment there were two blocks of 6 practise trials and the experimenter gave verbal feedback as to whether the response was correct or incorrect. Once the practise trials were complete the participant was reminded to respond as quickly as accurately as possible and the 2 blocks of 16 real trials began.

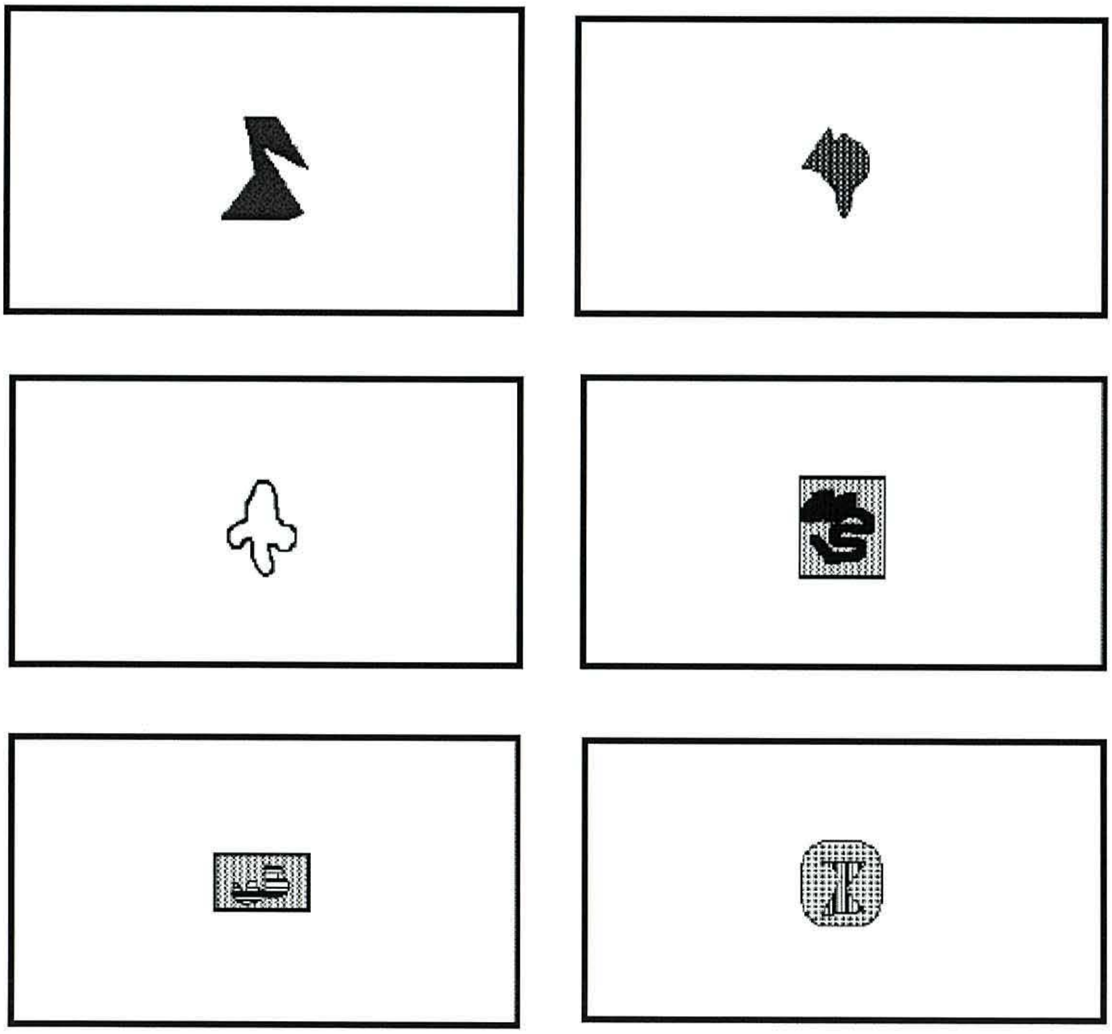

Figure 15. The abstract shapes used in Experiment 6. Participant number counterbalanced the appropriate response side.

Results

Anticipatory responses in this experiment were minimal for each age group and are presented in Table 3.

Table 3 Mean anticipatory responses (%) of all age groups for the two conditions of Experiment 6.

Age	2-shapes	6-shapes
7	0	0
12	0.98	0.20
15	0.20	0
Adults	0	0

The accuracy and mean response time was recorded for each age group for both the 2-shape and 6-shape conditions and the group data for each age level are presented in the following figures.

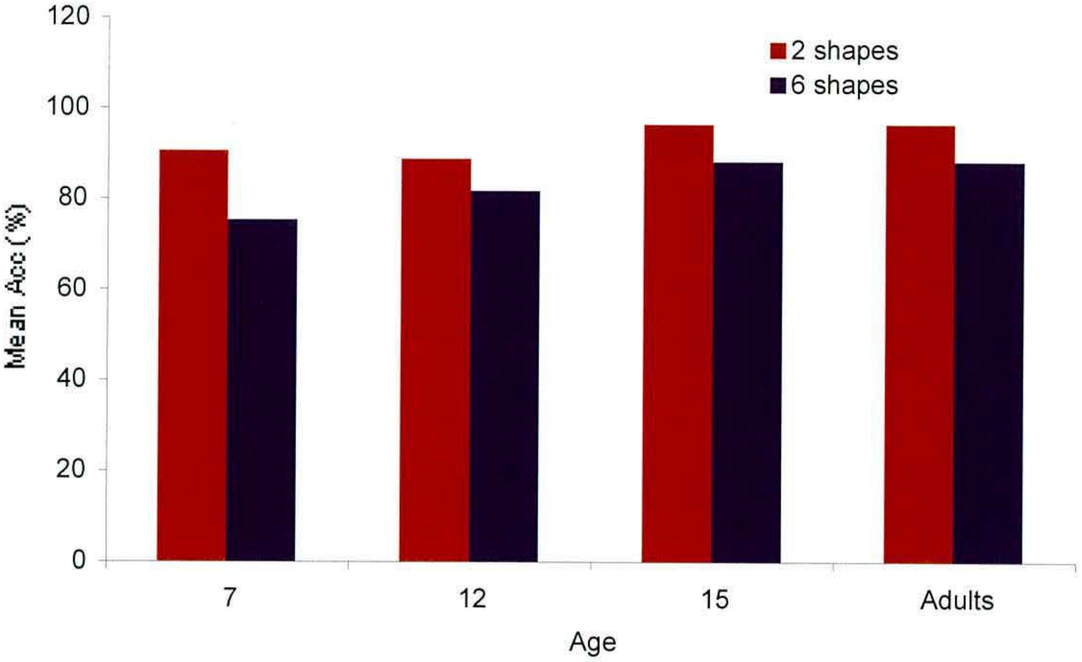

Figure 16. Percent accuracy on 2- and 6-abstract shapes tasks.

Accuracy in the 2-shapes condition is relatively high, above 85% for all four age groups, but accuracy in the 6-shapes condition appears to be subject to developmental differences. A repeated measures ANOVA on the accuracy data revealed a significant main effect of age, *F* (3,60) = 7.98 *p*<0.01; a significant main effect of task *F* (1, 60) = 70.08, *p*<0.01) and a significant interaction between these two variables *F* (3,60) = 2.77, *p*<0.05. Post-hoc analysis (Tukey's HSD) on the 2-shape data revealed that the 7-year olds and 12-year olds were significantly less accurate than the two older age groups. Post-hoc analysis on the 6-shape data (*F* (3,60) = 5.77, *p*<0.01) revealed significant differences between and 7- year olds and the two older age groups. Despite a developmental delay being present in both the experimental and control conditions the effect is stronger in the experimental condition, as indicated by the significant interaction in the repeated measures ANOVA. This can be seen graphically in Figure 16 above.

RT data for each of the four age groups from both the two shapes and 6 shapes conditions are presented below.

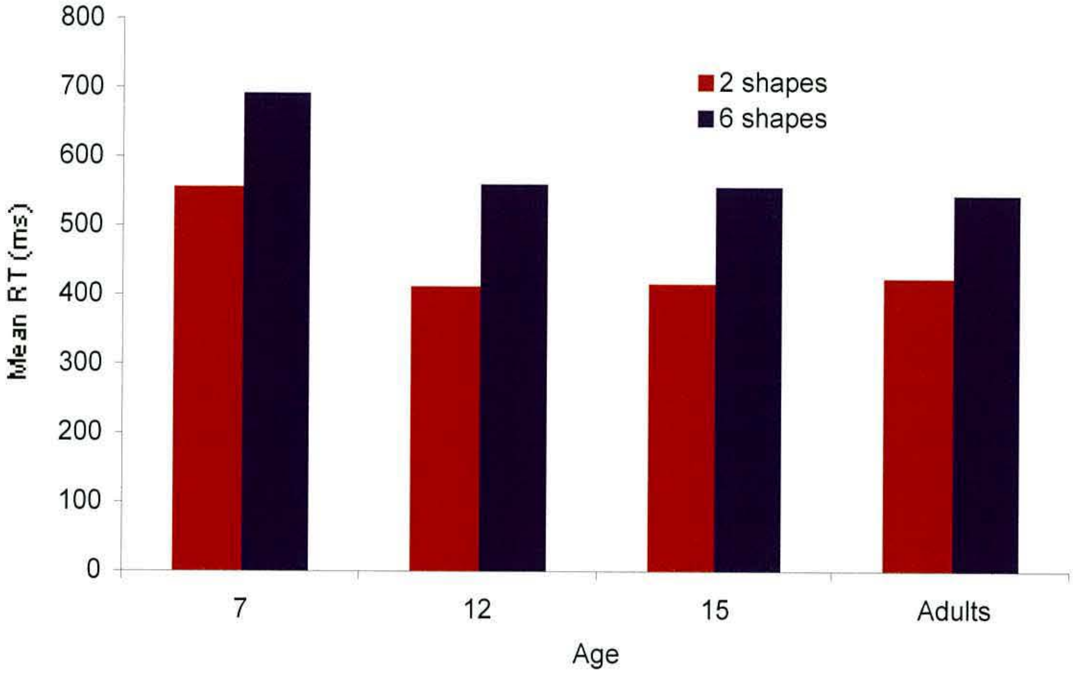

Figure 17. Reaction times (ms) to 2- and 6-abstract shape tasks

A repeated measures ANOVA on the above data revealed a main effect of age, *F* (3, 60) = 17.30, *p*<0.01), a main effect of task, *F* (1, 60) = 229.46, p<0.01), but no significant interaction. Pot hoc analysis on the RTs of each task following significant one-way ANOVAs (*F* (3, 63) = 20.36, *p*<0.001 and *F* (3, 63) = 10.09, *p*<0.001 for the 2- and 6-shapes respectively) both revealed significant differences between 7-year olds and all other age groups. This is to be expected due to the developmental differences in manual responses. If an overall interaction had been found between task and age, subsequent analysis would need to be conducted on the effect of additional load (i.e a higher working memory requirement) in the experimental condition. This would be calculated by subtracting the RTs from the control condition from the RTs of the experimental condition. In the present experiment there is no significant difference in the effect of load on RTs between the four age groups tested.

Experiment 6 — Discussion

This experiment tested the ability to hold information on-line. Measures of both accuracy and RT were taken for both the two shapes and six shapes conditions. A significant interaction between task and age group led to post hoc analysis in the form of Tukey's HSD. Performance, in terms of accuracy, on the experimental trials (six shapes) was poorer for the 7-year olds than for the two older age groups (15-year olds and adults). Repeated measures analysis on the RT data showed that although 7-year olds were (as expected) consistently slower on both tasks, there was no interaction between task and age. This suggests that effect of additional load to WM does not have a more adverse effect on RTs for any of the four age groups tested.

The accuracy of the 7-year olds' responses are more adversely influenced in the experimental condition than in the control condition. This experiment was designed to assess the organisation and storage abilities of WM, reflecting those utilised during AB tasks. Results from this experiment indicate that when a heavier demand is placed on this WM function, 7-year olds are more adversely affected in terms of accuracy than are older participants. This is thought to reflect an underdevelopment in this WM function due to the earlier developmental stage of frontal lobe growth in these participants. RT may not be an appropriate measure for illustrating developmental delay in this WM function. The AB is measured in terms of percent T2 correct and is a measure of accuracy. It seems, therefore, that accuracy is a better measure of this function if comparisons to, and conclusions about, AB performance are to be made.

Experiment 7 – A measure of inhibitory function.

This second task tests inhibitory functions of the frontal lobe. There are two conditions in this experiment: the congruent dots tasks which does not require inhibition and is simply a same side response to a presented stimulus; and the incongruent trials whereby participants have to inhibit the prepotent same side response and instead make an opposite side button press. The incongruent trials require greater executive control and as such are expected to yield poorer performance in all age groups. If this ability is subject to developmental delay due to continued frontal cortex growth, then the effect of additional WM load in the experimental trials will affect younger participants more than older participants.

Method

Participants.

The participants are the same as those who completed Experiment 6

Design.

Each participant receives 4 practise trials followed by 20 experimental trials for the congruent and then the incongruent conditions.

Apparatus

Stimuli appeared within the presented rectangle at either the left or right of fixation (+). Each stimulus was of dimensions 61 x 63 pixels (2.22 x 2.15 cm) and had 72 x 72ppi resolution.

Procedure

The participant was shown the stimuli for the task and the appropriate response button for each (examples of the stimuli are given in Figure 18). Participants completed the control condition (congruent trials) followed by the experimental condition (incongruent trials).

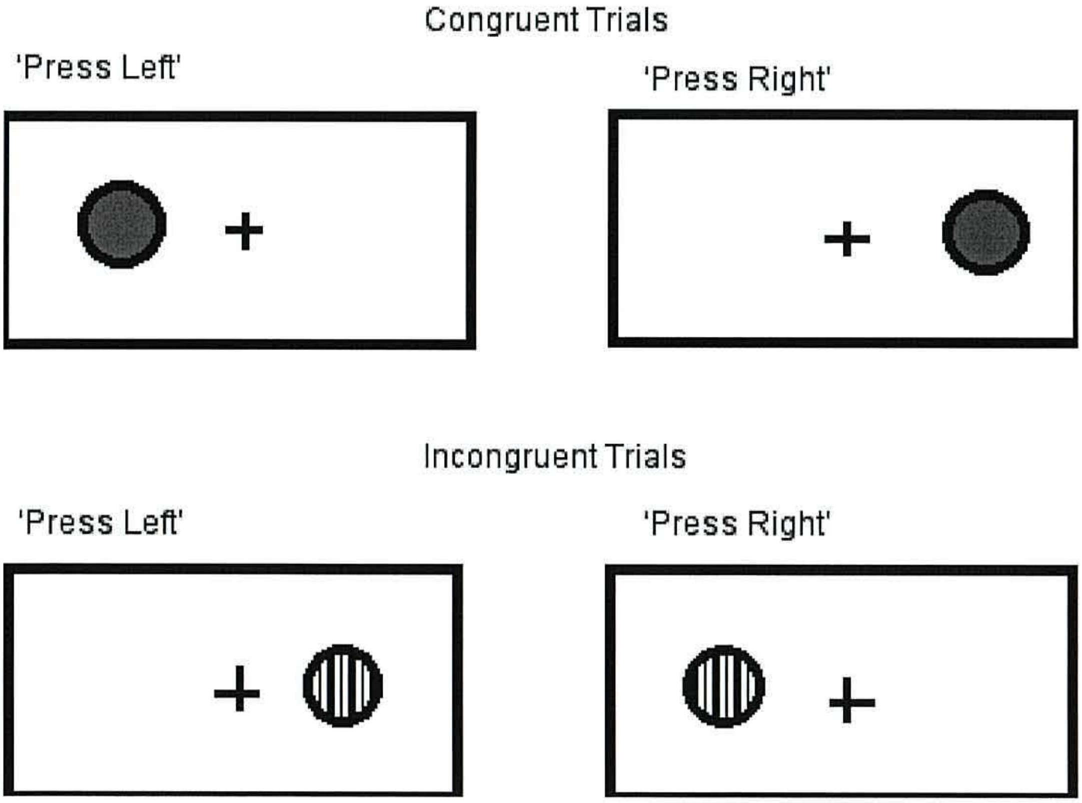

Figure 18. An example of the congruent and incongruent trials for Experiment 7.

Results

Responses were recorded in the same way as in Experiment 6. Anticipatory responses (<200ms) were discarded from analysis and are presented in Table 4.

Table 4. Mean anticipatory responses (%) of all age groups for the two conditions of Experiment 7.

Age	Congruent	Incongruent
7	1.17	0.39
12	1.56	1.17
15	2.73	0.78
Adult	1.17	0.78

Accuracy rates and RTs were calculated in the same way as for Experiment 6. The mean accuracy rates and response times were recorded for each age group for both the congruent and incongruent conditions and the group data for each age level are presented in the following figures. Correlational analysis between individual RT and accuracy scores within each age group did not suggest a speed-accuracy trade-off.

Mean accuracy for each trial type was again calculated in the same way as the accuracy for Experiment 6 and the data is presented below in Figure 19.

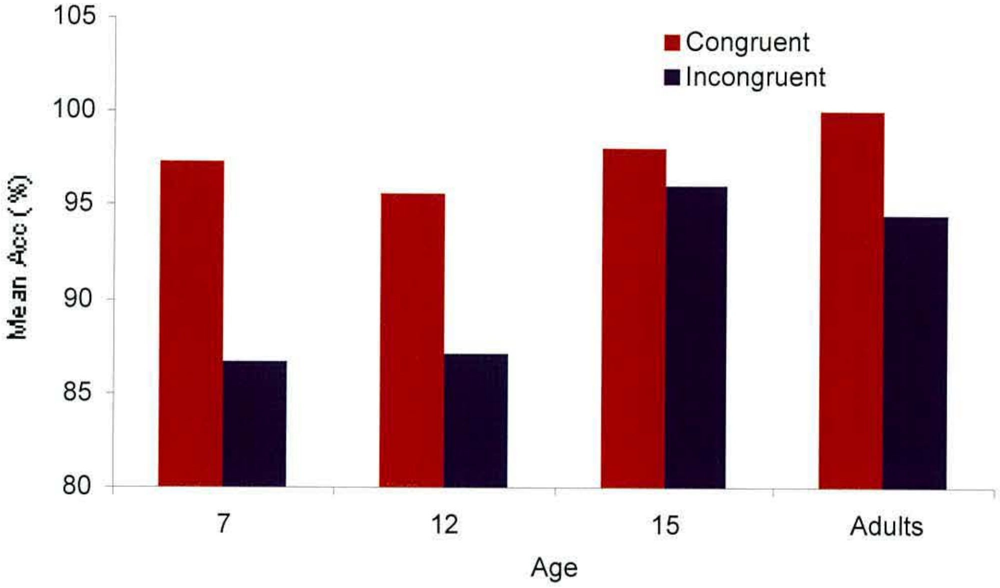

Figure 19: Mean percent accuracy for congruent, incongruent and mixed dots tasks for each age group.

Accuracy in both the congruent and incongruent trials appears to be high (over 85%) for all age groups. Analysis in the form of a repeated measures ANOVA on the accuracy data revealed a significant main effect age $F\ (3,60) = 2.97\ p<0.05$ and of condition $F\ (1, 60) = 17.70$, $p<0.01$, but no significant interaction. All age groups showed poorer accuracy for the incongruent dots trials, but the difference in accuracy scores for the two conditions does not vary between age groups.

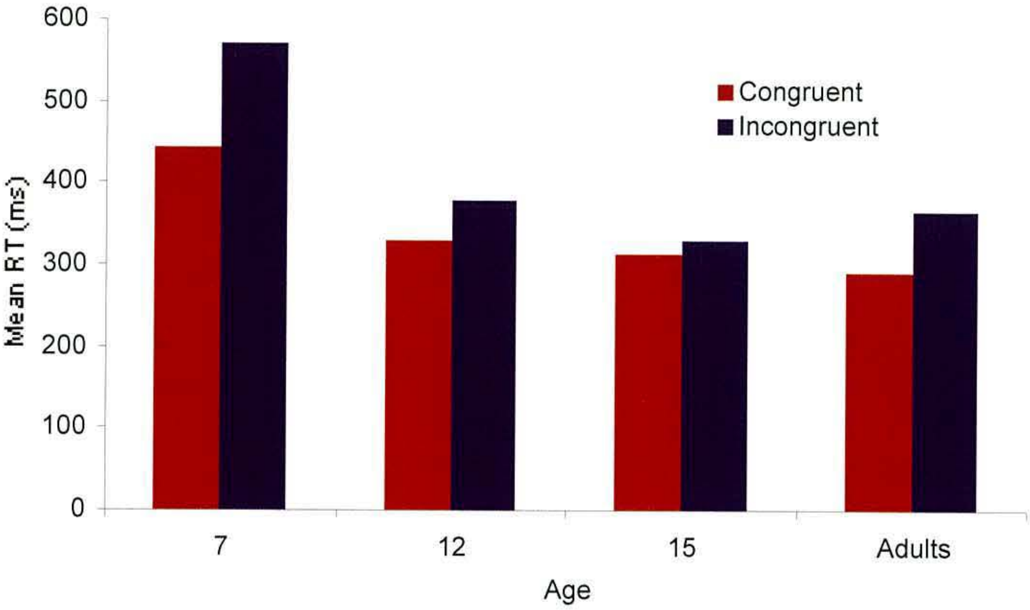

Figure 20. Mean group RTs (ms) for congruent and incongruent dots tasks.

A repeated measures ANOVA on the above data revealed a significant main effect of age, *F* (3, 60) =32.23, p<0.01, a main effect of task, *F* (1, 60) = 93.04, *p*<0.01 and a significant interaction, *F* (3, 60) =4.41, *p*<0.01. Post-hoc analysis in the form of Tukey's HSD on WM load (the difference in RTs between the experimental (incongruent) and control (congruent) dots trials) establishes whether the additional inhibitory control affects younger participants more adversely than older participants. Tukey's HSD revealed significant differences in the effect of load between 7-year olds and 12-year olds. However the effect of load did not vary between 12-year olds and the two oldest groups.

Experiment 7 — Discussion

Analysis of accuracy data in this experiment revealed main effects of age and condition, but no significant interaction. Figure 20 reveals that all age groups showed significantly slower response times to incongruent trials than to congruent trials. ANOVA revealed that the effect of load (incongruent RT minus congruent RT) was greatest for 7-year olds and had the least impact on 12-year olds.

The results suggest that although inhibitory control does not have a greater effect on accuracy in younger participants compared to older ones, RTs *are* affected. When response inhibition is required, RTs of 7-year olds are more adversely affected than are older participants. Patients with frontal lobe damage also show problems with inhibition (Lhermitte, 1983) and inhibition is considered to be one of the executive functions (Baddeley, 2001) that operate in networks involving the prefrontal cortex (Kane and Engle, 2002).

Experiments 6 and 7 — Summary and Discussion

Experiment 6 investigated the developmental differences in the WM function that is utilised during the AB - that of visuo-spatial capacity. 7-year olds yield significantly less accurate responses when this aspect of WM is loaded, than do older age groups. This developmental difference supports the findings described in Chapter 2 and the suggestion that these differences are due to poorer executive functioning governing VSTM update during the AB. Experiment 7 demonstrated that the frontal lobe functioning of the participants used in Experiment 3 (the AB task) are developmentally different. Frontal lobe patients have been known to show poor inhibitory control (Lhermitte, 1983) and Experiment 7 assessed the inhibitory control functions of the current participants. Although accuracy was unaffected, RTs in conditions of high inhibitory control were slower than in the control condition for all age groups. The difference in the RTs between experimental and control conditions was greatest for the 7-year olds. This demonstrates an underdevelopment of this frontal function at this age, as reported by Case (1922) and supports the claim that the prolonged AB that is related to age, is in fact due to an earlier developmental stage of frontal growth. 'Frontal growth' does not simply imply increased biological matter, since this is almost fully developed by the age of 18 months (Hashimoto et al., 1991) instead it refers to the increased myelination of neurons and their connections to other regions of the cortex (Thatcher, 1991). Connections with areas of the cortex come 'on-line' at different points in development. The increase in RT to trials where inhibition is required may reflect the slower connections between the appropriate regions of the cortex. Research into the developmental time course of spatial attention has revealed that the efficient use of strategies is not fully accomplished in children (Taylor and Khan, 2000) and this may account for the poorer performance of 7-year olds in the shapes task. For example, an older participant may observe the stimuli (e.g. Figure 15) and give the shapes names. It would then be possible to reduce the demand on the executive by remembering that x, y and z required left responses and all the others required right responses.

Results presented within this chapter indicate poorer frontal function in younger participants. These measures, of storage capacity of the visuo-spatial sketchpad and of the executive function of inhibition, may be linked to the efficient use of strategies.

These differences illustrate the fact that the frontal lobes of humans continue to develop until the age of 20. The pattern of results here suggests that these two particular functions have reached mature levels much earlier than adulthood, or age 20. However, rather than disputing theories of cognitive growth (Case, 1992; Hashimoto et al. 1991) results suggest that the tasks were not as difficult as they could have been. The inhibition task, for example, may simply have been too easy, and hence no age differences in load were seen. Both the AB and the visual search tasks of the next chapter require the central executive either for the organisation and storage (AB) or update (visual search) of VSTM. Baddeley (1992) described working memory as the storage *and* manipulation of information held on line and D'Esposito, Detre, Aslop, Shin, Atlas and Grossman (1995) reported greater activation of the dorsolateral PFC when these two operations occur concurrently. Perhaps a greater developmental difference in the visuo-spatial aspect of WM would have been seen if tasks of this type had been presented.

Diamond (2002) detailed an experiment from which Experiment 7 of the current chapter was adapted. In Diamond's full version of the task blocks of mixed trials were administered in addition to congruent and incongruent blocks of trials. This required a constant task switch between the sets of stimuli, whereby responses varied between 'same side' or 'opposite side' requirements. As such, these tests would be a stronger measure of working memory and would give more information regarding developmental differences than the ones presented here. The current chapter assessed one aspect of working memory (holding information on line) and also inhibition and was therefore more concerned with frontal lobe functioning than working memory ability. More extensive assessment of the given participants using tests of working memory ability, specifically VSTM update, would provide an interesting addition to these findings.

Chapter 4 – Spatial Attention

Abstract

Chapter 4 presents two visual search task experiments to investigate developmental differences in spatial attention. Both temporal and spatial attention tasks are reliant on the frontal cortex (e.g. AB: Richer and Lepage, 1996; Visual Search: Taylor and Khan, 2000) and both utilise WM. Experiment 8 of the current chapter investigates the developmental differences in *spatial* attention between 7-year olds and adults. Previous research (Lobaugh, Cole and Rovet, 1998; Ruskin and Kaye, 1990; Thompson and Massaro, 1989) has reported similar patterns of performance for children and adults in visual search tasks, but children have shown steeper slopes of search times in conjunction trials. Experiment 8 presents a visual search task using the same stimuli as those used in the Attentional Blink (AB) task (Experiment 3). RTs in this visual search task are slower for 7-year olds than for adults, but when the slope/mean RT ratios are calculated, there is no significant age difference in performance. Experiment 9 successfully generalises this finding to stimuli other than those used in the AB task (Experiment 3). Visual search requires post-perceptual VSTM update, which is governed by the central executive (Duncan and Humphreys, 1989; Wolfe, 2003). In contrast to the processes required during the AB, the cognitive ability does not appear to be subject to developmental delay. The results are discussed in relation to the frontal lobes and their contribution to executive function.

Visual search tasks

Spatial attention will be investigated in this chapter using visual search tasks. A visual search paradigm allows investigation into target detection either by its separable features or by their conjunction (Treisman and Gelade, 1980). If the 'glue' of focussed attention is not required to detect features in an array then detection time should be unaffected by the size of the display in which the target appears. Thus, in single feature search, target detection rates will form a flat function across set size. Conversely, in conjunction tasks where the target can only be identified by the 'gluing' together of two or more features, increased display size will result in increased target detection time (Treisman et al., 1980). Surrounding distracter items each share one feature with the target in a conjunction search and as such require serial analysis and comparison with a target representation held in VSTM.

Attentional Engagement Theory (AET, Duncan and Humphreys, 1989) considers the similarity between targets and distracters and also between distracters and distracters. The most difficult search is when the target shares a feature with each of the distracters (conjunction search), but the distracters have high heterogeneity amongst themselves. AET states that when items are selected for entry to VSTM, selection is based on the weight of the item (determined by its similarity to the target) assigned during a parallel perceptual stage of processing. Items in an array that are perceptually similar to each other will have the same weight (weight linkage) and the more strongly these parts are linked, the greater is the tendency for them to be selected or rejected from entry to VSTM together. Serial search is not item by item as suggested by Treisman et al. (1980), but instead is by small clusters of items within the display. Entry of these subsets to

VSTM is governed by the central executive of WM and once the capacity limited VSTM has been filled it must be flushed before a further subset of items may enter. It is this rate of entry of items to VSTM that governs search times and is responsible for the increased search slopes in conjunction trials.

The executive functions of WM are considered to have an important role on the selection of items into VSTM in visual search tasks, and a developmental improvement in executive functions has been reported. There have been a limited number of spatial attention studies conducted with children (Cole and Rovet, 1998; Lane and Pearson, 1983; Thompson and Massaro, 1989) and patterns of performance are similar to those of adults. In a typical visual search experiment slopes of RT in feature search trials are flat across display size, whereas search slopes in conjunction trials are positive across display size. In comparative studies, the search slopes in conjunction trials are steeper in older age groups than younger ones (Ruskin and Kaye, 1990; Trick and Enns, 1998). ERP experiments (Taylor and Khan, 2000) have shown shorter wave latencies of ERP components in older participants, indicating more efficient processing. Decreased anterior positive peaks with increasing age demonstrates increased frontal processing in younger children and Taylor and Khan conclude that their results may reflect either an increase in attentional processing capacity with age, or an improvement in search strategy. This chapter attempts to replicate these findings using participants from the oldest and youngest age groups of Experiment 3, and does so using the same stimuli as those used in Experiment 3.

Two visual search experiments are presented in Chapter 4. Each participant completed both single feature and conjunction search conditions for each experiment and responses were ‘present’ or ‘absent’ to the target shape. The target was present on 50% of the trials and was embedded in a display that contained 2, 10, or 20 items. Experiment 8 used the same stimuli as the targets from Experiment 3 (Chapter 2)—the target shape was always a red isosceles triangle that pointed up, and the distracters were red isosceles triangles pointing down and blue isosceles triangles pointing up.

General Methods

Participants

The children in the following experiments were recruited from a local school and all sessions with the children took place at the school. Adults were students from the University of Wales, Bangor who were participating for course credit. All participants had normal or corrected to normal vision.

Apparatus and Stimuli.

All stimuli for the experiment were created using MacDraw and converted into images using iMaker 3.3.8. The experiment was programmed and run on an iMac using Vsearch 3.3.8. The same stimuli were used for this experiment as were used in Experiment 3 (Chapter 4) and as such were isosceles triangles that were red or blue and of dimensions 22.9mm x 41.6mm. Each item had a resolution of 72 x 72 ppi. Responses were made to the keyboard of the iMac using keys that had been assigned to 'present' and 'absent' responses.

The display occupied the full screen (918 x 720mm) and the stimulus items appeared randomly in a 6 x 5 item matrix. The horizontal spacing of the items was 153mm with 10mm clearance and the vertical spacing was 144mm with 10mm clearance. Items appeared either in a 2, 10 or 20 item display. The target was present on half of the trials. In conjunction search trials, where two distracter types are specified, each type of distracter is counterbalanced so that it appears equally often, and with equal frequency, on each type of trial (display size).

In single feature search or 'pop-out' trials the distracter differed from the target only on one dimension, for example colour. In conjunction search the distracters shared one dimension each with the target, but did not share a feature with each other. Therefore target –distracter similarity was high and distracter-distracter similarity was low.

Design.

Each participant was asked to complete 2 conditions: feature search and conjunction search. For each condition participants completed 20 practise trials followed by four blocks of 30 experimental trials. Of the 120 trials for each experimental condition there were 20 present and 20 absent trials at each of three display sizes (2, 10 and 20 items). Participant number counterbalanced allocation to initial experimental condition. Each experiment took approximately 40 minutes to complete.

Procedure

Informed consent was obtained from all participants (or parents of 7-year olds) prior to participation in the study. In each condition participants were asked to view the computer screen from a distance of approximately 50cm and make a present or absent judgement regarding the target item. Responses were made via the computer. The visual display remained present on the screen until a response was made. Short breaks were taken between blocks of trials where necessary.

Experiment 8 — Visual Search task with triangle stimuli

This first visual search task investigates spatial attention in adults and 7-year olds using the same stimuli as the target items in the AB stream presented in Experiment 3 (Chapter 2). The experiment was designed to assess whether the developmental differences seen in working memory would be evident in a measure of spatial attention, as they were in temporal attention. If this is the case, 7-year olds will show a steeper slope of target detection rates over the three display sizes in the conjunction task than will adult participants. This would represent a slower rate of entry of items into VSTM than the adults and, since VSTM selection is governed by the central executive, would also reflect the developmental difference in working memory between these two age groups.

Method

Participants.

Sixteen participants, eight adults (18-20 years old) and eight 7-year olds (mean age 7y 9m; age range 6y 11m – 8y 2m), took part in this experiment.

Design

The target stimulus in both conditions of the current experiment was always a red isosceles triangle that pointed up (see Figure 21 for an example of the stimuli). In the single feature or parallel search the distracter items varied on one dimension from the target and as such were always blue isosceles triangles that pointed up. In the conjunction search the distracter items were blue isosceles triangles pointing up and also red isosceles triangles pointing down. These stimuli ensured that correct detection of the target item required the conjunction of orientation and colour in this task.

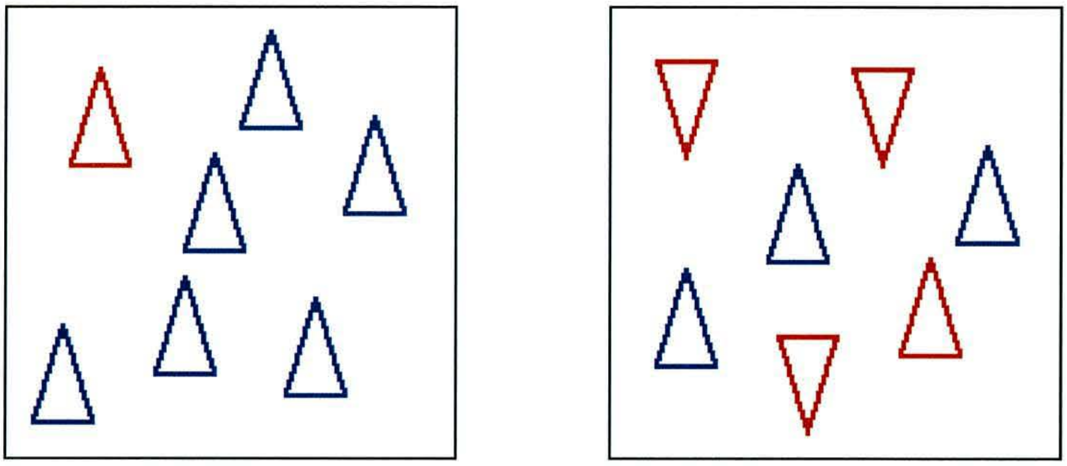

Figure 21: Examples of the target and distracter shapes in single feature and conjunction searches used in Experiment 8.

Procedure

The procedure remains the same as in the general methods.

Results.

The mean reaction time (ms) was calculated for each participant and an age group mean presented. Reaction times (RT) more than 3 standard deviations from the mean were eliminated from all analyses.

Table 5: Descriptive statistics for the search functions in Experiment 8.

	7-year olds				Adults			
	Feature		Conjunction		Feature		Conjunction	
	Present	Absent	Present	Absent	Present	Absent	Present	Absent
Slope (ms/item)	0.36	-3.14	70.06	144.77	0.58	-0.25	32.94	61.07
Intercept (ms)	836.7	1017.3	1111.3	951.7	448.6	461.7	525.8	493.0
Mean RT (ms)	840.6	983.8	1858.6	2495.9	448.6	461.8	877.2	1144.3

Table 5 shows the descriptive statistics for Experiment 8. The data will be analysed for each age group before between groups comparisons are made. The data is analysed in terms of slope/mean RT ratios for each participant. This allows for the developmental differences in mean RT in this between-subjects experiment.

Table 6: Errors (%) for 7-year olds and Adults as a function of display size

	7			Adults		
	2	10	20	2	10	20
Conjunction						
Present	4	9	18	4	6	8
Absent	3	6	1	2	1	2
Feature						
Present	6	6	6	3	3	5
Absent	2	3	3	3	3	3

Single Feature versus Conjunction search in adults

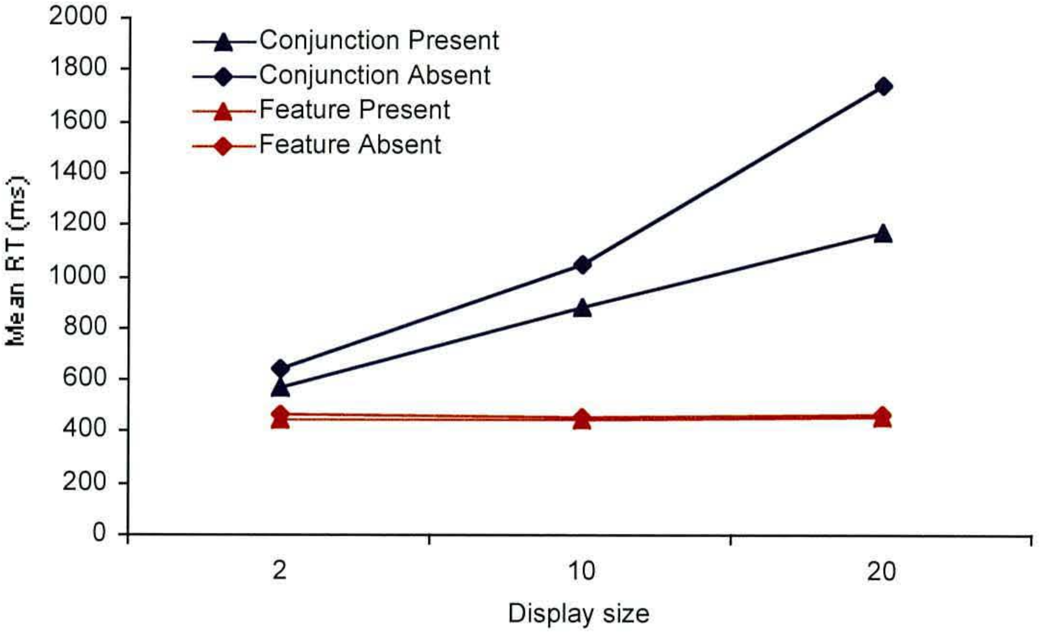

Figure 22: Visual search results with triangle stimuli for adult participants[11]

A repeated-measure ANOVA conducted using the slope/mean RT ratios of this data revealed a significant main effect of task (*F* (1, 7) = 109.0, $p<0.001$) and of target (*F* (1, 7) = 18.89, $p<0.01$) and a significant interaction between the two variables (*F* (1, 7) = 37.83, $p<0.001$). This shows that the slope/mean RT ratio is significantly different for each task (conjunction or feature) and is also significantly different for each target condition (present or absent). The interaction shows that the difference in slope/mean RT ratios between target absent and target present trials is different for each task. A repeated-measure ANOVA on the single feature data reveals no significant differences between target conditions, whereas a repeated-measure ANOVA on the conjunction trials data shows a significant main effect of target condition (*F* (1, 7) = 26.76, $p<0.01$).

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[11] This scale is not linear, since the increments are not equal (2,10,20). This is the case throughout this chapter of the thesis.

Figure 22 illustrates that in the conjunction search the slope of RT over display size is significantly steeper for target absent than target present trials.

Single Feature versus Conjunction search in 7-year olds

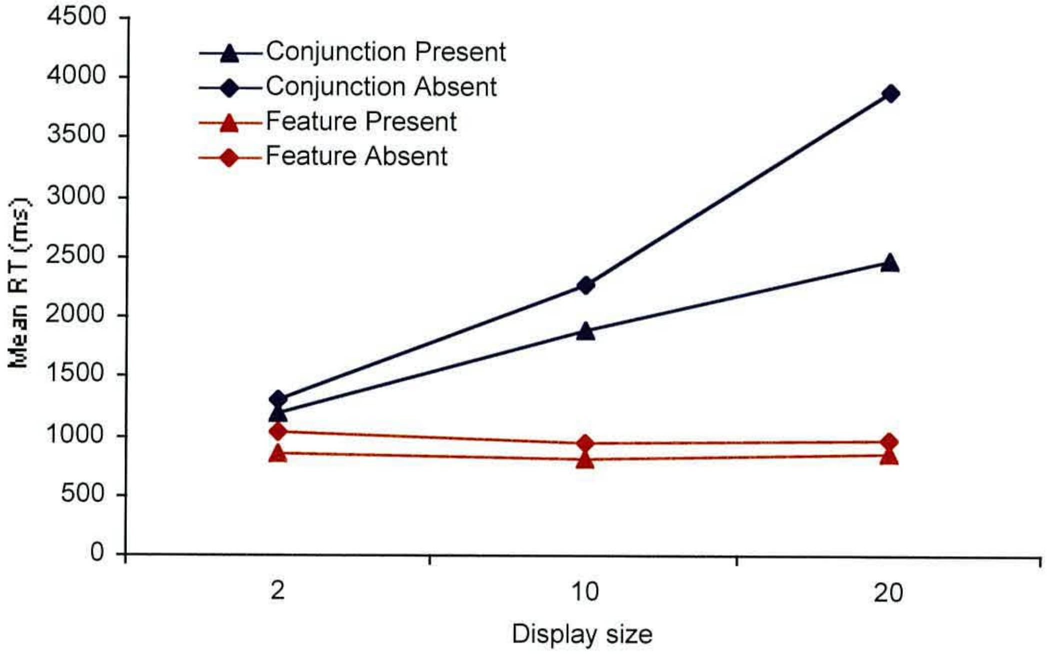

Figure 23: Visual search results with triangle stimuli for 7-year old participants.

A repeated-measure ANOVA conducted using the slope/mean RT ratios of this data revealed a significant main effect of task (*F* (1, 7) = 348.63, *p*<0.001) and of target (*F* (1, 7) = 17.65, *p*<0.01) and a significant interaction between the two variables (*F* (1, 7) = 18.37, *p*<0.01). This shows that the ratio of the slope to mean RT is significantly different for each task (conjunction or feature) and is also significantly different for each target condition (present or absent). The interaction shows that the difference in slope/mean RT ratios between target absent and target present trials is different for each task. A repeated-measure ANOVA on the single feature data reveals no significant differences between target condition, whereas a repeated-measure ANOVA on the conjunction trials data shows a significant main effect of target condition (*F* (1, 7) = 18.67, $p<0.01$). Figure 23 illustrates that in the conjunction search the slope of RT over display size is significantly steeper for target absent than target present trials.

Comparison between Adults and 7-year olds

A mixed ANOVA was carried out and revealed a main effect of task (*F* (1, 14) = 356.05, $p<0.001$), target (*F* (1, 14) = 35.57, $p<0.001$) and an interaction between task and target (*F* (1, 14) = 43.71, $p<0.001$). This suggests that the pattern of performance does not differ between age groups. A repeated measure ANOVA conducted on the feature search data reveals no main effects or any interaction between age and target condition. This shows that the function of RT over display is flat and that the slope/mean RT ratio is the same for each age group and is not significantly different between target conditions. A repeated measures ANOVA conducted on the conjunction search data reveals a main effect of target (*F* (1, 14) = 41.05, $p<0.01$), showing a significant difference between target present and absent slope ratios, but there is no main effect of age or any interaction involving age. This suggests that the pattern of performance is the same for each age group.

Experiment 8 – Discussion

The main findings of this study were that single feature search is unaffected by display size. This is illustrated by the flat function of reaction times over display size in the target present and target absent trials of the feature search condition for each age group. Distracter items share one feature with the target, but are there is high homogeneity between distracter. The weight linkage between distracters will therefore be high and there will therefore be a greater tendency for the distracters to be rejected together. This facilitates efficient selection of the target item to VSTM. There was no significant difference between the performance of adults and 7-year olds in the feature search trials.

The slope of RT for the conjunction trials is steeper for the target absent than target present trials and when the data is analysed by slope/mean RT ration, this pattern of performance is the same regardless of age. The conjunction search trials reveal that as the number of items in a visual display increase, the time taken for the target to be detected also increases. This suggests a serial search where attention is being directed to each item (or a subset of items) in turn for comparison to an internally held representation of the target. The additional time required in these displays is a reflection of the attentional demands put upon a system and indicates that smaller subsets of items are being passed to VSTM. Since smaller groups of items can be passed at any one time, it takes longer for the target to be detected. Both age groups exhibited a typical visual search performance with target absent trials yielding steeper slopes of RT over display size than target present trials. The slope of RT over display size was not steeper in the 7-year olds indicating that their performance did not significantly differ from that of adults. According to the Attentional Engagement Theory (Duncan and Humphreys, 1989) when there is high similarity between targets and distracters, search is less efficient. Search is also impaired when the distracter-distracter similarity is high. In Experiment 8, each distracter shares a feature with the target, but distracters have high heterogeneity. Each item in a visual array gains or loses selection 'weight' for entry into VSTM depending on its similarity to the target representation. Since each distracter shares one feature with the target, distracter weights will be equal. This does not facilitate rejection of any one subset of distracters. To this end, the visual array must be searched serially until the correct target representation is found. However this is not an item by item search and instead areas of the visual scene are analysed in sections and these sections are passed to VSTM by the central executive for further analysis. Once the limited capacity VSTM has been filled, it must be flushed before a further subset of the total array can be passed by the central executive.

Experiment 8 has investigated the spatial attention abilities of the oldest and youngest age groups from the temporal investigation of Experiment 3 and normalisation of the data has revealed that the pattern of performance is the same for each age group. These results build on the findings of previous research into developmental differences in spatial attention (Lobaugh, Cole and Rovet, 1998; Taylor and Khan, 2000) and takes the mean RT of each participant into consideration. The overall RTs are slower in 7-year olds than adults, and the slope of RT increases more steeply in conjunction trials for the younger participants. However, the slope/mean RT ratio suggests that the effect of additional items to the visual array does not affect 7-year olds more adversely than adults. This suggests that spatial attentional abilities are indeed 'adult-like' by the age of 7 and this is contrast to the developmental difference seen in temporal attention. Experiment 8 utilised the same stimuli as the AB task (Experiment 3), but it is important to demonstrate that the finding can be generalised to other stimuli and that there is not something unique about these triangle stimuli. Therefore Experiment 9 replicates Experiment 8 but uses alternative stimuli.

Experiment 9 — Replication with alternative stimuli

Experiment 8 failed to show a developmental difference in spatial attentional abilities: Experiment 9 attempts to support this finding using alternative stimuli. This experiment uses T-shape items, which have been used in previous visual search tasks (e.g. Duncan and Humphreys, 1989).

Method

Participants

Participants were the same as those in Experiment 8. Sessions with adult participants ran on the same day as Experiment 8, but allocation to the first task was counterbalanced. 7-year olds completed the two tasks on separate occasions.

Design

The target stimulus in the current experiment was always an inverted red T-shape (see Figure 24 for an example of the stimuli). In the feature or 'pop-out' search the distracter items varied on one dimension and as such were always blue inverted T-shapes. In the conjunction search the distracter items were blue inverted T's and also red T-shapes that were rotated 90 degrees anticlockwise. All participants completed target present and target absent trials for both the feature and conjunction searches.

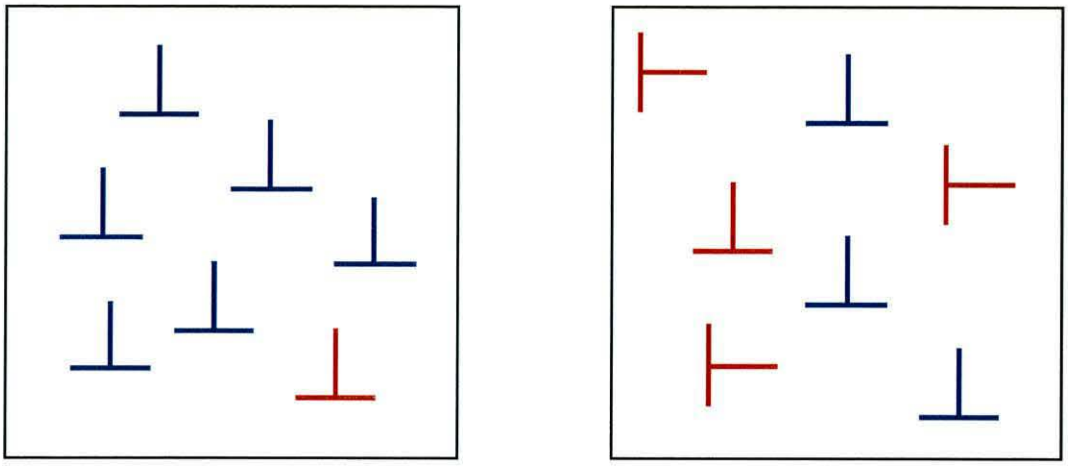

Figure 24: Examples of target and distracter shapes in single feature and conjunction search for Experiment 9

Procedure

The procedure remains the same as in the general method.

Results

The mean reaction time (ms) was calculated for each participant and an age group average presented. Reaction times (RT) more than 3 standard deviations away from the mean were eliminated from all analyses. The data is analysed in terms of slope/mean RT ratios for each participant. This allows for the developmental differences in mean RT in this between-subjects experiment.

Table 7: Descriptive statistics for Experiment 9.

	7-year olds				Adults			
	Feature		Conjunction		Feature		Conjunction	
	Present	Absent	Present	Absent	Present	Absent	Present	Absent
Slope (ms/item)	-1.82	5.7	82.5	107.1	1.9	0.2	32.4	62.2
Intercept (ms)	824.0	890.7	972.5	1298.3	427.3	481.8	571.1	591.4
Mean RT (ms)	804.7	951.7	1298.3	2440.4	447.2	484.2	916.5	1255.3

Table 7 shows the descriptive statistics for Experiment 9. The data will be analysed for each age group before between groups comparisons are made.

Table 8: Errors (%) for 7-year olds and Adults as a function of display size

	7			Adults		
	2	10	20	2	10	20
Conjunction						
Present	4	8	13	6	5	10
Absent	6	3	2	9	1	2
Feature						
Present	4	7	7	7	4	4
Absent	8	2	2	4	4	2

Single feature versus Conjunction search in adults

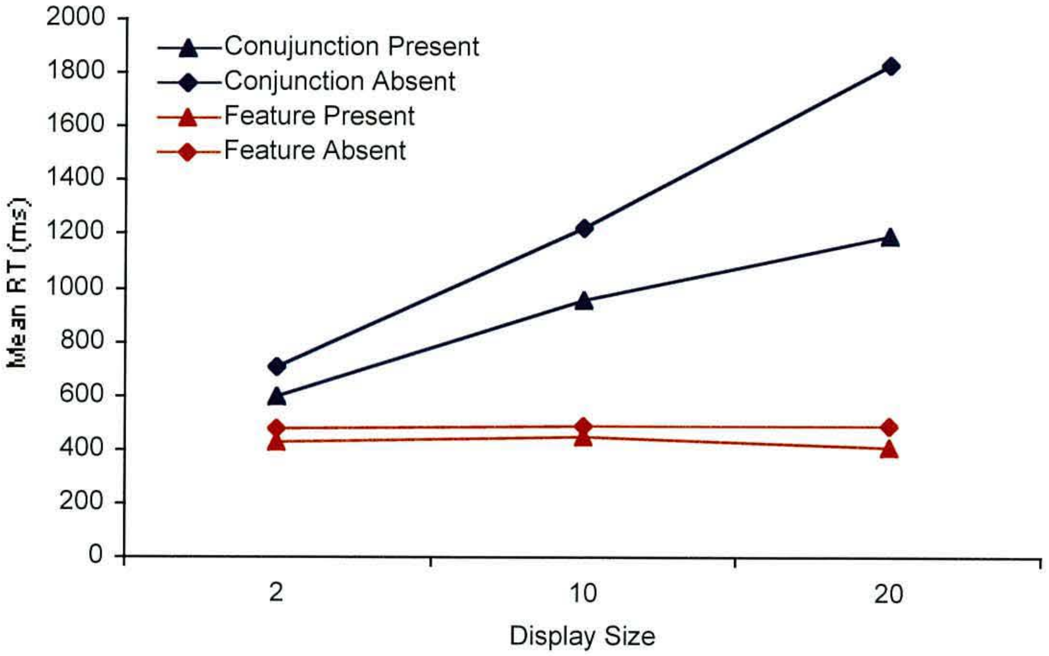

Figure 25: Visual search using T-shape stimuli with adult participants

Figure 25 presents the results from the adult participants for Experiment 9. A repeated measures ANOVA run on the slope/mean RT ratio data revealed significant main effects of task (F (1,7) = 522.21, p< 0.01), target (F (1,7) = 47.88, p < 0.01), and a significant interaction between task and target (F (1, 7) = 106.08, p<0.001). This suggests that the alternative stimuli used in Experiment 9 successfully yield a normal visual search pattern in adults. The significant main effect of task suggests that the pattern of performance in the conjunction and feature trials was significantly different and Figure 25 shows that the mean RT increases over display size for the conjunction trials. The main effect of target shows that the target-absent trials yield steeper slopes of RT than the target-present trials. The interaction shows that the pattern of performance of the two target conditions is different for each task (conjunction or feature). A repeated-measure ANOVA on the single feature data reveals no significant differences between target conditions, whereas a repeated-measure ANOVA on the conjunction trials data shows a significant main effect of target condition (*F* (1, 7) = 74.73, $p<0.01$). Figure 25 illustrates that in the conjunction search the slope of RT over display size is significantly steeper for target absent than target present trials.

Single Feature versus Conjunction search in 7-year olds

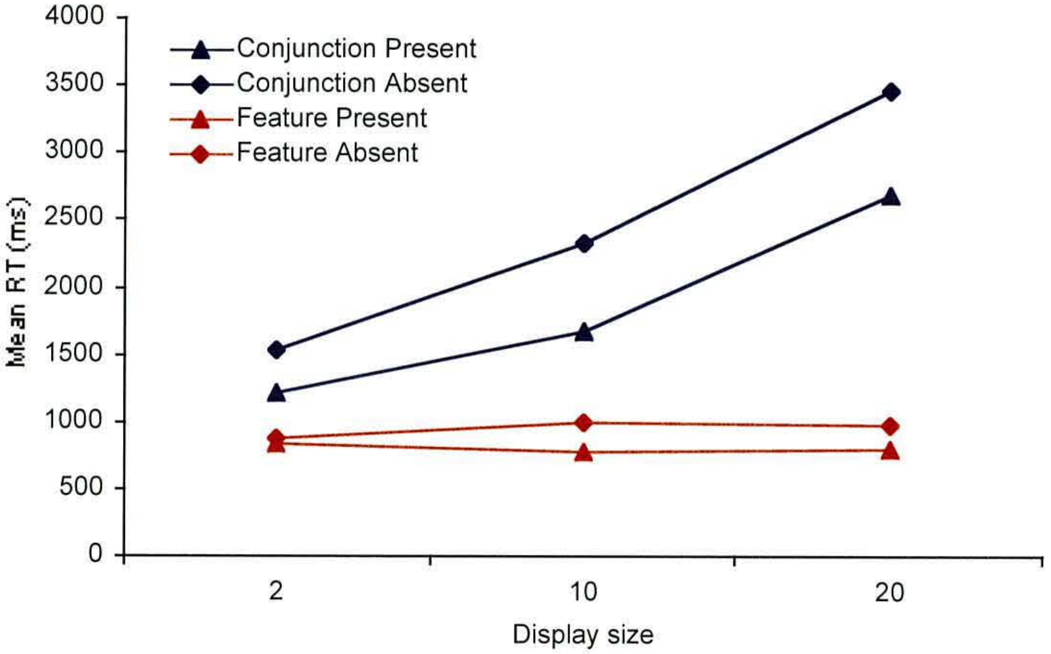

Figure 26: Visual search using alternative stimuli with 7-year old participants

A repeated measures ANOVA on the slope/mean RT data revealed a significant main effect of task (*F* (1,7) = 278.84, $p<0.001$), but no main effect of target or any interaction. This suggests that the slope of RT is significantly different for conjunction and feature searches, but for both types of trial the target absent and present slopes are not significantly different. A repeated measure ANOVA conducted on the single feature trials reveals no main effect of target suggesting that the slope of RTs for the target present and target absent trials are the same. This is a typical pattern of performance in visual search experiments and replicates that seen in Experiment 8. A repeated measure ANOVA conducted on the conjunction search trials also reveals no significant main effect of target. This is an unusual finding and Figure 26 indicates that the slopes of RT in the target present and absent trials are the same. Table 8 shows that, across display sizes, the error rates were higher in target present than target absent trials and that the number of errors increases with increasing display in the target present condition, especially for the 7-year olds. The average error rates per condition of this experiment are generally higher than in Experiment 8 and this suggests that this target discrimination task is more difficult than the triangles task. This difficulty particularly affects the 7-year olds, resulting in a much steeper slope of RT over display size in the target present conjunction trials.

Comparisons between 7-year olds and Adults

A mixed ANOVA was carried out and revealed a main effect of task (F (1, 14) = 719.20, $p<0.001$), target (F (1, 14) = 7.47, $p<0.05$) and an interaction between task and target (F (1, 14) = 5.13, $p<0.05$). This suggests that the pattern of performance does not differ between age groups. A repeated measure ANOVA conducted on the feature search data reveals no main effects or any interaction between age and target condition. This shows that the slope of RT is the same for each age group and is not significantly different between target conditions. A repeated measures ANOVA conducted on the conjunction search data reveals a main effect of target (F (1, 14) = 6.34, $p<0.05$), showing a significant difference between target present and absent slopes, but there is no main effect of age or an interaction with age. This suggests that, despite the unusually steep conjunction present slopes of the 7-year olds, the overall pattern of performance is the same for each age group.

Experiment 9 —Discussion

Experiment 9 replicated the findings of Experiment 8, that conjunction tasks yielded slower reaction times than feature search tasks for both age groups tested, and that in conjunction tasks, an increase in display size results in a slower reaction time. When the mean slope/RT ratios were analysed, there was no significant differences in performance between the 7-year olds and the adults and therefore the results support Experiment 8 that *spatial* attentional abilities are 'adult-like' in these tasks by the age of 7-years old. AET claims that when distracter-distracter similarity is low, but target-distracter similarity is high, search slopes will be steeper. Burgen and Julesz (1983) reported increases in serial search functions using T and L shapes and have accounted this unusual result to target-distracter similarity, leading to a more serial search function in these trials. When a display consists of T shapes in various orientations, each item in the display has a horizontal and vertical feature. The target item must be selected from same coloured distracters simply by assessing how the vertical and horizontal components are joined. This judgement is harder then the simple up or down judgement that was required in Experiment 8.

Experiments 8 and 9 Summary and Discussion.

The main aim of these experiments was to investigate any developmental differences that may be present in spatial attention over the age range of investigation for the temporal task. VSTM update of visual search tasks is governed by the central executive of WM and this is considered to be a function of the frontal cortex. Experiment 8 used the same stimuli as the target items from the RSVP stream in Chapter 2 (Experiments 2-5) and the results indicated, in contrast to the AB study, there was no difference in performance between adults and 7-year olds.

Adult data yielded a very typical pattern of results (Treisman and Gelade, 1980; Wolfe et al. 1989) for a visual search experiment, whereby RTs increase over display size in the conjunction task. This validated the choice of stimuli and gave a measure that could be used as a comparison for 7-year olds. The pattern of results for the 7-year was similar to the adults, and an ANOVA conducted on RT slope data for these two age groups revealed no significant differences in performance between the two age groups. This suggests that the rate of entry of items to VSTM is very similar for adults and 7-year old children. Selection of items to VSTM is governed by the central executive following comparison to a target template and therefore increased search slopes would reflect poorer working memory functioning. However, since the pattern of performance was not significantly different for the younger participants it would appear this spatial attentional ability is 'adult-like' by the age of 7-years old. This is in contrast to the temporal attention performance in Chapter 2 and this suggests dissociation in the developmental time course of the two aspects of visual attention.

It is important to establish that this result is not unique to one set of stimuli, and therefore Experiment 9 attempted to replicate this finding using alternative stimuli. The same pattern of results was seen with these stimuli, which strengthens the claim that working memory in spatial attention is 'adult-like' at age 7. Experiment 9, however yielded a slightly anomalous result in the target present trials of the conjunction search. The slope of RTs over display size in this condition was steeper than would normally be expected for both the adults and the 7-year olds, although this was only significant for the 7-year olds. This pattern was not seen in Experiment 8 and is therefore considered to be a reflection of the difficulty of the task. Error rates suggested that the participants made more errors in Experiment 9 than Experiment 8, supporting the claim that Experiment 9 employed more difficult target discrimination. In both Experiments 8 and 9, the target shared colour features with half the distracters and shared shape feature with the other half. Therefore the target-distracter similarity remains the same on this dimension between experiments. However target-distracter similarity is higher on the dimension of shape in Experiment 9. In this display targets and distracters share features even though their direction is different. Each item has a horizontal and vertical component and the only discriminating factor is how these features are combined. Results from ERP studies have also concluded that colour discrimination is easier than shape discrimination (Taylor and Khan, 2000) and this may account for some of the differences in the patterns of performance between these two experiments.

There is no overall developmental difference in performance in this spatial attention task and this is in contrast to the temporal developmental differences in Chapter 2. The cognitive operations of each type of task are different: the AB requires efficient consolidation and storage of target items in VSTM and visual search requires VSTM update. It may be that these executive functions have different developmental time course. Rympa and D'Esposito (2002) investigated the involvement of the prefrontal cortex during specific working memory tasks. They found increased activity in the ventrolateral PFC during functions of rehearsal maintenance associated with the capacity limited buffer, whereas activation in dorsolateral PFC was greatest during functions of encoding associated with subsequent retrieval success (and therefore organisation of VSTM). This cortical differentiation may explain why spatial attention is not subject to the same developmental delay as temporal attention.

Chapter 5 — Video game playing

Abstract

The aim of this chapter is to extend the findings from the previous chapters and to demonstrate that the developmental differences seen in visual attention and executive function are not limited to controlled laboratory settings. This chapter assesses video game playing performance on two Playstation® games specifically selected for their utilisation of executive functions. Successful illustration of developmental differences will provide ecological validity for the claims made in Chapters 2. The first game, Point Blank 3™ presents 8 tasks, which together represent a range of executive functions such as inhibition of response, target detection and selection, and sequencing. However the degree of manual dexterity required for this game may have been problematic for younger novice players. The second game, Space Invaders™ reduces the problem of manual dexterity by requiring simple left-right movements, but still utilises tasks of executive function. Both games successfully demonstrate a developmental difference in performance. Regression analysis on measures taken from this and previous chapters, reveals Point Blank 3™ score to be the best predictor of total AB magnitude. This builds on recent research findings that video game playing can improve temporal attention skills (Green and Bavelier, 2003). Results from this chapter suggest that video game playing *is* an appropriate, and externally valid, measure of executive functioning.

Video games

The 'real-world' applications for the findings in Chapters 2 are considered in this applied chapter. It is important to show external validity for these claims and demonstrate development of these aspects of visual attention outside the controlled setting of the laboratory. The present chapter illustrates developmental differences in performance for the participants who took part in Experiment 3 (AB task) and the tests of working memory (Experiments 6 and 7) on two video games. This performance is then directly related to total magnitude of the AB (i.e a laboratory measure of divided attention) using multiple regression analysis.

Subrahmaynam and Greenfield (1994) have shown a link between spatial skills ability and video game playing and Blumberg (1998) provided evidence to suggest that video game playing enhances strategies for divided visual attention. Very recently Green and Bavelier (2003) have shown a link between video game playing and changes in different aspects of visual attention over time. They tested the hypothesis that video game playing increases the capacity of the visual attention system. Green et al. used the flanker compatibility paradigm to asses video game players and non-video game players and successfully demonstrated that video game players have an enhanced attentional capacity. Results from three experiments revealed enhanced allocation of spatial attention over all eccentricities of the visual field, and not simply within the 0-5° from fixation range that would represent the normal video game playing zone. In a novel experiment, Green et al. investigated the effect of playing video games on temporal attentional abilities. They report higher T2 detection rates in an AB paradigm for video game players than non-video game players. The researchers also report that after only ten consecutive days of training (one hour a day) on an action video game, a group of non-video game players showed faster recovery on an AB task than a comparable group who played Tetris over the same period. This suggests that video game playing is not only related to individual differences in temporal attentional ability, but can also improve this skill.

Green et al. (2003) used violent combat games such as Medal of Honour for the experimental condition of their task —this game required detection of new enemies, tracking existing enemies, avoiding getting shot, etc. These skills utilise a number of executive functions, but this particular game had an adult theme and as such would be inappropriate for the current investigation. Therefore, for this developmental study, target shooting games using cartoon characters and space aliens were used. The selected games utilised various executive functions such as target detection, inhibition, strategic planning and rapid processing of the visual array. The games were novel to each participant and therefore if the frontal lobes are responsible for the types of skills involved then a developmental improvement would be expected. More importantly, an individual's score would be inversely related to their total AB magnitude.

Performance on the first game (Experiment 10), Point Blank 3™ showed a developmental pattern with better performance at ages over 7-years old. Experiment 11 addressed the potential confound from Experiment 10 of manual dexterity difficulties of younger participants and assessed performance on Space Invaders™, a game that required only left or right movements. This game also revealed a developmental improvement in scores over the four age groups tested, and therefore eliminated concerns about manual dexterity in this developmental study. Taken together these games provide an interesting measure of the two aspects of frontal function (holding information on line and inhibiting prepotent responses) with which this thesis is concerned. Since all participants in this chapter also took part in the AB task (Experiment 3) and tests of working memory (Experiments 6 and 7) it was possible to conduct a multiple regression analysis, and Point Blank 3™ score was shown to be the best predictor of total AB magnitude. This supports the findings from Green et al. (2003) demonstrating a link between visual attention performance on test conducted within the psychological laboratory, and video game playing ability.

General Methods

Participants

All participants who completed Experiments 3, 6 and 7 also took part in the two following experiments. There were 16 participants at each four age groups: Adults, 7-, 12-, and 15-year olds.

Apparatus

Each of the following video games were played on a SONY Playstation ® 2 game system attached to a SONY® 28" FD Trinitron colour television, model KV-21LS30U. Participants operated a hand held Analog Controller (DUALSHOCK®), but did not use the analogue stick control. Instead, the left hand manipulated direction using the cursor keys and the right hand operated the 'fire' button(s).

Design

Each of the following experiments is a between subjects design comparing performance across the four age groups. The dependant variable is the participant's final score on the video game.

Procedure

Prior to play, each participant was familiarised with the appropriate keys on the joy pad for each video game. In each case the experimenter demonstrated how to play the game before the participant began. Practise trials preceded experimental trials for each task.

Experiment 10

The first video game used for this chapter was Point Blank 3™. This was a target-shooting game that is divided into individual games utilising a range of executive functions. The tasks required functions of sequencing, on-line memory, matching to sample, visual discrimination, and feature integration. As such this video game enabled a real-world application of some of the functions assessed in previous chapters. This video game was chosen since there was no excess violence (only cartoon animals are located to be targeted). Each task required rapid visual processing since there were time limits, but participants had an unlimited supply of 'shots'. Each task in Point Blank 3™ required the participant to follow the 'rules' of a game and engage in rapid visual processing. Individual games utilised different aspects of frontal functioning and, as such, the eight games presented cover an appropriate range of tasks for WM assessment.

Although Point Blank 3™ can be played using a G-Con45™ gun, which is fired at the screen, all participants in this experiment used the Playstation®2 joy pad. The 'training trials' aspect of the main game was used in this experiment since this enabled individual exercises to be run. Specifically, 8 of the 'brain teaser' tasks were used.

Method

Design

Each participant was required to complete eight games, each assessing executive function. Each game provided unlimited 'shots' and they are described below:

- *Target show*: This game presented nine possible target locations represented by gold stars on three horizontal wooden slats. The numbers 1, 2 and 3 flashed onto three star-marked locations in numerical order and then the wooden slats flipped over so the reverse was presented. The reverse had targets in place of each star and the participants were required to shoot the appropriate target locations in the order in which the numbered locations were presented. Participants were given 25 seconds to complete as many trials as they could. A new trial begins if a correct sequence was executed, if participants made a mistake or after a short period of time had passed. This game required the participant to hold information on line and remember the appropriate pattern sequence.

- *Fans*: This was the first of a number of 'match-to-sample' games. Participants were presented with a sample fan that had a particular picture (a flower, or bamboo or aloe) on it. Beneath the target fan were five potential target locations occupied either by a fan or a bomb. Fans at each of the target locations rotated on the vertical axis so to occlude the image intermittently. One of the fans possessed the same target picture as the sample and the participant was to shoot the correct fan. Unlike the previous game, the screen did not change until a response had been made. Participants were to match as many of the fans to targets as possible. This game required rapid scanning of the visual array for target detection. As such this game used similar WM functions as those involved in visual search tasks.

- *Woodmen*: this was another 'match-to-sample' game whereby the target image was a character constructed of logs who had a particular stance (i.e hands above his head, or standing on one leg). The target image was presented in the centre at the top of the screen, beneath which were eight further woodmen, one of which matched the target sample. Participants had to shoot the matching image and were given 30 seconds to match as many as they could. A new trial began when the participants made a response or when a short period of time had passed. Again, this game required a rapid scan of the visual array, since the eight woodmen that could potentially be the target disappeared after only a few seconds.

- *Fireworks*: Three fireworks were shown to ascend into the night sky and were labelled with the numbers 1, 2 and 3. Participants were told to explode the fireworks by shooting them in the correct order. The fireworks began to descend once they had reached the top of the screen and faded out as they came down. Participants therefore had to shoot the fireworks before the images faded. A new trial began once all three targets had been shot in the correct order, once a mistake had been made or if the fireworks had descended far enough to fade. Participants were given 20 seconds to shoot as many fireworks as they could. This game required the participant to shoot the targets in the correct order and to inhibit shooting of targets when they were not appropriate.

- *Matching animal heads to bodies*: At the top of the screen participants were presented with an image of the rear half of a cartoon animal. In place of the head was an empty square with a question mark in it. Beneath the animal image were nine images of animals' heads. Participants were to select the appropriate head for the body. Participants were given 20 seconds to match as many heads to bodies as they could. Participants needed to asses what type of animal the target item was, and then select the appropriate response based on this judgement. There was an element of top-down processing in this game that would narrow the search amongst the distracters.

- *Matching faces*: In this matching game, a character was shown holding up a picture of another character's face. On either side there were nine faces and the target face was amongst these distracters. Distracters were varied between trials and sometimes the distracters were homogenous and on other occasions they were heterogeneous with a varying degree of similarity to the target. If a participant did not respond within a given time, a new target face was presented. A new trial began after this time or when a response had been made. Participants were given 25 seconds to match as many faces as they could. This game was very like a visual search task. Participants had to very quickly scan the visual array and discriminate the target item from the distracters. On some trials the target head was presented amongst homogenous distracters that were very similar to the target, and on other trials the distracters were highly heterogeneous.

- *Numbers and letters*: Participants were presented with a small grid image of a number or letter to the top left of the screen. This was the target shape. Beneath this image was a larger grid comprised of the same number of squares. The participant had to shoot out the squares on the larger grid that corresponded to the image presented in the smaller grid. Participants had as long as was required for each trial and a new trial began when either the correct image had been completed or a mistake had been made. The game lasted 25 seconds and in that time participants aimed to complete as many number and letter tasks as possible. Participants had to be accurate in their aim, and remember the appropriate target shape. This game required on-line visual memory for the correct target shape to be completed. Strategies could also be employed in this game to facilitate faster completion of the shape since it was not always faster to shoot the squares out in the way that the number or letter would be written.

- *Jumping items*: As with all the 'match-to-sample' games, the target image was presented in the centre at the top of the screen. In this game five items (animals, objects, balls etc) jumped up quickly from the bottom of the screen and fell back down again. Participants had to shoot the matching item before it fell out of range. Participants were given 20 seconds to correctly complete as many trials as they could. A new trial began when the correct item had been shot or when the object fell out of view. As with the matching faces game, this game sometimes presented homogenous distracters and sometimes presented heterogenous ones. This made detecting the correct item quite complex. The possible target items had to be processed very quickly since they did not remain on the screen for long.

Procedure

Initially the experimenter demonstrated how to play a game and then the participant completed one trial at the 'practise' skill level. After each game had been demonstrated and practised, the participant then completed each game at the 'beginner' skill level and the participant's score was recorded.

Results

The total score for each participant was calculated by adding the scores of each of the eight games together and a group mean was then calculated for each of the age groups tested[12]. The performance for each game is then presented for the four age groups. The results are presented below in 1000's.

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[12] There were no scores lying 3 SD's either above or below the mean for this experiment and therefore scores from all 16 participants in each age group were included in the analysis.

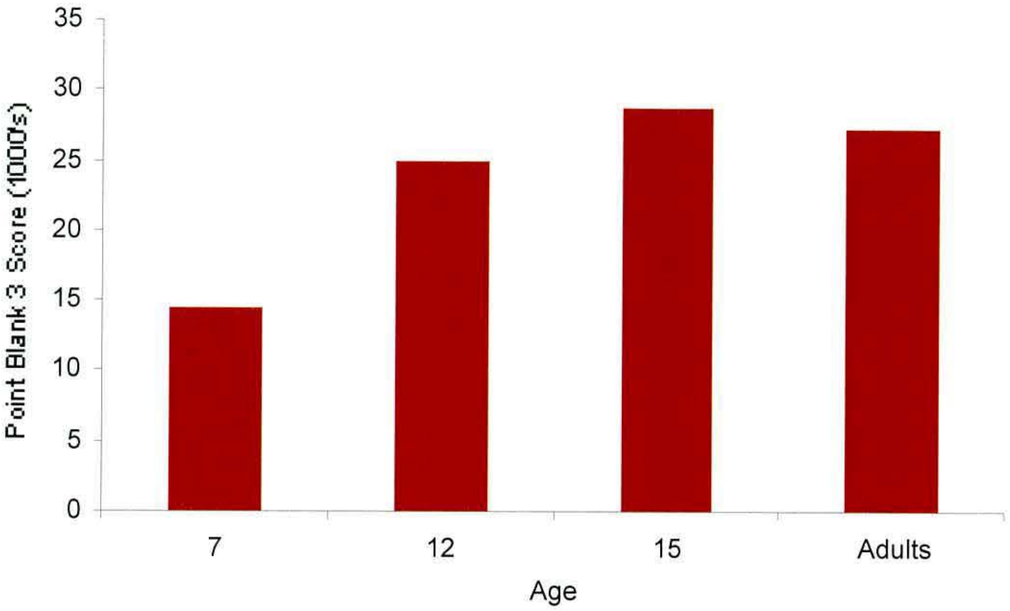

Figure 27: Mean Scores for each of four age groups on Point Blank 3™.

A one-way ANOVA was conducted on the above mean scores for the video game, Point Blank 3™. Following a significant result (*F* (3, 60) = 14.46, *p* <0.01). Tukeys' HSD revealed that the scores of 7-year olds were significantly lower than all other age groups.

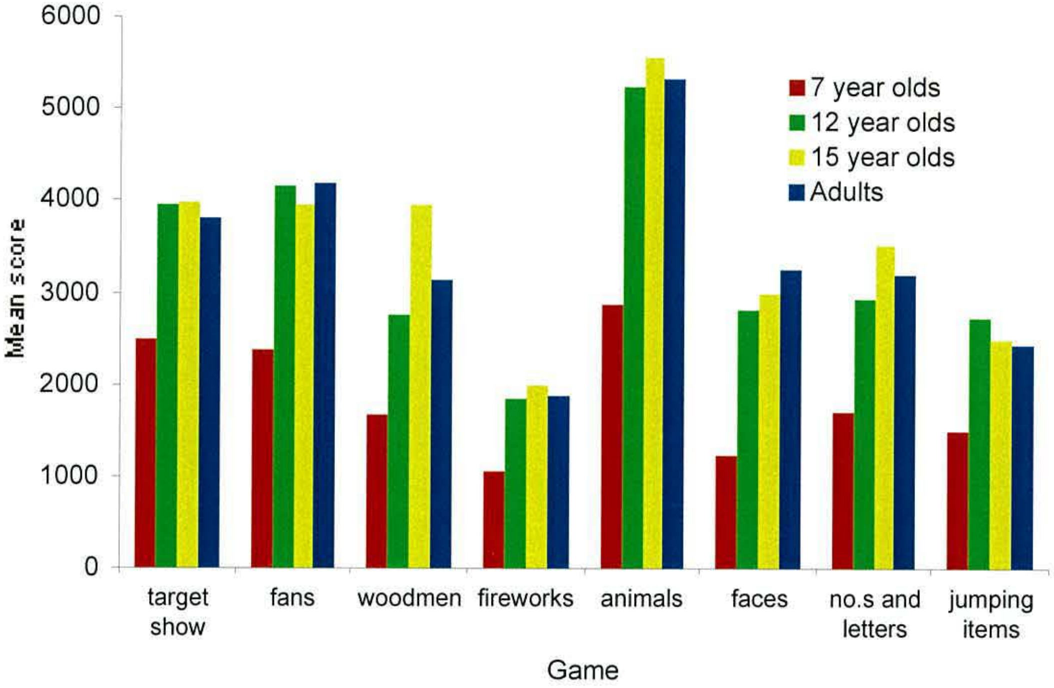

Figure 28: The developmental pattern of performance, over four ages, in the 8 games of Point Blank 3™

Although individual games utilised slightly different executive functions the pattern of performance over the four age groups similar for each game. Figure 28 illustrates that 7-year olds have the lowest scores in all games, and the three oldest age groups show comparable performance rates. A series of one-way ANOVAs with Tukeys HSD post hoc analysis confirmed that 7-year olds had significantly poorer scores than all other groups, and the scores of the three oldest groups were not significantly different from each other. This pattern of performance occurred on all games except the 'Woodmen' game. In the 'Woodmen' game, the 15-year olds had significantly higher scores than all other groups and the other three groups did not significantly differ from each other. The results of these analyses are presented in Table 9.

The ANOVA outputs are listed below with significance levels and the results of Tukey's HSD analysis.

Table 9: Output from a series of one-way ANOVAs conducted on the above data.

Game	*F* value (3, 60)	*p*
Target show	7.35	0.003 *
Fans	11.52	0.000 *
Fireworks	4.77	0.005 *
Animals	18.65	0.000 *
Faces	8.63	0.001 *
No.s and letters	9.67	0.000 *
Jumping items	5.32	0.003 *
Woodmen	4.85	0.004 **

* 7-year olds show significantly lower scores than all other groups

** 15 year olds show significantly higher scores than all other groups.

Experiment 10 — Discussion

Results from Experiment 10 revealed a developmental difference in scores on Point Blank 3™ with 7-year olds showing poorer performance on this video game than any other age group. This pattern of performance was the same over 7 of the 8 games that comprised Point Blank 3™. On the remaining game 15-year olds showed significantly higher scores than all other groups. This suggests that game-playing ability on Point Blank 3™ can be subject to developmental delay. The purpose of this experiment was to assess various executive functions in a 'real-world' setting. Success on visual attention experiments in previous chapters relied on executive functioning governed by the developing frontal cortex. Point Blank 3™ utilised executive functions such as on-line memory, target matching and sequencing in a real-world setting. More importantly, this game required rapid scanning of the visual field and rapid visual processing since each game had a time limit. Developmental improvements in rapid temporal visual attention were measured in Experiment 3 of Chapter 2 and individual performance on the AB task in relation to this video game and other tests of executive function was investigated and is presented following Experiment 11.

Point Blank 3 not only utilised the temporal aspects of visual attention, but also required some spatial monitoring of the screen. Target detection tasks were similar to the visual search task of Chapter 4, and particularly the 'matching faces' game utilised feature integration skills since the target face was sometimes very similar to its surrounding distracters. Although these factors meant that the overall game was a good measure of both temporal and spatial visual attention, the game also required a degree of manual dexterity. Once detected, a target could only be shot once the cursor had been moved to the correct location. This may have been more difficult for younger players, whose thumbs were sometimes not large enough to use the four-arrow cursor as one button, and instead had to move their thumb to press any one of the four direction keys. It is necessary, therefore, to assess the video game performance of these participants on a game that does not require this level of manual dexterity.

Experiment 11

Experiment 11 presents the second of the two video games used in this chapter. This game is Space Invaders™. Unlike Point Blank 3™, Space Invaders™ does not require extensive movement of the cursor and therefore the results may be less confounded with developmental differences in manual dexterity, making this game a more appropriate measure of visual attentional ability than Experiment 10. Space Invaders™ is a game that relies heavily on spatial awareness and visuo-spatial skills and therefore builds on the information provided by the more temporally based game used in Experiment 10.

Method

Design

Space Invaders™ required players to destroy aliens, which are occupying the sky. The game was divided into planets and within each planet there were 10 levels preceding the 'Boss alien'. Aliens appeared in blocks (approximately 20 to 50 aliens per level). A tank represented the participant's position at the bottom of the screen and could only be moved left or right. This version of Space Invaders ™ had been adapted from the original Space Invaders product licensed to Activision Inc by Taito ©. In this current version, aliens presented to the viewer were of a range of colours. In addition to simply destroying them all with single shots, participants could employ strategies using special shots obtained by destroying four like coloured aliens consecutively. When a special shot had been earned, the Head Up Display (HUD) showed a coloured in bar of the same colour as the alien and the type of special shot (i.e horizontal, left, right or diagonal burst) was written underneath[13]. These 'special' shots allowed destruction of one line of aliens and yielded more efficient game play than did individual shots. The adaptation of the game to employ such strategies made it a superb real-world assessment of strategic planning ability (c.f. Blumberg, 1998).

Whilst participants were destroying aliens they were also to be aware of mother ships which passed over head carrying bonuses such as shields and double-shot functions. Participants were to shoot at the mother ships to collect the bonus items. All aliens could potentially fire at the participant and did so randomly. There were therefore a number of task requirements to be carried out whilst the whole screen was monitored for both beneficial and costly events.

Procedure

As with Experiment 10, the experimenter first demonstrated the game and, in this experiment did so by playing through the first 4 levels of the first planet of Space Invaders™. This enabled introduction of each of the four alien types for this level. The participant was then given a practise trial. If the participant was successful in reaching the Boss Alien at the end of the level, only one practise trial was given. However, usually the participant's turn ended before that event, and s/he was allowed a second practise trial. Following practise, only one experimental trial was run and the score for each participant was noted.

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[13] This was explained to all participants prior to play and the colour of the bar represented the type of special shot. As such it was not necessary to be able to read the description under the HUD.

Results

A participant's score on the experimental trial of the game was recorded and converted into thousands. Scores that were 3 standard deviations above or below the age group mean were removed from the analysis[14]. An age mean was calculated for each group and the results are presented in Figure 29 below.

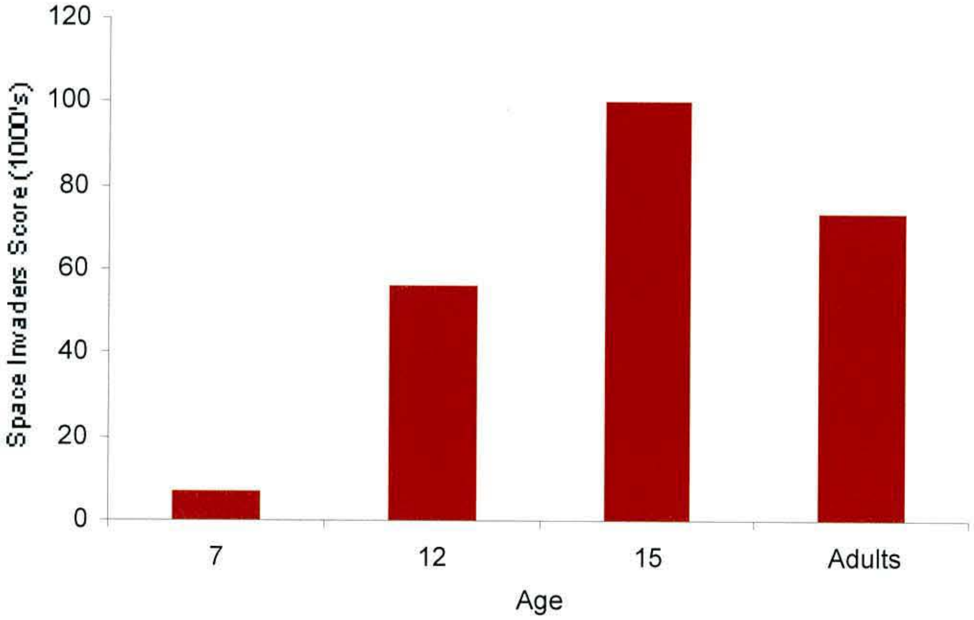

Figure 29: Mean scores from four age groups on Space Invaders.

A one-way ANOVA on the above data revealed significant differences between the mean scores of 7-, 12-, 15-year olds and adults. Post-hoc analysis on the form of Tukeys HSD showed that scores of the 15-year old participants were significantly higher than the 7-

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[14] This resulted in the removal of one 7-year old, one 12-year old and two Adults from the final analysis.

year olds and 12-year olds. However the 15-year olds' scores were not significantly different to the adults' scores.

Experiment 11 — Discussion

Scores on Space Invaders™ demonstrated a significant difference in video game playing between age differences. The 15-year olds yield significantly higher scores on this video game than either the 7- or 12-year olds. The average score of the 15-year olds was not significantly different to that of the adults, although Figure 31 suggests that 15-year olds yielded slightly higher scores. The pattern of results shown is similar to the global pattern seen in Experiment 10 and again suggests a developmental improvement in video game playing. This game seems to be slightly harder since 12-year olds were also significantly poorer than 15-year olds. The developmental trend is evident and, although not significant, the 15-year olds appear to show better performance than the adults. This shows support for the suggestion that children raised in a generation where television and computers are common place will exhibit better parallel processing than those raised in a more text-based generation (Greenfield, 1984; Greenfield, Brannon and Lohr, 1994; Roe and Muijs, 1998)[15]. However, it may also be the case that 15-year olds have increased exposure to video games compared to the adult participants tested.

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[15] However this did not appear to be evident in the AB task – adults exhibited a shorter AB duration than did 15-year olds.

Space Invaders™ utilises many executive functions such as inhibition, target selection, sequencing, and also visual monitoring of the whole screen. Unlike Experiment 10, this game did not require a high degree of manual dexterity and therefore the higher scores are taken to show improved video game performance. Success on this game required the participant to monitor the screen and avoid being shot, whilst utilising strategies for maximal destruction of the enemies. Throughout the game mother ships passed over the top of the aliens and, when shot, these released bonus items. Observing the HUD whilst playing enabled the participant to be aware of, and use the special shots that could destroy more than one alien at a time. Use of these led to a better game strategy and therefore an increased score. Even the very young children were able to use these since they were colour coded, although observation of the participants during the game suggested that the 7-year olds did not maximise their special shot potential. This use of strategy alone reflects frontal functioning and may have contributed to the poorer scores shown by 7-year olds.

The use of strategy develops over the age range tested in this thesis (Roberts et al., 1991) and previous chapters have illustrated the advantage that this skill has in working memory and visual attention tasks. Bumberg (1998) claims that video games are an ecologically valid measure for the development of selective attention and reports that frequent video game players have an improved use of strategy in such situations. This is a view that is shared by Greenfield, deWinstanely, Kilpatrick and Kaye (1994) who have linked video game playing with an enhanced ability on divided attention paradigms.

The ability to monitor the whole screen and divide attention between the attack, the defence and the presence of mother ships is advantageous to game playing. In accordance with current literature improved visuo-spatial ability seems to be connected with better performance on video games. Greenfield (1994) claims that long-term video game playing increases spatial skills.

Results of this experiment and the previous one show a developmental improvement in video game playing performance. In line with current literature this is considered to be, at least in part, a reflection of the development of spatial attentional skills associated with the development of the frontal cortex. The main focus of this thesis, however, is temporal attention and the purpose of this applied chapter was to try and develop a link between the development of temporal attention and video game playing (using executive functions). Recent research has illustrated a cause and effect relationship between video game playing and performance on the AB in adults. The aim of the remainder of this chapter is to establish what correlation, if any, there might be between performance on these two video games and developmental performance on the AB.

Prediction of Total AB Magnitude using Regression Analysis

Since all participants who completed the developmental AB experiment (Experiment 3) also took part in the two video game tests presented above and all tests of working memory (Chapter 3) it was possible to investigate the relationship between these variables and total AB magnitude. A multiple regression analysis was carried out on the variables that had an approximately linear relationship with total magnitude of the AB. These variables were the effect of load on accuracy of the shapes task and the effect of load on the RT of the dots task, and Point Blank 3™ score (in 1000's, PB3) because these variables showed significant age differences in Chapter 3 [16]. Age did not have a linear relationship with total AB magnitude and was therefore not included in this analysis. Only participants whose scores were included in both Experiment 10 and 11 were included in this analysis.

Table 10: Summary of regression analysis: the effect of load on RT of both the shapes and dots tasks, and Point Blank 3™ score as predictors of total AB magnitude.

Predictors	B	Total magnitude R^2
Shapes Accuracy Load	-0.227	0.337*
Dots RT Load	0.142	
PB3	-3.66	

* $p<0.001$

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[16] The effect of load on RT was calculated by subtracting RT on the easy/control condition from the hard/experimental condition and for accuracy the experimental accuracy was subtracted from the control condition.

Regression analysis revealed that, taken together, the above three variables account for 34% of the variance in total AB magnitude. However, only PB3 score explained a significant portion of total magnitude for the participants who took part in Experiment 3. The correlation between total AB magnitude and total Point Blank 3 score is shown below in Figure 30, with grouped components for each age group.

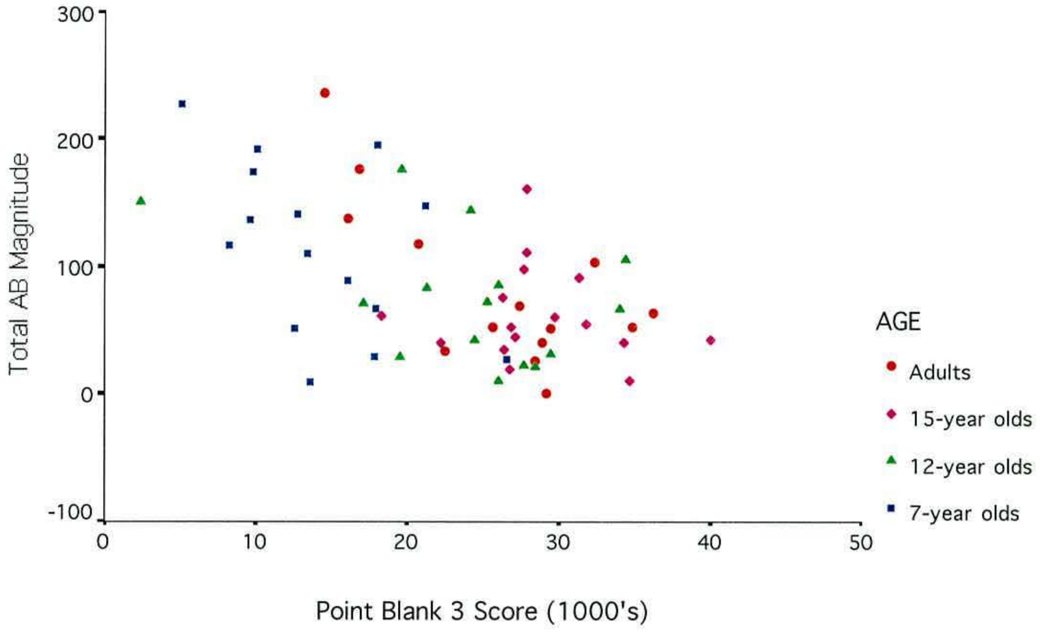

Figure 30: Scatterplot of Total AB Magnitude against Point Blank 3 Score (in 1000's).

The regression plane of total magnitude and PB3 was significantly different from zero ($F = 9.50$, $p < 0.001$). Point Blank 3™ score was negatively related to total magnitude and the regression coefficient was –3.66 (95% confidence interval = -5.272—2.048). Since the confidence interval does not encompass a positive value, it can be concluded that the population coefficient for PB3 is negative ($t = -4.548$, $p < 0.001$). PB3 is negatively related to total magnitude of the AB: as the score on PB3 increases by one unit, total magnitude decreases by 3.66 units.

The multiple regression analysis is conducted on all participants and does not take age into account. Figure 32 presents the correlation between total AB magnitude and overall Point Blank 3™ score, and depicts the ages of each participant. When the correlation between total AB magnitude and Point Blank 3™ score is conducted for each age group, only the 7-year olds and Adults show significant negative correlation ($r= -0.511$, $p<0.001$ and $r= -0.718$, $p<0.01$ respectively). This finding supports that of Green and Bavelier (2003) that video game playing in adults can affect the temporal duration of the AB and also suggests that same may be true for 7-year olds. It appears that the video game performance of 12- and 15-year olds is not correlated with AB magnitude and this may be due to increased video game exposure in these age groups. Figures 28 and 30 illustrate this point by revealing high game scores for these two age groups.

Experiments 10 and 11 Summary and Discussion.

Experiment 10 demonstrated a developmental improvement in video game playing. The selected game, Point Blank 3™, utilised various executive control functions and as such was deemed to be an appropriate and ecologically valid task for assessing the functions of the developing frontal cortex. There were concerns over the manual dexterity required by this task and therefore a subsequent experiment presented a video game that operated solely on left-right movements. This game, Space Invaders™ also showed developmental differences, hence alleviating concerns regarding manual dexterity differences over age. Experiment 10, which utilised executive functions, was a temporally based visual task whilst Experiment 11 was more concerned with visuo-spatial ability particularly that of monitoring a visual array and dividing attention between concurrent tasks in that array.

Results of experiments 10 and 11 support the claims of previous research into the effect of video games on cognitive development. The pattern of results from these two experiments suggest that 15-year olds have better video game playing ability than adults. This supports the suggestion from Greenfield (1984) that young children can outperform adults due to the fact that the environment in which they have been raised had a high involvement of parallel processing requirements from television and visual media, compared to the serial processing requirements of reading from previous generations. An alternative suggestion is that 15-year olds have greater exposure to video games than do the adults in these experiments. The age range of the adult participants was 20- to 45-years old, however approximately 13 out of the 16 participants were in their 20's and therefore the difference in scores between 15-year olds and adults is unlikely to be due to a generation gap. Blumberg (1998) stated that improved selective attention is positively linked to video game playing ability and Greenfield, deWinstanley, Kilpatrick and Kaye (1994) have shown that expert video game players demonstrate an improved ability to divide their attention across the visual field. Green and Bavelier (2003) have recently shown improvements in temporal attentional ability in an investigation using the Attentional Blink. Green et al. not only showed that video game players have improved temporal attention abilities, but also that non video game players could significantly reduce their recovery time on an AB task after only ten days of video game training.

Although the developmental differences here, together with previous research, suggest that video game playing may be an appropriate test of temporal visual attention no direct link can be made from these measures alone. Therefore the relationship between performance on the AB task and the two working memory tasks, as well as scores on a video game, was assessed. These variables (the difference in accuracy scores between the two shapes conditions and the difference in RT between the two dots conditions) were the ones that showed a linear relationship with AB magnitude, and therefore age alone could not predict total AB magnitude.

Multiple regression analysis in the current chapter shows performance on a novel video game, Point Blank 3™ to be the best predictor of total AB magnitude. All participants who took part in these video game measures had also previously completed the AB task (Experiment 3) and the working memory tasks (Chapter 3). The regression coefficient between PB3 score and total AB magnitude showed a significant negative correlation (-3.66), suggesting that a high score on the video game is correlated with smaller total AB magnitude. This negative correlation was most pronounced in 7-year old and adult participants. Since this game was novel to all participants a high score represents a participant who has an increased ability at playing video games (possibly a frequent player). This result is comparable to those of Green and Bavelier (2003) and suggest that video game playing performance is related to temporal attentional ability in a dual task paradigm and that video games may effectively reflect visual attentional abilities outside of the psychology laboratory.

Suggestions that divided attention strategies improve with age (Blumberg, 1998; Taylor and Khan, 2000) are supported in this chapter. Greenfield, de Winstanely, Kilpatrick and Kaye (1994) demonstrated that expert video game players have an improved ability to divide attention across a visual field and this is supported by Green and Bavelier's findings that video game playing reduces the duration of an attentional blink.

Chapter 6 – General Discussion

The primary aim of this thesis was to investigate the developmental time course of temporal attention as indexed by the Attentional Blink (AB). The AB represents the temporal duration (after first target detection) that is required for attentional processes to recover in order to successfully report the second of two targets. Luck, Vogel and Shapiro (1996) demonstrated that targets items in an RSVP stream are processed to a level of semantic awareness and are subsequently passed to a second stage of processing for full identification and consolidation (Chun and Potter, 1995). Items are then held within this durable store, VSTM, until a response is required (Chun and Potter, 1995; Shapiro, Driver, Ward and Sorenson, 1997; Shapiro, Raymond and Arnell, 1997). The central executive is needed to efficiently organise and store the target representations within VSTM (Vogel, Luck and Shapiro, 1998) and if insufficient attention is available between consolidation of the first target and initial processing of the second target, confusion arises and second target detection rates are lowered. It is only with increased temporal separation between the targets (typically 350-500 ms) than both targets can be detected and accurately reported.

The organisation and storage capacities of the visuo-spatial aspects of the central executive are utilised during the consolidation of target items in VSTM and imaging studies have revealed that these functions operate in cortical networks that involve the prefrontal

(specifically dorsolateral prefrontal) cortex (Kane and Engle, 2000; Rympa and D'Esposito, 2002). Cortical networks engaging the frontal cortex are activated during AB tasks (Marois, Chun and Gore, 2000; Richer and Lepage, 1996) and this area of the human cortex is one of the last to become fully developed (Case, 1992; Hashimoto et al., 1995; Stuss, 1992; Thatcher, 1991).

Despite extensive literature discussing the theories of the AB (Chun and Potter, 1995; Raymond, Arnell and Shapiro, 1995; Raymond, Shapiro and Arnell, 1992; Shapiro, Raymond and Arnell, 1994; 1997) and also a body of work that utilises the AB to investigate the temporal attentional abilities of various patient groups (Husain, Shapiro, Martin and Kennard, 1997; Richer and Lepage. 1996; Shapiro, Hillstrom and Husain, 2002) until now there has been no report of the developmental aspects of this phenomenon.

It seemed appropriate to suggest that the pattern of performance in such temporal attention tasks may differ with increasing age. Therefore the first experimental hypothesis of this thesis addressed the relation between performance during the AB and increasing age. The five experiments described in Chapter 2 confirmed that a successful AB pattern could be established with stimuli that would be appropriate for children (coloured shapes) and that developmental differences in temporal attention exist. The temporal duration of the AB progressively reduces with increasing age, from 7-years of age to adulthood. This was illustrated by progressively older participants requiring less time to recover their attentional processing capacity in order to successfully detect and report the second target when it was presented in close temporal proximity of the first reported target. A particularly prolonged AB was observed in 7-year olds, with temporal recovery not occuring until approximately 1200 ms after T1 presentation. This interesting finding raised questions regarding the source of the developmental progression.

A major role has been theorised for working memory in the control of selective attention (de Fockert, Rees. Frith and Lavie, 2001). In accordance with a late selection account of the AB (Chun and Potter, 1995) the executive functions of working memory are implicated in the efficient storage of information in VSTM and for the retrieval of this information for subsequent report. The evidence from imaging studies (Marois, Chun and Gore, 2000) and patient studies (Husain, Shapiro, Martin and Kennard, 1997; Richer and Lepage, 1996) supports the involvement of the frontal lobes in dual-target tasks. Therefore the developmental progression of visual working memory and its neuro-anatomical substrate (the frontal lobes) is considered to be a potential cause of the improvement in the temporal processing with age. Although aspects of working memory and frontal lobe function are known to develop over the age ranges tested, a direct measure of the frontal function of the participants from the AB task was necessary. Only in this way could the hypothesis regarding the influence of frontal development in these participants be accepted.

Once a developmental difference in the pattern of the AB had been established (Experiments 3 and 5), supporting evidence for the development of WM and therefore the frontal lobes was sought using tests of the central executive and visuo-spatial skills. Measures to assess frontal lobe ability and development were subsequently taken from all participants who had completed the AB task (in Experiment 3). As reported in Chapter 3, visual working memory capacity and the executive function of inhibition were tested in different age groups (Experiments 6 and 7). The two tasks used tapped aspects of frontal lobe function that are required during tests of visual attention.

De Fockert et al. (2001) investigated the impact of increased perceptual load on working memory during visual search tasks which assess spatial working memory. They claimed that working memory exerts a control over visual selective attention in the human brain. It is well accepted that the more anterior portions of the brain that are considered necessary for selective attention continue to develop into early adulthood, with full maturation seen around age 20 (Case, 1992; Stuss, 1992). Experiment 6 revealed a developmental improvement in accuracy for the task assessing the ability to hold visual information on-line. This assessment of visual working memory capacity may reflect general developmental differences in VSTM which were required during the AB. Given that inhibitory functions have been shown to be deficient in patients following frontal lobe surgery (Lhermitte, 1983), tasks requiring inhibition were presented in Experiment 7 to assess frontal lobe development. The developmental reduction in RT observed in Experiment 7 demonstrated frontal lobe developmental delays in the same participants as Experiment 3. These developmental differences were taken as support for the hypothesis that differences across age groups in the AB task resulted from central executive involvement in VSTM.

Although significant results have been obtained in Chapter 3, it may have been possible to achieve clearer outcomes by improving the procedures used. The inhibition task may have benefited from a task-switch by presenting congruent and incongruent response trials alternately within one block of trials for instance. This would have prevented the participants from simply applying the strategy: ‘respond opposite’. Incorporating a task-switch has been used in recent experiments (Diamond, personal communication) to great effect. However, the small number of trials (16) for each condition that were presented to participants in the present version may have limited the use of a strategy. Furthermore, the visual memory task used by Diamond (personal communication) was a measure of the visuo-spatial sketchpad. Again, this task could be adapted to directly measure working memory. This would involve the presentation of stimuli at a left or right location, which would represent congruent or incongruent responses, and therefore would involve the two aspects of working memory (temporary maintenance and manipulation of information) which, together, yield greater prefrontal activation (Smith and Jonides, 1999).

Developmental differences have previously been described in spatial attention tasks using visual search paradigms (Casco, Giduli and Greco, 2000; Lobaugh, Cole and Rovet, 1998; Ruskin and Kaye, 1990; Taylor and Khan, 2000; Thompson and Massaro, 1989; Trick and Enns, 1998). Increased RTs and slopes of RT over display size have been reported for younger participants. Corresponding theories have also implicated executive control in WM, but in the update (rather than the organisation and the storage) of VSTM (Duncan and Humphreys, 1989; Wolfe, Cave and Franzel, 1989). A secondary line of inquiry was whether developmental differences in spatial attention seen in previous research could be replicated (1) over the age range of concern to this thesis and (2) with the specific stimuli that have been used in the investigation of the AB. The data collected in Chapter 4 was analysed according to mean slope/RT ratios for each participant, therefore accounting for developmental differences in mean RT. Each age group (7-year olds and adults) exhibited normal patterns of visual search performance with each of the two stimulus sets, but there was no significant difference in performance between the two age groups. The 7-year olds did not show steeper slopes of RT over display size for conjunction trials in 7-

year olds than adults in either task. RTs in a visual search task reflect the speed of entry of items into VSTM (Wolfe, 2003) and this is governed by the central executive of WM. The rate of entry of items to VSTM appears to be the same for 7-year olds and adults.

The Attentional Engagement Theory relates the slope of RT over display size to the size of the group of items that can be passed to VSTM at any one time. When attentional capacity is reduced, or target-distracter similarity is high, the manageable size of the group of items is reduced, and the slope of RTs becomes steeper. A non-significant difference between the performance of each age group suggests that attentional capacity does not vary between 7-year olds and adults. This is contrast to the results of Chapter 2 that illustrated a developmental delay in temporal attentional ability. Results of this thesis therefore seem to suggest that the cognitive functions of temporal and spatial visual attention have differential developmental time course. Temporal attention tasks requiring central executive organisation and storage in VSTM are subject to developmental delay and this is in line with the time course of development of the frontal lobes. The cortical areas of the AB task have been localised as the dorsolateral PFC whereas the executive function of VSTM update that is operational during visual search tasks has been more closely associated with the ventrolateral PFC. These distinct areas of the frontal cortex may become fully developed at different rates. However, it may be the case that it is the cortical networks associated with each task that have differential development. Although the anterior portions of the brain (specifically the frontal lobes) are one of the last areas to become fully developed, this development is not structural and instead represents increased myelination and strength of connections with the more anterior portions of the brain. Experiments 6 and 7 gave support to the claim that some working memory functions are underdeveloped prior to adulthood and the specific functions investigated in Chapter 3 may be operational during the temporal divided attention task in Chapter 2. These findings support the theory of WM involvement in AB (Chun and Potter, 1995; Shapiro, Caldwell and Sorenson, 1997; Vogel, Luck and Shapiro, 1997). Clearly no all WM functions follow the same developmental time course since those operational during visual search tasks are fully mature by the age of 7-years old. Functional brain imaging studies may help to establish which functions or cortical areas are subject to developmental delay, and where the distinction lies.

A subsequent line of investigation in this thesis was to demonstrate the ecological validity of these claims using measures of WM function and attentional requirements outside of the psychology laboratory. Chapter 5 carried this investigation into the field of video game playing performance of the participants that had completed the AB task and the tests of WM and inhibitory function. Video game performance has previously been linked to spatial ability (Greenfield, 1984; Subrahmaynam and Greenfield, 1994) and to improved use of strategies in a selective attention task (Blumberg, 1998; Roberts, Brown, Wiebke and Haith, 1991). Two video games revealed a developmental progression in game playing ability, which peaks at age 15.

Measures of game playing alone are not enough to assess whether video games are an appropriate external measure of visual attention, and therefore further analysis was required. All participants who undertook the AB experiment (Experiment 3) had also taken part in the testing of frontal lobe function and working memory function

(Experiments 6 and 7) and both the video games (Experiments 9 and 10). It was therefore possible to conduct a multiple regression analysis between total AB magnitude and the other variables tested. Variables displaying a linear relation with total AB magnitude were entered into the equation. The first video game, Point Blank 3™ was a good predictor of AB magnitude. This supported the recent findings from Green et al. (2003) demonstrating improved temporal attentional abilities in video-game players compared to non video-game players. Green et al. have also shown a significant improvement in the attentional abilities of non video-game players following one week of video-game practice. Therefore, video games do appear to be an appropriate and ecologically valid measure of attentional abilities. Results described in Chapter 5 support the central tenet of this thesis: working memory, related to frontal lobe growth, develops over the first 20 years of life and affects attentional performance.

Throughout this thesis there has been no discussion of any gender differences in performance on these measures of executive function. The genders of participants are not reported here and gender allocation was not always balanced within age groups. There is certainly an argument for the potential gender differences in video game playing and, given the claims this thesis makes regarding the similarities in performance levels between video games and temporal attentional tasks, it seems reasonable to suggest that this would be an interesting line of investigation. The developmental differences in temporal attentional abilities are clear, however, and insight into how much of this developmental progression is due to male or female participants would be informative.

It is interesting to note that complex cognitive functions specific to humans such as language processing are very advanced at an early stage of development whilst fundamental attentional systems are still immature. Language production and comprehension is acquired comparatively early in development, for example children's phonological productions begin to resemble those of adults at age 2- to 4-years old and written language begins to become internalised during the early school years (Carroll, Snowling, Hulme and Stevenson, 2003). Comparative levels of linguistic competency were demonstrated for 10-year olds and adults in a measure of word relationships (Secord, Wiig and Williams, 1988) indicating that *preadolescents* had multiple perceptions of word relationships and performed at adult levels. These functions are complex measures of cognitive ability that appear to show full maturation over a shorter developmental time course than the temporal attention measures described in this thesis.

The present work has demonstrated that adolescents (7-15 year olds) are immature in terms of divided attention. Kail and Park (1990) measured visual cognitive skills in children and reported that, with sufficient practice, 11-year olds are able to demonstrate performance in mental rotation tasks comparable to adults. Is the delay in maturation observed within this thesis unusual or would the children reach adult levels with training? Batty and Taylor (2002) measured visual categorisation in children aged 7- to 15-years old and in adults based on three ERP components: (1) P1, representing early visual processing or encoding; (2) N2, representing stimulus categorisation and (3) P3, representing a final stage of evaluation or memory update. Maturational changes in latencies preceded amplitudes across the age range studied. Batty and Taylor reported no significant age differences in P1 latencies, suggesting that even when presented for only 80 ms, the speed of visual processing in children as young as 7-years old was at adult level. The N2 reached adult levels by the age of 9, but *amplitude* changes during adolescence suggests that improvements develop late and continue into adulthood. The P3 latency did not reach adult levels until the age of 12. These results demonstrate that although the task was relatively easy, the underlying neural process is still developing over the age range studied, with working memory update being the last to develop. Stimuli in the present RSVP task (Experiment 3) were presented for approximately 90 ms and T2 detection rates in single target tasks were similar across age ranges. This is compatible with the early development of visual processing abilities reported by Batty and Taylor. The late development of the P3 component supports the current hypothesis: the developmental delay in attentional ability is specifically due to poor working memory function. It seems that when this function is measured temporally, full maturity is observed later.

Future Studies

At what age does the AB become adult-like?

Results presented in Chapter 3 show that the AB is subject to a developmental delay and that performance is not adult-like even by the age of 15 years. Despite continued frontal development until the age of 20, it is not the case that all frontal functions are underdeveloped until that age. This point was illustrated in Chapter 3, where 15-, or even 12-year olds displayed adult-like performance in certain situations despite developmental differences. The portion of the frontal cortex relevant to the AB is specifically the dorsolateral prefrontal cortex and this region and its connections may become fully developed prior to age 20. This issue could be investigated in a more specific manner if tests of the AB were run on participants aged 16-, 17-, 18- and 19-years old. Measures at each of these ages would give a clearer picture of when this dual target deficit is minimal (i.e at an adult level of performance).

It is documented that the cortex does not develop in a smooth fashion. Five rapid stages of growth have been proposed (Thatcher, 1991): (1) between birth and age 5; (2) between ages 7 and 9; (3) between ages 11 and 13; (4) between ages 14 and 16 and (5) between ages 18 and 20. These growth spurts do not represent physical growth since the cortex has an adult like appearance by the age of 18 months, but rather corresponds to phases of neural myelination. The frontal lobe is one of the last areas to fully develop since cortical growth proceeds from the posterior to the anterior of the brain. The current investigation has measured developmental differences in temporal attentional ability at four distinct ages. These represent the final four stages of growth as proposed by Thatcher. Following this model, the AB is expected to be even more prolonged in participants below the age of 7 years. Thatcher proposed five periods of rapid growth, suggesting that frontal development reaches a plateau between these stages, e.g. between age 5 and age 7 and again between age 9 and age 11. A measure of AB function from individual age groups may reflect these growth spurts and plateaus. If the waves of cortical growth were mirrored in AB performance, a stronger argument could be put forward for the developmental influence of this cortical area in temporal attentional ability.

A link between video game playing and visual search tasks

Results of the current thesis support recent findings that improved temporal attention, which can be characterised by the AB, is related to video game playing ability (Green and Bavelier, 2003). Despite results indicating improved spatial skills with heavy game playing (Subrahmanyam and Greenfield, 1994), there has been no body of work relating intensive visual attention practice to visual search performance. Visual search performance can be measured by estimating the rate of entry of items (or clumps of items) to VSTM, and video game playing has been proposed to reduce the temporal refresh rate of attentional capacities (Green and Bavelier, 2003). It therefore seems reasonable to suggest that heavy video game players would show shallower slopes of RT over display size in a visual search task. In a similar procedure to Green and Bavelier, this measure could be achieved by measuring visual search task performance at time t_1, issuing one hour of video game practice every day for 10 days, and then measuring visual search performance again at time t_2. Participants in a control condition could play a video game that does not require rapid visual processing, avoiding spatial awareness games such as Tetris. For instance, a game requiring low-level executive processing and unspeeded responses would be appropriate as a control condition.

The use of video games as a clinical tool

Results of Green and Bavelier's (2003) paper, together with the correlation between video game performance and the duration of a temporal reduction in attentional capacity, suggests that video games may have a beneficial effect. Previous work with Attention Deficit Disorder (ADD) children (Pope and Bogart, 1996) has indicated that video game playing can aid attention span when a participant is able to monitor his or her brain wave patterns. As the player maintains attention he or she is more likely to win the game, in this way the ADD child has an internal motivation to try and maintain attention span over the trials. This research was extended from a biocybernetic system that has been used to assess the automated maintenance of pilot engagement.

Current findings suggest that habitual game playing improves frontal lobe performance on the AB task (a finding that may extend to other attentional measures). This suggests video games may be used as a training tool for frontal lobe patients or for children who appear to suffer from dysexecutive syndromes. Long-term improvements in temporal attentional abilities were demonstrated in Green and Bavelier's (2003) paper, suggesting that video games not only focus attention for the immediately following task, but practice may have a lasting effect. Further developments in this field of research may have important implications for educational psychologists. If it was the case that playing 20 minutes of video games at the start of each school day helps children with attentional deficits to focus their minds, this could be a very positive procedure to implement since the children would perceive the task as a 'treat' rather than a 'treatment'. The implications for the video game industry of such findings would be warmly welcomed as a counter point to reports of reduced socialisation and other detrimental effects of video games playing.

Conclusions

This thesis was an investigation into the developmental aspects of temporal visual attention and the ecological validity of these findings when measured through video game playing.

Significant Achievements:

- The temporal recovery of attentional resources for accurate target detection in a dual-target task is not mature before adulthood (age 20).
- This developmental pattern is related to the progressive improvement and the maturation of the frontal lobes and their connections to other cortical regions. Here the performance of the visuo-spatial sketchpad and inhibitory control mechanisms were less efficient in younger participants.
- The pattern of developmental performance was, however, not mirrored by measures of spatial attention. This result suggests that the attentional abilities and the operations of the central executive during these spatial tasks develop earlier than those utilised during the AB. The dichotomy in results suggests differential development of executive functions, which may be attributed to the dorsolateral/ventrolateral division of PFC.
- Ecological validity was obtained by using video game tests in all the participants who completed the AB task. In line with recent findings, video game performance is related to temporal attentional recovery duration.

These findings have significant implications for future research in this area, specifically the advancement of knowledge regarding frontal executive functions and their development. The video game investigation brings this research into the domain of socially relevant questions and modern technology and allows clinical and educational hypotheses to be drawn.

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