Attentional contributions to children's limited visual short-term memory capacity: Developmental change and its neural mechanisms



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"Millions of items of the outward order are present to my senses which never properly enter into my experience. Why? Because they have no interest for me. My experience is what I agree to attend to. Only those items which I notice shape my mind - without selective interest, experience is an utter chaos..."

William James, The Principles of Psychology (1890)

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Abstract

Attentional contributions to children's limited visual short-term memory capacity: Developmental change and its neural mechanisms

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It is increasingly recognised that, in adulthood, attentional control plays an important role in optimising the ability to encode and maintain items in visual short-term memory (VSTM). Memory capacity limits increase dramatically over childhood, but the mechanisms through which children guide attention to maximise VSTM remain poorly understood. Through a number of experiments manipulating different parameters, the current thesis aimed to explore the developmental trajectories of the neurocognitive mechanisms underlying selective attention within VSTM and to examine whether variations in attentional control are accompanied by individual differences in VSTM capacity. Chapters 2 and 3 investigated the development of attentional orienting in preparation for encoding and during maintenance. Younger children emerged as less able than older children and adults to orient attention to internally held representations. Therefore, Chapter 4 tested whether younger children's attentional orienting is differentially affected by memory load. While attentional orienting prior to encoding was more beneficial when required to remember a greater number of items, cueing benefits during maintenance were similar across load conditions. Chapter 5 investigated whether temporal

parameters influence younger children's variable ability to orient attention during maintenance. Attentional orienting operated more efficiently on transient iconic traces rather than on VSTM representations due to passive decay of the memory traces as a function of time. Chapter 6 assessed whether the characteristics of the memoranda constrain the efficiency of attentional orienting within VSTM. Attentional orienting supported differentially the maintenance of familiar and meaningless items and pinpointed the quantitative improvement of mnemonic strategies over development. Finally, Chapter 7 examined the temporal dynamics of prospective and retrospective orienting of attention in VSTM. Children deployed neural pathways underpinning attentional orienting less efficiently than adults and differentially across the two orienting conditions suggesting their neural dissociation. Overall, findings from the current thesis define how children develop the ability to deploy attentional control in service of VSTM.

Chapter 1: General Introduction

Think of a busy primary school classroom, full of stimuli: books and pencils on the desk, pictures on the walls, the teacher writing various notes on the blackboard etc. To successfully cope with such a complex environment, children have to encode and maintain in memory only the information that is relevant to their current goal. As children are typically assessed on how much and how well they remember information, encoding and maintaining information in memory is considered a gateway to learning. While all children may understand that selecting and keeping in mind a small portion of the bulk of information around them is necessary for adaptive behaviour, a few of them will inevitably fail to do so. Are failures to remember information attributed solely to memory capacity limitations that cause forgetting or do attentional constraints play a role too? How do adults manage to cope with similar complex environments? Is it that our memory capacity expands so considerably as we grow that it allows us to store more information at any given moment, or do other cognitive processes that operate on perceptual and stored information function more efficiently to enhance remembering? Or is it both? In short, why do adults demonstrate better VSTM performance compared to children and, even within these age groups, why do some individuals perform better than others? These questions represent the motivation of the present thesis.

An extensive and yet growing research body with adult and child populations has resulted in multiple accounts aspiring to explain remembering and its constraints. As discussed in detail later, these accounts range from pure storage capacity limitations (Cowan, 2001; Luck & Vogel, 1997) to decay (Barrouillet, Bernardin, &

Camos, 2004; Burgess & Hitch, 1999; Towse, Hitch, & Hutton, 2000) and interference (Lewandowsky, Duncan, & Brown, 2004; Lewandowsky & Oberauer, 2009; Oberauer & Lewandowsky, 2008), both in the context of verbal and visual short-term memory. A noteworthy advancement in the adult field is the recent emphasis on interactions between visual memory and selective attention (Awh, Vogel, & Oh, 2006; Chun, 2011; Chun & Turk-Browne, 2007; Gazzaley, 2011; Gazzaley & Nobre, 2011; Nobre & Stokes, 2011; Postle, 2006; Stokes & Nobre, 2011) in an attempt to shed light on the nature and flexibility of visual short-term memory (VSTM). Especially in the context of visual information, various processes have been proposed to play a role in this, including selective attention prior to encoding and during maintenance (e.g., Lepsien & Nobre, 2006), attentional refreshment (e.g., Raye, Johnson, Mitchell, Greene, & Johnson, 2007), and spatial rehearsal (e.g., Awh & Jonides, 2001). One major shortcoming though of this new line of research is that it has focused nearly exclusively on these interactions in adults, leaving the developmental changes in these mechanisms largely unexplored.

Understanding the relation between selective attention and visual short-term memory (VSTM) / visual working memory (VWM) from early childhood has important theoretical and practical implications. On one hand, developmental studies can provide insights into how adults reach the adult end-state and can resolve controversies that exist in the adult literature. For example, it can demonstrate whether two seemingly similar cognitive processes in adulthood are developmentally and functionally dissociated, by tracing their developmental trajectories, thereby demonstrating that they emerge at different time points in the lifespan and exhibit different maturation rates (Baddeley & Hitch, 2000; Hitch & Halliday, 1983; Hitch,

1990). On the other hand, both processes are heavily involved in early learning and academic achievement (e.g., Amso & Johnson, 2006; Bull & Scerif, 2001; Cowan et al., 2005; Hitch, Towse, & Hutton, 2001; St Clair-Thompson & Gathercole, 2006; Stevens & Bavelier, 2012), are correlated with intelligence (e.g., Conway, Kane, & Engle, 2003), and can contribute to our knowledge about neurodevelopmental disorders that share deficits in attentional control and WM (Barkley, 2006; Cockcroft, 2011; Cornish, Cole, Longhi, Karmiloff-Smith, & Scerif, in press; Gathercole et al., 2008) and allow the development of more efficient treatments.

This thesis aims to provide a systematic examination of the interplay between visuo-spatial selective attention (location-based selection in all instances, "attentional orienting" henceforth) and VSTM / VWM by examining individuals from early childhood to young adulthood. The focus is primarily on the effects of attentional orienting on VSTM. However, throughout the thesis, related cognitive processes such as interference, decay, rehearsal, and dual coding are also discussed. I begin the thesis by broadly reviewing recent evidence demonstrating the interaction between selective attention and VSTM / VWM in adults and to a lesser extent in children. Subsequently, I present a number of experiments that I carried out to investigate in depth the changes in the mechanisms underlying the interactions between attentional orienting and VSTM / VWM across development whilst also considering additional non-attentional processes that may also be relevant.

1. *Interactions between selective attention and STM / WM: Review of empirical evidence in adults*

1.1. Models of selective attention in adults

During the course of everyday life a vast amount of information from current sensory input and from memory competes for representation. The balanced and successful execution of the task at hand requires focusing on what is most relevant based on current goals and expectations. This is achieved via *selective attention*, a set of heterogeneous processes that regulate and direct behaviour by selecting and focusing on a fraction of the competing external and internal stimuli while inhibiting the irrelevant and/or distracting stimuli. Selective attention is therefore vital for protecting the brain from being overloaded with information (Ridderinkhof & van der Stelt, 2000). According to the biased-competition model, attention biases some visual stimuli over others through a distributed fronto-parietal neural network and stimuli that win the competition for representation will be encoded and stored in memory for later retrieval and control of action (Desimone, 1998; Desimone & Duncan, 1995; Duncan, 1998).

Selective attention has been investigated extensively using the Posner cueing paradigm (also known as the "spatial cueing" paradigm), in which participants must typically detect, discriminate, or locate a target preceded by a spatial cue. The seminal work of Posner and colleagues (Posner, Snyder, & Davidson, 1980; Posner, 1980; Posner & Cohen, 1984), which formulated one of the most influential models of attention, demonstrated that guiding attention to spatial locations before target presentation with the use of attention cues can bias further processing to benefit participants' perceptual discriminations and decisions. In this context, deployment of

selective attention can be achieved via *orienting mechanisms*, that is, by means of focal shifts to spatial locations that dynamically bias and enhance the processing of the selected information. Following Posner's work, a great number of behavioural studies with adults (Hawkins et al., 1990; Hommel, Pratt, Colzato, & Godijn, 2001; Luck, Hillyard, Mouloua, & Hawkins, 1996; Pratt, Radulescu, Guo, & Hommel, 2010; Prinzmetal, McCool, & Park, 2005; Ristic, Friesen, & Kingstone, 2002; Tipples, 2002; Van der Stigchel & Theeuwes, 2007; Yantis & Jonides, 1990) provided further support that attentional orienting can modulate processing of incoming stimuli in favour of those appearing at cued locations. The neural bases of these biases are well understood in adults (Baluch & Itti, 2011; Capotosto, Babiloni, Romani, & Corbetta, 2009; Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Corbetta, Miezin, Shulman, & Petersen, 1993; Corbetta & Shulman, 2002; Desimone & Duncan, 1995; Hopfinger, Buonocore, & Mangun, 2000; Kanwisher & Wojciulik, 2000; Kastner & Ungerleider, 2000, 2001; Lauritzen, D'Esposito, Heeger, & Silver, 2009; Luck, Woodman, & Vogel, 2000; Morgan, Hansen, & Hillyard, 1996; Posner & Petersen, 1990; Posner & Rothbart, 2007).

1.2. Models of STM / WM in adults

VSTM / VWM is another important process for human cognition, as it is responsible for temporarily keeping active in mind the information that is most relevant to our on-going behaviour. VSTM capacity is thought to be limited (Cowan, 2001, 2010; Luck & Vogel, 1997; Todd & Marois, 2004) and internal representations held in memory are subject to interference from other concurrently or subsequently presented material (Awh & Jonides, 1998; Baddeley & Logie, 1999; Broadbent & Broadbent, 1981). Given that a central role of attention is to select the information

that is task-relevant and inhibit the rest, theoretical models of short- and working-memory[1] (STM / WM) stipulate that attention controls the encoding of information into STM and its manipulation during maintenance in the form of executive processes (Baddeley, 2002a, 2003; Baddeley & Hitch, 1974; Cowan, 1999, 2005; Engle, Tuholski, Laughlin, & Conway, 1999; Kane, Bleckley, Conway, & Engle, 2001; Kane et al., 2004).

In this parallel and equally vast literature, the two most influential models of working memory (WM) to date, proposed by Baddeley and Hitch (1974) and Cowan (1999) suggest distinct WM architectures but both include an attentional component. According to Baddeley and colleagues (Baddeley & Hitch, 1974; Baddeley & Logie, 1999), WM involves four components: a domain-general system, known as the *central executive*, an attentional system that regulates and acts upon the other components; two domain-specific slave systems, the *phonological loop* and the *visuo-spatial sketchpad*, that are specialised for the short-term storage of phonological and visual/spatial information respectively; and the *episodic buffer* (Baddeley, 2000), a temporary storage system that is responsible for binding information originating from the two slave-systems and integrating them into chunks (Allen, Baddeley, & Hitch, 2006; Baddeley, Allen, & Hitch, 2011), and for allowing the slave systems to interact with long-term memory (LTM) and the central executive. Although the central executive is thought to be of highly limited capacity, it is a critical component as it has a supervisory function and is responsible for co-ordinating the flow of information between the slave systems and their

[1] It should be noted that these two terms have been used interchangeably in the literature. For consistency, I use the term short-term memory (STM) to refer to the capacity of individuals to maintain a small amount of information in mind for a short-term period. I use the term working memory (WM) to refer to the capacity of individuals to maintain a small amount of information in mind while processing other information at the same time that are required for the execution of a task.

communication with LTM via the episodic buffer. It is also responsible for implementing a number of executive functions operating on the information stored in the slave systems such as attentional control (i.e., selecting the incoming information), attentional focusing, attention switching, dual-task performance, and selecting and manipulating information in LTM (Baddeley, 2002a, 2002b, 2003; Baddeley & Hitch, 1974; Baddeley, 1998). Yet, its precise nature remains somewhat elusive as the executive processes involved remain highly intercorrelated, although separable (Miyake et al., 2000), and the model does not offer a precise account of how these separable executive processes interact with the domain-specific slave systems responsible for storage.

Cowan (1988, 2005, 2011), on the other hand, considers WM as an embedded-process within LTM rather than a separate system. He proposes that WM represents a subset of LTM representations, such as physical and semantic item features and current thoughts, which are in an active state at any given instance. According to Cowan, a further subset of these active WM representations is considered to be in the *focus of attention*. Active representations are unlimited in number but are limited temporally as they are prone to decay and interference, whereas representations within the focus of attention are capacity limited to 3-5 chunks (Cowan, 1999, 2001) but are immune to decay and interference. In this unitary model of WM, the focus of attention refers broadly to processes involved in the active maintenance of stored representations in a limited capacity memory system rather than to the control of information flow as it is the case for central executive. Moreover, the focus of attention is assumed to be controlled both by voluntary and involuntary attentional processes. Oberauer (2002) extended Cowan's model by

claiming that only a single item can reside within the focus of attention at any given moment (Oberauer & Bialkova, 2009; McElree, 2001, 2006 but see Gilchrist & Cowan, 2011).

While both models by Baddeley and Cowan offer theoretical descriptions of a WM architecture (multicomponent vs. unitary respectively) and in part of the role of attention in WM, each one exhibits limitations in providing mechanistic accounts of how the basic mechanisms of attention in function of WM are implemented in the context of encoding and maintenance. For example, the *multicomponent model* does not detail precisely the encoding processes involved in WM, presumably because these operate on perceptual representations that fall within a different cognitive domain than memory. Nevertheless, it has explained the maintenance processes involved in STM by showing evidence of a verbal rehearsal mechanism maintaining the information stored in the phonological loop and an inner scribe mechanism maintaining the information in the visuo-spatial sketchpad (Logie, 2011; Logie, 1995, 2003). In contrast, the *unitary model* has explained encoding in the context of activated features in LTM, yet it has not tackled directly the mechanism(s) involved in actively maintaining the items in the focus of attention. Cowan (1992) proposed a memory scanning process of the items stored in STM that potentially keeps them in the focus of attention, however this process was studied only for verbal and sequentially presented material, leaving unclear the maintenance mechanism responsible for visual and/or simultaneously presented material. It is essential for a model of WM to be able to account precisely for how domain-general processes such as selective attention interact with domain-specific systems such as storage capacity for both verbal and visuo-spatial material and at different stages within the

information processing stream, i.e., prior to encoding and during maintenance. Recent studies (see following sections) demonstrate that by understanding the commonalities and differences across the domains of attention and STM / WM, we can enrich our knowledge about their relation.

1.3. Interactions between selective attention and VSTM: experimental paradigms in adults

The majority of studies in the attentional orienting literature focus on investigating how visual attention biases the processing of external stimuli in a limited capacity perceptual system. Our everyday activities nonetheless rely as much on the selection of external stimuli as on our ability to operate on internal representations. Hence, it is crucial to understand how we manipulate information held in VSTM to optimize our performance. A direct comparison of attentional processes operating on externally- vs. internally-focused representations provides a fruitful organising taxonomy because paradigms used to investigate externally-focused attention can drive hypotheses on how representations are held in VSTM and vice versa (Chun, Golomb, & Turk-Browne, 2011). One of the early experiments that used cues to guide attention to internal representations was the classic iconic memory experiment conducted by Sperling (1960). In this experiment, Sperling presented participants with a brief (50ms) visual array of three rows, each one including four letters, and asked them to remember the letters for later recall. In some trials, immediately after the array, he provided participants with a "tone" cue which indicated which of the three rows to report ("partial-report" condition). He found that participants performed better in this "partial-report" condition than in the "whole-report" condition in which they were required to recall all letters. Based on this

finding, he proposed that representations remain accessible shortly after stimulus offset. Averbach and Coriell (1961) extended Sperling's result with visual cues (i.e., a vertical bar near one of the letters). These seminal experiments set the basis for studying and establishing attentional biases within memory in more recent studies with adults.

Griffin and Nobre (2003) built on Sperling's and Posner's ("spatial cueing") paradigms to examine whether spatial cues also bias representations held in VSTM according to current task-goals and if so, whether these cues act similarly to cues biasing the encoding of perceptual representations into VSTM. To achieve this, they presented adult participants with visuo-spatial cues that either guided their attention retrospectively to locations of items held internally in VSTM ("retro-cues") or oriented their attention to locations of perceptual items in advance of their encoding into VSTM ("pre-cues"). Findings showed that, in addition to benefiting from pre-cues, adults' memory improved as much following retro-cues, demonstrating thus that internal representations can be flexibly modulated by visuo-spatial cues presented during maintenance even as late as four seconds from stimulus offset. Furthermore, hemodynamic and electrophysiological studies illustrated that overlapping brain circuits (Nobre et al., 2004) and similar patterns of neural dynamics (Griffin & Nobre, 2003) characterise orienting in preparation for encoding and orienting during VSTM maintenance, although additional involvement of frontal areas and potentials were present when orienting attention towards internal representations (Griffin & Nobre, 2003; Nobre et al., 2004). These and other studies (Kuo, Stokes, & Nobre, 2011; Landman, Spekreijse, & Lamme, 2003; Lepsien, Griffin, Devlin, & Nobre, 2005; Lepsien & Nobre, 2006, 2007; Lepsien, Thornton, &

Nobre, 2011; Makovski & Jiang, 2007; Makovski, Sussman, & Jiang, 2008; Matsukura & Hollingworth, 2011; Matsukura, Luck, & Vecera, 2007; Nobre, Griffin, & Rao, 2008; Ruff, Kristjánsson, & Driver, 2007; Schmidt, Vogel, Woodman, & Luck, 2002; Sligte, Scholte, & Lamme, 2008, 2009; Vandenbroucke, Sligte, & Lamme, 2011; Woodman, Vecera, & Luck, 2003) collectively suggested that representations held in VSTM are flexible and attentional orienting in adults optimises encoding and maintenance in iconic- and VSTM both at the behavioural and neural level.

1.4. Mechanisms mediating the interactions between selective attention and VSTM / VWM

While the above studies established that attention cues bias VSTM representations, it remains to be understood how exactly orienting of attention modulates information processing in service of memory to enhance VSTM performance. Such knowledge would reveal the precise mechanisms via which deployment of attention facilitates the maintenance of items in VSTM. At an early stage in the memory stream, attentional orienting prioritises selected items over others for encoding into VSTM / VWM (Schmidt et al., 2002). At a later stage, it has been proposed that attentional orienting during maintenance enhances the active maintenance of relevant items and/or suppresses the activation of irrelevant items (Lepsien & Nobre, 2006, 2007), protects the representation of the selected item from decay or interference during the retention interval (Makovski & Jiang, 2007; Makovski et al., 2008; Matsukura et al., 2007), and/or provides direct retrieval routes to items in memory by prioritizing the comparison process of the selected item with the probe (Astle, Summerfield, Griffin, & Nobre, 2011). Despite these possible

accounts, there is no consensus in the adult literature on how exactly cues during maintenance operate on VSTM representations.

One possibility is that orienting of attention during maintenance functions as a simple process of visual imagery. Raye and colleagues have shown that *refreshing* a just activated representation (i.e., briefly thinking about an item that was just presented) resuscitates, increases, or prolongs its representation during maintenance (Raye et al., 2007; Raye, Johnson, Mitchell, Reeder, & Greene, 2002; Roth, Johnson, Raye, & Constable, 2009). In the context of visual competition within VSTM, *refreshment* could simply refer to selectively thinking back to (or visualising) a single item amongst competing mnemonic stimuli which boosts its representation against the others. Yi, Turk-Browne, Chun, and Johnson (2008) found that such a process modulates perceptual encoding into VSTM. In their experiment, they presented participants with pairs of scene frames and asked them to make a speeded category judgment on the second frame while measuring hemodynamic repetition attenuation activity in the visual cortex, a neural index of memory. The first frame was always followed by a second frame which came from one of three conditions: a "repeat" condition during which the same scene frame appeared again, a "refresh" condition during which an empty frame appeared and therefore an accurate judgment required the participant to think back to the first frame, and a "skip" condition during which a new scene frame appeared and therefore the participant neglected the first frame. Results showed that the repetition attenuation activity was equal in the repeat and refresh conditions and greater than the attenuation activity observed during the skip condition, thus demonstrating that *refreshment* functioned in the same way as perceptually encoding the information twice.

Other “attention-based” processes such as spatial rehearsal have been suggested to mediate VSTM (Awh & Jonides, 2001; Awh & Jonides, 1998) and could potentially explain how cues act to bias representations held in VSTM. Awh and colleagues (Awh, Jonides, & Reuter-Lorenz, 1998) carried out a series of dual-task experiments during which they asked participants to first memorize a stimulus presented in one of 108 possible locations on a screen, and then respond whether a probe, presented after a variable retention interval, occupied the same location as the initial stimulus (50% matching probability). During the retention interval participants were required to carry out a secondary speeded task that on some trials (25% matching probability) shifted their attention to the location of the initial stimulus. In the first experiment participants were asked to memorise the location of the initial stimulus whereas in the second experiment they were asked to memorise its identity. Awh et al. hypothesized that if spatial allocation of attention towards memorised locations occurs in a similar fashion to spatial allocation reported in perceptual tasks (e.g., Posner, 1980) then a memorised location enhancement should be observed. Also, if memory enhancement is not the result of stimulus- or strategy- driven orienting, then it should be observed in the first experiment but not in the second. Indeed, participants discriminated probe location faster when it matched the memorised location but only when they were explicitly asked to memorize its location. No enhancement was found when participants memorized the identity of the stimulus. To further support their argument that spatial attention has a functional role in spatial WM, in a third experiment using a similar paradigm Awh et al. introduced a secondary interference task during the retention interval whose successful execution required a discrimination decision. This secondary interference

task contained two conditions: a “shifting-attention” condition and a “static-attention” condition. In the “shifting-attention” condition, Awh et al. prevented participants from shifting their attention to the memorised locations by requiring them to shift their attention to non-memorised locations in order to make an accurate discrimination judgment. They then compared performance to that of the “static-attention” condition which required no attentional shifts. As predicted, participants’ probe accuracy for the memorised locations was significantly decreased when they shifted their attention away from the memorised locations compared to the static-attention condition. This result demonstrated the functional significance of attentional orienting in the active maintenance of spatial locations in VWM. Based on their findings, Awh et al. argued that spatial attention acts as a rehearsal process during the retention interval of spatial WM similarly to how verbal rehearsal acts during the maintenance of verbal information in WM. Further neuroimaging results supported their claims of a spatial rehearsal process during VWM by demonstrating enhanced neural and electrophysiological activity in visual areas contralateral to the memorized locations as well as in IPS and superior parietal lobule areas (Awh, Anllo-Vento, & Hillyard, 2000; Awh et al., 1999; Postle, Awh, Jonides, Smith, & D’Esposito, 2004). Other studies have shown that these areas are also activated during pure spatial attention tasks (e.g., Corbetta, Miezin, Shulman, & Petersen, 1993; Nobre et al., 1997). Overall, the great overlap in the fronto-parietal cortices and their functional connections to temporal and lower-level visual cortices (Awh & Jonides, 1998, 2001; Corbetta, Kincade, & Shulman, 2002; Ikkai & Curtis, 2011; Kelley & Lavie, 2011; Sergent, Ruff, Barbot, Driver, & Rees, 2011; Stokes, 2011) observed in attention and memory tasks requiring attentional orienting to

representations during VSTM maintenance (Lepsien et al., 2011; Nobre et al., 2004) and resistance to distractor interference during WM maintenance (Olesen, Macoveanu, Tegnér, & Klingberg, 2007), corroborates the tight links between the two cognitive domains.

Another possibility stemming from the study of Awh et al. (1998) is that attention is specifically involved in avoiding interference from irrelevant items presented during maintenance which share features with the to-be remembered items and therefore serves to protect internal representations during VSTM maintenance. In a series of experiments, Ueno and colleagues (Ueno, Allen, Baddeley, Hitch, & Saito, 2011) presented participants with a memory array of four items, each one in a different shape and colour, followed by a probe item displayed after a delay period, and asked them to indicate whether the probe was the same as one of the array items. During the delay period, participants saw either a blank screen ("no-suffix" condition) or a *suffix* (i.e., an item that sometimes shared similar features to the memory array, e.g., colour, shape, or both; "suffix" condition) that was to be ignored. Results showed that the suffix impaired probe recall in all instances demonstrating that interference for memory items can occur even when individuals do not engage in explicitly memorizing the interfering item. What could this result mean then in terms of how attention acts to enhance VSTM? As Ueno et al. proposed, there should be a filtering process that prohibits interfering and/or irrelevant items from entering VSTM and disrupting the maintenance of the representations held in VSTM (see also Ueno, Mate, Allen, Hitch, & Baddeley, 2011 for further investigation of this issue). Indeed, interference is a process that has been studied extensively recently with regards to how it can affect the maintenance of the to-be-remembered items

(Oberauer, 2009; Oberauer, Farrell, Jarrold, Pasiecznik, & Greaves, 2012; Oberauer & Lewandowsky, 2008) and relates to the on-going debate as to whether forgetting is caused from representation interference or memory decay (Barrouillet & Camos, 2009; Barrouillet, Portrat, Vergauwe, Diependaele, & Camos, 2011; Cowan & Aubuchon, 2008; Lewandowsky et al., 2004; Lewandowsky, Geiger, Morrell, & Oberauer, 2010; Lewandowsky & Oberauer, 2009; Lewandowsky, Oberauer, & Brown, 2009; Portrat, Barrouillet, & Camos, 2008). Opponents of the interference-based account propose that concurrent processing disrupts the maintenance of the memoranda which in turn hinders the formation of stable internal representations and the longer this processing activity is the poorer the memory performance is (Barrouillet et al., 2004; Barrouillet, De Paepe, & Langerock, 2012; Portrat et al., 2008; Towse et al., 2000; Vergauwe, Barrouillet, & Camos, 2009) arguing in favour of a decay-based hypothesis.

1.5. Additional factors mediating the interactions between attention and VSTM / VWM

The studies discussed above demonstrated a functional role of selective attention in VSTM / VWM. However, the relation between the two processes is not unidirectional as evidence also indicates biased attentional allocation from the VWM content (Astle, Nobre, & Scerif, 2010; Downing, 2000; Kim, Kim, & Chun, 2010; Kumar, Soto, & Humphreys, 2009; Olivers, Meijer, & Theeuwes, 2006; Soto, Heinke, Humphreys, & Blanco, 2005; Soto, Hodsoll, Rotshtein, & Humphreys, 2008; Woodman, Luck, & Schall, 2007). Thus, the nature of VSTM capacity seems to be modulated by other factors relating to the nature of the stimuli, in addition to attention. Alvarez and Cavanagh (2004) demonstrated that manipulating the

characteristics of the memoranda (e.g., by increasing the *visual information load* and thus making the objects more difficult to remember) affected VSTM capacity corroborating that the nature of VSTM is flexible to some extent and visual storage capacity fluctuates depending on the memoranda. In more detail, they tested participants' VSTM with a change-detection task (e.g., Luck & Vogel, 1997) that involved objects from five different classes of information load: Snodgrass line drawings (Snodgrass & Vanderwart, 1980), shaded cubes, random polygons, Chinese characters, letters, and coloured squares. Results showed that participants' capacity ranged from 1.6 for shaded cubes to 4.4 for coloured squares, with the remaining classes falling somewhere within this range. Importantly, Alvarez and Cavanagh found a negative linear relationship between capacity and information load, with increasing information load per object (i.e., difficulty to remember the object) associated with decrease of the total number of objects that could be maintained in VSTM. However, in another study Eng, Chen, and Jiang (2005) used classes of objects with similar perceptual difficulty to those used by Alvarez and Cavanagh (2004) but manipulated the array duration to examine whether poor memory performance is due to encoding limitations rather than capacity limitations per se. Similar to previous results, they found that object difficulty predicted VSTM capacity. Critically though, the variance in memory performance was better explained by shorter array durations, indicating that in addition to capacity limits and object difficulty, additional processes affecting encoding may constrain VSTM capacity. Taken together, these findings demonstrate that the relation between attentional processes and VSTM / VWM capacity is bi-directional and perhaps

examining the changing interactions of the two can provide further insight to their intertwined mechanisms.

1.6. Further insights on the links between selective attention and VSTM from individual differences and aging studies

In conclusion, different accounts – which are not mutually exclusive – have been proposed to explain how attention may operate on VSTM in adults. Altogether, the empirical evidence corroborates that the efficiency of attentional control constrains how adults maximise the use of their limited VSTM capacity (Awh & Vogel, 2008; Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003; Clapp, Rubens, & Gazzaley, 2010; Cowan & Morey, 2006; Fukuda & Vogel, 2009, 2011; Kane et al., 2001; Kane & Engle, 2003; Linke, Vicente-Grabovetsky, Mitchell, & Cusack, 2011; Machizawa & Driver, 2011; McNab & Klingberg, 2008; Palva, Monto, Kulashekhar, & Palva, 2010; Redick, Calvo, Gay, & Engle, 2011; Rutman, Clapp, Chadick, & Gazzaley, 2010; Vogel & Machizawa, 2004; Vogel, McCollough, & Machizawa, 2005; Zanto & Gazzaley, 2009) and begins to explain how adults typically cope with success in our complex environment. Still, it remains unclear whether changes in attentional control play a similar role in the development of VSTM and VWM.

Aging studies indicate that the tight links between selective attention and VSTM / VWM observed in adults persist later in life with the older adults exhibiting more difficulties in *using predictive cues* to guide attention (Bollinger, Rubens, Masangkay, Kalkstein, & Gazzaley, 2011), in *refreshing* a just-presented item (Johnson, Mitchell, Raye, & Greene, 2004; Johnson, Reeder, Raye, & Mitchell, 2002; Raye, Mitchell, Reeder, Greene, & Johnson, 2008), and in *suppressing*

irrelevant information (Gazzaley et al., 2008; Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Jost, Bryck, Vogel, & Mayr, 2011). These, in turn, result in VSTM impairments and overall poor VWM performance in old compared to young adults. Aging findings highlight even more the need to trace the relation between selective attention and VSTM from earlier in life because children's STM capacity is more limited compared to adults (see next section for a review) and, based on the aging deficits findings, this may depend at least in part on developmental changes in attentional control.

2. Interactions between selective attention and STM / WM: Review of empirical evidence in children

2.1. Development of STM capacity

While scientists have begun to untangle the role of selective attention in VSTM within the adult population, developmental studies have primarily focused on studying the development of attention and STM in isolation, and not on their possible interactions, such as how VSTM may be modulated by attention. Therefore, it remains unclear whether changes in attentional control play a similar role in the development of VSTM and VWM. Children's STM capacity increases dramatically between 3 to 12 years (Gathercole, Pickering, Ambridge, & Wearing, 2004; Gathercole, 1998, 1999); however, what drives these changes is better understood for the verbal than for the visual domain (Cowan, Nugent, Elliott, Ponomarev, & Saults, 1999; Cowan & Alloway, 2009; Logie & Pearson, 1997; Pickering, 2001). Changes in subvocal rehearsal (e.g., Gathercole, Adams, & Hitch, 1994; Hitch, Halliday, Dodd, & Littler, 1989), articulation speed (e.g., Hulme, Thomson, Muir, &

Lawrence, 1984), time-based decay (e.g., Barrouillet & Camos, 2001; Towse, Hitch, & Hutton, 1998), and a priori knowledge of the to-be-remembered items (e.g., Bjorklund, 1987; Gathercole, Frankish, Pickering, & Peaker, 1999) are only a few of the accounts proposed to explain changes in STM capacity over childhood. I return to these accounts in the individual experimental chapters. Here, I review evidence for the contribution of attention to VSTM / WM development in broad terms.

2.2. Models of selective attention and WM in childhood

Like STM, attentional control undergoes dramatic improvement during childhood (Enns, 1990; Johnson, 2011; Plude, Enns, & Brodeur, 1994; Scerif, 2010). The basic processes involved in selective attention are thought to be present early in life, although the efficiency in deploying attention voluntarily to selected information improves with age. A great number of behavioural studies using the Posner cueing paradigm with children as young as 6 years of age and adults showed that attentional orienting can modulate the processing of incoming stimuli in favour of those appearing at the cued locations in all age groups, although these biases are less pronounced in children compared to adults as indicated by their poorer accuracy and slower responses compared to adults (e.g., Akhtar & Enns, 1989; Brodeur & Boden, 2000; Brodeur & Enns, 1997; Enns & Brodeur, 1989; Goldberg, Maurer, & Lewis, 2001; Iarocci, Enns, Randolph, & Burack, 2009; Ristic & Kingstone, 2006; Schul, Townsend, & Stiles, 2003; Wainwright & Bryson, 2002, 2005).

Given the adult findings reviewed in the earlier sections, it is possible that developmental changes in attentional control may constrain the developmental trajectory of STM. This assumption is also supported by the early proposal that top-down attentional control mediates both attentional orienting and STM / WM (Posner

& Raichle, 1994). Indeed, models of childhood memory development include a domain-general attentional controller, i.e., central executive (Baddeley & Hitch, 2000; Gathercole et al., 2004; Hitch & Halliday, 1983), although changes in the way in which the central executive modulates the slave systems over developmental time are difficult to map. Perhaps, this is due to the fact that the central executive in the WM model of Baddeley and colleagues contains correlated but distinct processes (e.g., selective allocation of attention to goal-specific information, inhibition of irrelevant information, and communication with the episodic buffer which binds the features originating from the domain-specific systems) whose impact on the domain-specific systems may follow different developmental trajectories. Likewise, findings show that the domain-specific slave systems become efficient at different time-points in development and therefore differ in the extent to which they make demands on this domain-general attentional system at different age periods (Alloway, Gathercole, & Pickering, 2006). These findings are in agreement with the *developmental fractionation* account according to which different cognitive processes follow different maturation rates (Hitch, 1990).

Similarly, in terms of the second leading model of WM reviewed earlier, Cowan's model, it is not clear whether better memory performance across age groups can be accounted for solely on the basis of capacity changes in the focus of attention. A number of recent child studies using a modified adult change-detection task (Cowan et al., 2005; Riggs, McTaggart, Simpson, & Freeman, 2006; Riggs, Simpson, & Potts, 2011; Simmering, 2012), which is considered a conventional measure of VSTM capacity in the adult literature (Luck & Vogel, 1997), replicated previous findings demonstrating a steady development in VSTM capacity which was

measured with traditional span tasks (e.g., Gathercole et al., 2004; Luna, Garver, Urban, Lazar, & Sweeney, 2004). However, these studies provided no insights about the potential role of selective attention on VSTM in childhood. For example, Cowan and colleagues (2005) presented 7-, 8-, 9-, 10-, 11- and 12-year-olds and young adults with an array of coloured squares that varied in load size (4, 6, 8, or 10 items) for 250ms, followed by a test array that sometimes differed in the colour of one of the squares. Results showed a linear increase in capacity with age, ranging from approximately 3 items for 7- and 8-year-olds, to 4 items for 9-, 10-, 11-, and 12-year-olds, and 5 items for young adults, demonstrating that children can store fewer items in VSTM than adults. Yet, this study did not examine whether adults' performance is characterized by more efficient attentional processes of certain kinds compared to children, and therefore it was difficult to understand precisely which processes could explain adults' superior capacity. Children may be able to encode the same number of items in VSTM with adults but fail to maintain them, leading to more fragile internal representations being available at the time the test array appears.

2.3. Selective attention as a candidate factor for explaining developmental differences in VSTM

Given that VSTM capacity is strictly limited, attentional filtering has been found to play a critical role in adults (Vogel et al., 2005) and the ability to selectively allocate attention to a portion of the presented items and inhibit the irrelevant items is refined with age, at least in service of perception (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Durston et al., 2002; Enns, Brodeur, & Trick, 1998). As demonstrated in the adult literature, adopting attentional strategies such as recruiting top-down attentional mechanisms prior to encoding of information into VSTM and

during maintenance improves memory performance (e.g., Awh & Jonides, 1998; Griffin & Nobre, 2003), whereas memory recall suffers under attentional disruption (e.g., Awh et al., 1998; Ueno, Allen, et al., 2011). Therefore, it is possible that the poorer VSTM performance of children compared to adults is not solely due to the more limited storage capacity in childhood but is perhaps due to adults' better information encoding and maintenance by recruiting their superior attentional skills to perform the tasks.

It has already been shown that the ability to "refresh" items in visual memory relates to poor VSTM / VWM performance in old compared to young adults (Johnson et al., 2002; Raye et al., 2002, 2008), however these processes have rarely been investigated in children, and when they have, they have been explored in the verbal rather than in the visual domain (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; Tam, Jarrold, Baddeley, & Sabatos-DeVito, 2010). For example, Tam and colleagues (Tam et al., 2010) assessed whether nonverbal attentional refreshment mechanisms support maintenance in 6- and 8-year-olds by asking them to perform verbal memory tasks while engaging in verbal and visuo-spatial processing. Performance was poorer under both concurrent processing requirements compared to a baseline task, suggesting that both overt phonological rehearsal and attentional refreshment play a role in memory maintenance (similar attentional refreshment mechanisms have been proposed to influence verbal WM in childhood by Barrouillet et al., 2009 and are discussed in more detail in Chapter 4). However, Tam et al. employed verbal tasks analogous to the traditional span tasks and therefore the potential involvement of attentional refreshment in VSTM maintenance across childhood remains largely unexplored.

Recent empirical evidence points to attentional factors playing a role in the development of VSTM capacity. For example, Cowan, Morey, AuBuchon, Zwilling, and Gilchrist (2010) asked 7-year-old children, 12-year-old children, and adults to perform a simple change-detection task under differing attentional conditions. Attention was directed non-spatially by asking participants to focus on distinct coloured items of a particular shape within an upcoming to-be-remembered array of variable load sizes and ignore the coloured items of the other shape [e.g., in every trial participants saw an array of 4 items each presented in a different colour (2 circles and 2 triangles) or an array of 6 items, each one in a different colour (3 circles and 3 triangles), and they were required to remember only those 2 or 3 coloured items of a particular shape]. After a delay, a single probe item appeared in one of the previously occupied locations and participants had to judge whether the probe was presented in the same colour as the item that previously occupied that location. The probe always had the same shape as the item presented at that location but sometimes its colour changed to a completely new colour, to the colour of another attended item that occupied a different location, or to the colour of an ignored item. The probability of the probe being present in the attended or ignored items varied across block-conditions resulting in four different attentional conditions: In the "1-shape" condition, all items had the same shape, therefore no attentional filtering was needed. This condition served as the baseline. In the "100%-0%" condition, half of the array items belonged to the attended-shape items and half to the ignored-shape items but the probe was always in the attended items, therefore attentional filtering was guaranteed to be the most successful strategy. In the "80%-20%" condition, half of the array items belonged to the attended items and half to the ignored items but the

probe was in the attended items 80% of the trials and in the ignored items in the remaining 20% of the trials. Finally, in the "50%-50%" condition, the probe was in the attended items 50% of the trials and participants were instructed to pay attention to all shape items. Cowan et al. (2010) showed that while 7-year-olds had overall poorer capacity compared to 12-year-olds and adults, the pattern of performance across the attentional conditions differed depending on the load size of the array: in small arrays in which participants had to attend a subset of two items, age groups did not differ in how they dealt with ignored changes. In contrast, in large arrays in which participants had to attend a subset of three items, 7-year-olds differed from 12-year-olds and adults in their ability to detect changes in the attended items and filter out the changes in the unattended subset, suggesting that both basic limitations in storage capacity and attentional abilities influence developmental differences in VSTM capacity.

In order to better understand the underlying increase in storage capacity with regards to encoding, Cowan, AuBuchon, Gilchrist, Ricker, and Saults (2011) carried out a follow-up experiment in which the array items were presented sequentially for 1s each, instead of simultaneously, to allow for slow encoding. They also added an articulatory suppression condition to rule out the use of verbal strategies in the older age groups. The age-related differences in VSTM persisted, thus, the authors concluded that basic changes in the capacity to store items in memory, rather than encoding differences or attentional filtering, underpin developmental changes in VSTM capacity. Yet, the contribution of visuo-spatial biases to maintenance in VSTM could not be assessed because attention was always oriented to a non-spatial target dimension (shape) and prior to encoding the to-be-remembered items.

Indeed, studying visuo-spatial attentional orienting has provided a further point of convergence between attention and VSTM / VWM in adults, but their interaction has rarely been investigated within a developmental framework (Astle & Scerif, 2011; Scerif, 2010). Ross-Sheehy, Oakes, and Luck (2011) elegantly demonstrated how salient visuo-spatial (peripheral) attention cues facilitate the detection of a change in VSTM in infants as young as 5 and 10 months of age, but the two age groups differed in the type of attention cues they benefitted from. In two experiments, they tested infants with a change-detection task during which a sample array of 3 items was followed by a test array. In Experiment 1, the sample array was preceded by a peripheral cue that marked the location of one of the three squares that could change colour in the test array. In Experiment 2, one of the three squares that could later change colour rotated slowly during the sample and test arrays; this motion in an otherwise static background acted as an attention cue similar to Experiment 1. Results showed that for 10-month-olds, spatial cues benefited change detection when they were presented in advance of the sample array, with a procedure that resembles the one used in adults (e.g., Schmidt et al., 2002), whereas for 5-month-olds relative motion of the square to-be-changed benefited change-detection. These results bolster the idea that attentional orienting facilitates the encoding of information in VSTM from early in life and stress that change-detection failures are not accounted for exclusively by storage limitations. Rather, they establish that, when the attentional context is optimal for a specific age group, even very young infants are able to improve their limited VSTM capacity. However, the mechanisms through which spatial cues operate within VSTM in childhood are less well understood.

2.4. Interactions between selective attention and VSTM: an experimental paradigm in children

A recent behavioural study bridged the spatial attentional cueing and VSTM literatures in childhood by examining 7-year-olds', 10-year-olds' and adults' memory when centrally presented cues oriented attention prospectively or retrospectively to highly familiar and perceptually distinguishable items in memory (Astle, Nobre, & Scerif, 2012). Results showed that, despite poorer overall memory in children, all age groups benefited from the spatial cues. However, children benefited less when orienting occurred during maintenance than in preparation for encoding, whereas the opposite pattern held for adults, highlighting developmental changes in how attentional orienting influences VSTM maintenance. The developmental differences persisted even when taking into account overall baseline differences in memory, suggesting that children were less efficient in orienting attention to optimise maintenance compared to adults. Furthermore, children's variable cueing benefits during the maintenance period predicted span on traditional VSTM and VWM measures, pointing to how individual differences in visuo-spatial attentional control could contribute to VSTM capacity. However, for a number of reasons detailed in the following experimental chapters, the precise cognitive mechanisms through which these visuo-spatial attentional biases operate on VSTM remain to be investigated.

For example, the study by Astle et al. (2012) did not estimate storage capacity with the *K* measure to provide direct comparisons with recent developmental studies favouring an increase in storage capacity (Cowan et al., 2005; Riggs et al., 2006) and opposing the contribution of attentional filtering and differential encoding to

developmental changes in memory performance (Cowan et al., 2011, 2010). Furthermore, the extent to which these developmental differences depend on the nature of the orienting cues and whether their effects on VSTM maintenance are voluntary or automatic remain unexplored. The competition for representation in our limited visual system is biased by both top-down and bottom-up processes (Desimone & Duncan, 1995; Egeth & Yantis, 1997; Kastner & Ungerleider, 2000) and it is important to understand how these two processes influence encoding into- and maintenance within VSTM over development. Tam et al. (2010) already remarked on how children's attentional refreshment during verbal maintenance may be either controlled and voluntary or automatic in nature; this awaits investigation in the visual domain. Furthermore, Ross-Sheehy et al. (2011) employed peripheral cues that were equally likely to direct attention to the location of a change as to the other locations, suggesting that attentional benefits for VSTM encoding, at least in young infants, are automatic.

2.5. Neural overlap between selective attention and VSTM in childhood

Perhaps the answer to whether developmental changes in attentional control drive increases in VSTM storage capacity can be given by developmental cognitive neuroscience. Findings indicate that the fronto-parietal neural circuits supporting developmental changes in attentional control and VSTM / VWM overlap but have only been studied in isolation (Booth et al., 2004; Booth et al., 2003; Klingberg, Forssberg, & Westerberg, 2002a; Konrad et al., 2005; Kwon, Reiss, & Menon, 2002; Scherf, Sweeney, & Luna, 2006). Furthermore, specific brain regions such as the dorsolateral prefrontal cortex (DLPFC) and the IPS that are involved in encoding and maintenance processes in adults (Ranganath, DeGutis, & D'Esposito, 2004;

Ungerleider, Courtney, & Haxby, 1998), undergo a protracted development from childhood to adulthood (Bunge & Wright, 2007; Crone, Wendelken, Donohue, van Leijenhorst, & Bunge, 2006; Diamond, 2002; Jolles, Kleibeuker, Rombouts, & Crone, 2011) indicating that the development of these brain regions accompany improved behavioural performance in older compared to younger individuals. Unfortunately, the neural changes underlying improvements in the combined context of attentional control and VSTM across development have rarely been explored directly so far. In one study, Olesen et al. (2007) presented 13-year-olds and young adults with a VSTM task that on some trials contained distractors during maintenance while measuring hemodynamic brain activity. Participants were presented with 3 blue circles that were followed by a flashed line, after a pseudorandom delay, and which crossed the location previously occupied by one of the circles. Participants were required to click on the location where the line intersected the circle. Distractor trials involved the presentation of 3 yellow circles during the delay interval. As expected, children had poorer behavioural performance and suffered more than adults when faced with distractors. In addition, adults elicited greater activity in DLPFC, including the superior frontal sulcus and IPS compared to children during item maintenance, suggesting that this fronto-parietal network was recruited to create stable internal representations. However, during the distractor interval, children elicited brain activity in the superior frontal sulcus but adults did not, suggesting that, in contrast to adults, children may have maintained the irrelevant information in VSTM rather than the relevant information. These results provide evidence for greater maintenance difficulties in childhood than in adulthood.

Wendelken, Baym, Gazzaley, and Bunge (2011) provided further neural evidence that selective attention biases maintenance in VSTM. In their study, 8-13 year-olds and young adults saw 2 images of faces and 2 images of scenes that were alternated pseudorandomly and depending on the condition they were instructed to either remember the faces and ignore the scenes ("face" condition), remember the scenes and ignore the faces ("scene" condition), or passively view all images ("passive" condition). After a 3s delay interval, a probe image appeared and participants had to respond whether the probe was one of the previously presented images. In the face condition the probe was always a face image, in the scene condition the probe was always a scene image, and in the passive condition the probe was an arrow for which participants had to indicate its pointing direction (i.e., left or right). Results showed that attention to scenes elicited increased activity in parahippocampal area (PPA) and the magnitude of this attentional modulation increased with age and reached a plateau at 14 years of age. In addition, during this condition and within the child-group, DLPFC activity was highly correlated with age with older children eliciting stronger DLPFC activity compared to younger children. These findings corroborate the suggestion that refined attentional control biases the maintenance of information in VSTM and results in better memory performance, potentially explaining storage limitations in childhood compared to adulthood. Following these findings, the need to understand more precisely how cognitive and neural changes in attentional processes contribute to age-related changes in VSTM is further increased.

3. Objectives of the DPhil thesis

The succesfull recall of information from memory depends on three different stages, i.e., encoding, storage, and retrieval with additional maintenance processes taking place between them; constraints in any of these stages may result in limitations of children's memory. So far, adult studies alone have failed to locate the precise stage and/or processes whose constraints can explain VSTM limitations, yet they have enriched our knowledge with a number of possible accounts that developmentalists can draw on. By relying on the adult framework to study the attentional constraints on VSTM in childhood, developmental findings can in turn inform the adult literature by pinpointing differential development and/or constraints for the seemingly similar VSTM encoding and maintenance stages in adults (e.g., Griffin & Nobre, 2003). Hence, it seems beneficial to examine these memory stages across development in a way that would allow on one hand for direct comparisons among them (e.g., encoding vs. maintenance) and that would help on the other hand identify the distinct processes – if any – that mediate them and enhance or impact upon recall (e.g., different attention-based processes, memory load, temporal decay, characteristics of the memoranda etc). To do so, one needs to employ similar tasks across the age groups; unfortunately, the adult and child literatures have been progressing independently so far (Astle & Scerif, 2011). Child studies are still employing traditional WM and STM span tasks to study capacity development (Chuah & Maybery, 1999; Gaillard, Barrouillet, Jarrold, & Camos, 2011; Gathercole & Pickering, 2000; Hamilton, Coates, & Heffernan, 2003; Logie & Pearson, 1997; Pickering, Gathercole, Hall, & Lloyd, 2001) and although these are informative about WM development per se, the specific contribution of the attentional and STM

processes on the performance being measured is unclear (i.e., is it due to changes in attention or memory capacity limitations per se or both?). This approach is not ideal for determining exactly how attentional control operates within VSTM in childhood. In contrast, adult studies have moved away from the traditional span tasks to employ modifications of the cueing paradigm (e.g., Griffin & Nobre, 2003; Nobre et al., 2004; Nobre et al., 2008) which allow for understanding the impact of attentional control on VSTM encoding and maintenance. A recent developmental study (Astle et al., 2012) has demonstrated that such a paradigm is promising for understanding the role of selective attention in VSTM over development.

In this context, a systematic investigation of the precise neurocognitive mechanisms through which visuo-spatial attentional biases operate on VSTM across ages, with an adaptation of the cueing paradigm to the child population, can offer remarkable new insights on the attentional contributions to encoding and maintenance. The current DPhil aims (1) to examine the cognitive mechanisms through which visuo-spatial attention operates within VSTM, (2) to investigate the relations between individual differences in visuo-spatial attention and VSTM and VWM capacity, and (3) to uncover the neural processes that support these mechanisms at different ages. These aims will be tackled by pursuing four overarching themes:

(1) The effects of distinct attentional orienting parameters on VSTM (Chapters 2 and 3).

(2) Factors mediating poor attentional orienting within VSTM by younger children (Chapters 4 and 5).

(3) The role played by the characteristics of the to-be-remembered items in VSTM (Chapter 6).

(4) The neural processes underlying changes in the relation between attentional orienting and VSTM (Chapter 7).

Chapter 2: Development of attentional orienting and VSTM I: The role of cue characteristics

While interacting with our information-rich environment, we are often called to shift our attention to task-relevant information by symbolic cues such as arrows. However, even more often our attention is abruptly captured by unanticipated peripheral stimuli. Many studies have been undertaken to investigate the neurocognitive mechanisms underlying orienting following symbolic cues and abrupt onsets (e.g., Corbetta & Shulman, 2002; Jonides, 1981; Posner, 1980; Prinzmetal, McCool, & Park, 2005; Rosen et al., 1999; Yantis & Johnston, 1990; Yantis & Jonides, 1990). The investigation of attentional mechanisms involved in orienting is typically based on a central dichotomy: *volitional*/*endogenous* for central cues (i.e., attention is intentionally moved by the person based on internal goals and expectations) vs. *reflexive/exogenous* for peripheral cues (i.e., attention is automatically captured by external stimuli). This distinction is often predicated on the fact that central, symbolic cues confer behavioural advantages when they are predictive of target location whereas peripheral cues lead to benefits independently of their predictive value, although fully unpredictive central cues and fully predictive peripheral cues are rarely studied over development, as argued by Ristic and Kingstone (2009). Here, I stray away from this distinction because manipulations of cue validity are not directly investigated in the current experiment (but see Experiment 2, Chapter 3).

Beyond this crucial volitional/reflexive axis, central and peripheral cues differ along multiple dimensions such as the locus of presentation relative to the

target location (direct overlap for peripheral cues vs. distal position for central cues) and the symbolic nature of central cues as opposed to the typically non-symbolic peripheral cues. Recent findings demonstrated that the spatial proximity of cues to the target location, in addition to the symbolic value of arrow cues, influences attentional orienting in adults (Leblanc & Jolicoeur, 2010; Pratt et al., 2010), raising the possibility that even for 7-year-olds cues presented peripherally may yield greater benefits than central cues. Also, symbolic cues must be cognitively interpreted to infer the target's location out of the simultaneously presented stimuli. Longer RTs for central than peripheral cues have qualified central cues as more capacity-demanding in processing than peripheral cues (as discussed in Iarocci et al., 2009; Jonides, 1981) suggesting that arrows may become overlearned symbols for adults compared to children.

When investigated in service of simple target detection or discrimination, attentional orienting effects stemming from central and peripheral spatial cues follow differential developmental trajectories (Brodeur & Boden, 2000; Brodeur & Enns, 1997; Brodeur, Trick, & Enns, 1997; Goldberg et al., 2001; Iarocci et al., 2009; Pearson & Lane, 1990; Ristic & Kingstone, 2009; Wainwright & Bryson, 2002). Peripheral cues consistently result in greater differences in the speed of detection and recognition for stimuli appearing at cued than uncued locations for children in the age range of 5 to 9 years old compared to adults (Akhtar & Enns, 1989; Brodeur et al., 1997; Enns & Brodeur, 1989), whereas results on developmental differences in the size of validity effects stemming from the central cues have been mixed (Goldberg et al., 2001; Pearson & Lane, 1990; Wainwright-Sharp, 1995; cited in Goldberg et al., 2001).

Although multiple studies have investigated developmental differences in central and peripheral cueing effects, the two effects have been generally examined in isolation, and only rarely have the effects of central and peripheral orienting been compared using the same experimental parameters across ages (e.g., Iarocci et al., 2009). Importantly, little is known about the effects of peripheral cues on later recall from VSTM (e.g., Berryhill, Richmond, Shay, & Olson, 2012 with adults only). In the context of memory, attention cues have mainly been studied during retrieval (e.g., Nelson & Goodmon, 2003; Theeuwes, Kramer, & Irwin, 2010; Tulving & Osler, 1968). However, attentional disruption is more detrimental to performance during encoding than during retrieval (Naveh-Benjamin, Craik, Gavrilescu, & Anderson, 2000). Therefore, it is important to understand how attention cues contribute to VSTM encoding and maintenance. A now established line of research with adults (reviewed in Lepsien & Nobre, 2006) has documented that attention cues presented both prior to encoding and during maintenance can bias VSTM to optimise performance, but further study is needed to understand how these processes change with age and more specifically whether they are differentially modulated by central and peripheral cues.

Experiment 1: Development of attentional orienting prior to encoding and during maintenance in VSTM and the nature of the cues

Despite the growing literature on mechanisms of attentional orienting in VSTM in adults (detailed in the General Introduction), the processes by which, over developmental time, adults eventually achieve attentional control of incoming and

maintained visual representations have been examined less extensively. In a recent behavioural study that combined the spatial attentional cueing and VSTM literatures in childhood by examining 7-year-olds', 10-year-olds' and adults' memory with a modified adult cueing paradigm (see Griffin & Nobre, 2003), Astle et al. (2012) revealed developmental differences in the benefits drawn from predominantly valid cues orienting spatial attention prior to encoding and while maintaining items to be later recalled from VSTM. However, it is not clear what drove these age-related differences in that study because large centrally presented cues may have conflated central and peripheral orienting effects, and variable cue validity may have influenced children and adults differentially. Therefore, a systematic investigation of the precise cognitive mechanisms through which visuo-spatial attentional biases operate on VSTM is needed. At least two mechanisms may be responsible: an increase in the efficiency to control and direct attention in service of memory over time or an improvement in the ability to interpret and follow central symbolic arrow cues. The two accounts cannot be differentiated on the basis of the findings of Astle et al. (2012) who only used centrally presented cues.

The aim of Experiment 1 was to tease the two interpretations apart by examining whether the physical characteristics of cues are responsible for developmental changes in attentional cueing benefits on memory performance. To investigate this, I used central and peripheral cues that fully predicted the spatial location of an item in memory to investigate the degree to which participants' encoding in VSTM and maintenance would benefit from these cues despite their physical differences. Such an experimental manipulation could distinguish among

alternative factors underpinning developmental changes in the ability to orient attention in VSTM.

First, based on the findings of Astle et al. (2012), I hypothesized that attention cues would benefit VSTM retrieval for all age groups, but I expected smaller benefits with attention cues presented during maintenance in children than in adults and compared to cues presented prior to encoding. Second, I hypothesized that, if these developmental differences in cueing benefits reflect children's improving attentional control rather than difficulties in interpreting or using central symbolic cues, then I should observe similar performance in central and peripheral cues within each age group. If, on the contrary, the specific characteristics of the cues drive the developmental differences during maintenance, then older participants should benefit from retro-cues to a greater degree than young children when the cues are centrally but not peripherally presented. Finally, I explored the extent to which attentional control as measured with a traditional attention orienting paradigm relates to memory capacity. I hypothesized that attentional cueing benefits during maintenance would relate to individual differences on well-validated and standardised measures of VSTM and VWM capacity that are commonly used to study these constructs in childhood (Astle et al., 2012).

Methods

Participants

Forty children (15 boys and 25 girls) between 6 and 8 years old (M=6.9 years old, SD=.62; "7-year-olds" henceforth), 40 children (17 boys and 23 girls) between 10 and 12 years old (M=10.8 years old, SD=.63; "11-year-olds" henceforth), and 36

adults (15 males and 21 females) between 18 and 34 (M=23.7 years old, SD=3.91; "adults" henceforth) participated in this experiment. Twenty children in each child group and 15 adults completed the central-cue task ("central-cue groups"); the remaining children and 21 adults completed the peripheral-cue task ("peripheral-cue groups"). Adults in the central-cue group were recruited from the University of Oxford whereas adults in the peripheral cue-group were recruited from the Experimental Psychology Lab (EPL) and the Department of Psychology at the University of Cyprus.

Measures

Attentional Orienting Task: The experimental task was developed with E-prime 1.2 (Psychological Software Tools, Pittsburgh, PA) to measure the visual orienting of attention and VSTM capacity. The task is presented schematically in Figure 1.

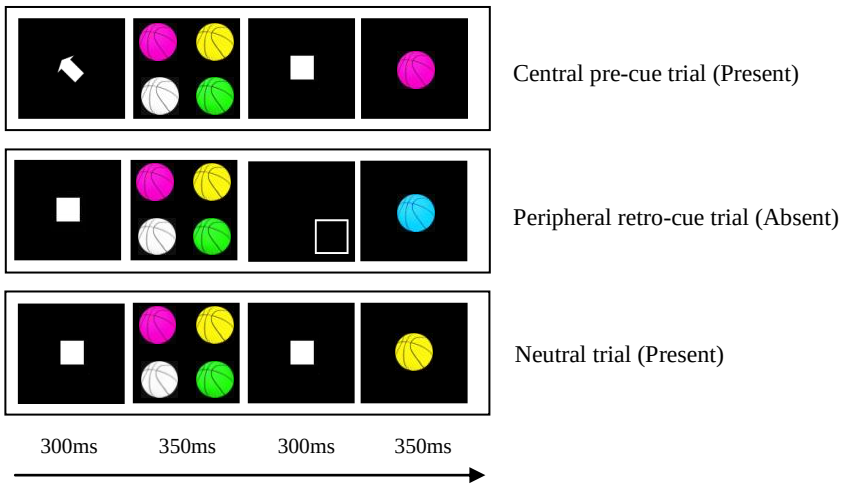


Figure 1. Schematic illustration of the central-cue and peripheral-cue tasks and the 3 trial-types. Items are magnified relative to the background for display purposes.

In each trial participants viewed briefly an array of four peripheral and uniquely coloured items ("memory array" henceforth), followed by a single central coloured probe item after a variable delay. Participants were instructed to indicate whether the coloured probe had been present in the preceding memory array by pressing the mouse buttons (left for present and right for absent). Memory array items were identical line drawings of objects or cartoons (e.g., balls), drawn from a set of seven colours (blue, green, yellow, orange, magenta, red, and white), and were symmetrically arranged, each centred at 2.87° lateral and 2.87° azimuthal eccentricity from a central fixation point. Each item subtended 1.64° x 2.05° of visual angle from a distance of 70 cm. The fixation point subtended a visual angle of 0.16° and all items were presented on a black background. Memory arrays were preceded or followed by cues that were informative (100% valid, i.e., they accurately indicated the location of the probe in the memory array) or uninformative in nature depending on the type of trial ("trial-type" henceforth): pre-cue, retro-cue, and neutral trials.

In *pre-cue* trials, an informative spatial cue preceded the memory array and guided participants' attention to one of the upcoming items of the memory array, while a neutral cue (an uninformative spatial cue) followed the memory array, to control for any alerting effects that could have resulted from a new stimulus being presented at that time point. In *retro-cue* trials, a neutral cue preceded the memory array, again to control for the equivalent event in pre-cue trials, while an informative spatial cue was presented after the memory array and guided participants' attention internally to the mental representation of one of the already encoded items of the

memory array. In *neutral* trials, uninformative cues preceded and followed the memory array and participants had to make a decision without any spatial indication as to whether the probe was presented in the memory array. Two experimental groups were tested. In the central-cue groups, the informative cue was a white arrow presented centrally (0.82° x 0.82°). In the peripheral-cue groups, the informative cue was a white square outline (1.64° x 2.05°) presented at the location subsequently or previously occupied by one of the memory array items. The neutral cue (a white filled square, 0.82° x 0.82°) was centrally presented in both cases. Figure 2 illustrates a sample trial with the temporal parameters used.

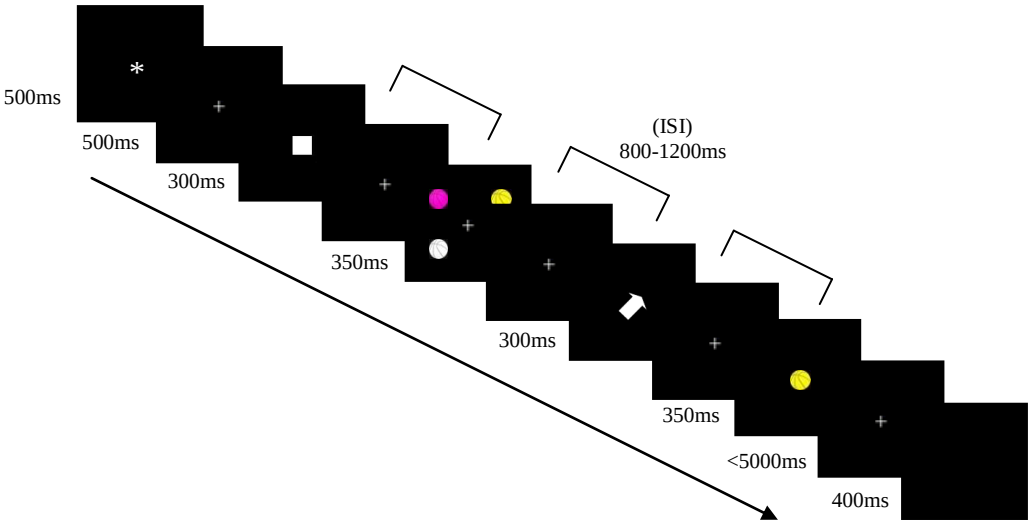


Figure 2. Schematic illustration of the sequence of events and their temporal parameters on each test trial.

Each trial began with an asterisk (500ms) signalling the start of a new trial followed by a fixation point that remained visible throughout the trial. Five hundred ms later, a cue (informative or uninformative depending on the trial-type) appeared

for 300ms. After a randomly varied fixation interval (800, 1000, 1200ms), the memory array appeared for 350ms, followed by another randomly varied fixation interval (800-1200ms). These inter-stimulus intervals (ISIs) were varied to reduce temporal expectation (Griffin & Nobre, 2005). Subsequently, another cue (informative or uninformative depending on the trial-type) appeared for 300ms. Finally, after a variable fixation interval (800-1200ms), the probe appeared for 350ms followed by a fixation point that remained on the screen until a response was made or until a maximum of 5000ms elapsed. Then, a blank screen was presented for 400ms until the next trial began. All trials were of equal duration despite the random selection of ISIs.

The task consisted of two practice blocks of 6 trials each so that participants could familiarize themselves with the task, followed by 4 test blocks of 48 trials each, totalling 192 experimental trials: 128 (66.6%) probe-present and 64 (33.3%) probe-absent trials. The first practice block was a slower version of the test blocks to ensure that participants understood the task, whereas the second practice block employed the timing parameters of the test blocks. Half of all test trials (50%) were cued (equally likely to point to one of the four possible spatial locations) and the other half (50%) were neutral. Of the probe-present trials over the four blocks, 32 were pre-cue, 32 were retro-cue, and 64 were neutral trials. Of the probe-absent trials, 16 were pre-cue and 16 were retro-cue trials, to ensure that cues did not simply signal a "present" response, and 32 were neutral trials. These trials were presented over 2 "pre-cue" blocks, containing pre-cue and neutral trials only, and 2 "retro-cue" blocks, containing retro-cue and neutral trials only to prevent children from being confused by a continuous change of cue-types across trials. Test blocks were

counterbalanced across the task and across participants. Cued and neutral trials occurred randomly within each test block. Test blocks alternated throughout the task and were counterbalanced across participants.

Reaction time and accuracy for each response were automatically recorded by the computer. On practice trials, participants received visual feedback about their performance from the computer screen (correct, incorrect, no response) and oral feedback from the experimenter after each trial to ensure that they understood the task completely. On test trials, participants received visual feedback on the computer screen about the number of correct responses after every 16 test trials and at the end of a block. If at the end of a block a participant received a total score equal to or lower than 16 out of 48, then s/he was presented with an encouraging sentence stating "You tried really hard! Do you think you can score higher?". If the participant scored between 17 and 32 then s/he was presented with the sentence "Good job! Can you score even higher?". Finally, if the participant received a score equal or higher than 33 then s/he was presented with "Wow! You are doing a great job!".

Development of stimuli for the Attentional Orienting Task

Three hundred and ninety seven line drawing images were collected from the World Wide Web and 142 of those were further processed in 3 steps using the Adobe Photoshop software to create the memory array items. First, the background of those 142 images was converted to black. Second, the filling of each image was coloured processed and was replicated in 9 unique colours: blue, green, yellow, orange, magenta, red, white, grey, and brown, resulting in 1278 new images. Third, all images were resized to equal dimensions. Pilot testing indicated that grey and brown

colours were difficult to discriminate from white and orange respectively so they were excluded from the task. Therefore, 550 images across 7 colours (blue, green, yellow, orange, magenta, red, and white) were eventually used. Six additional images, a white arrow in 4 distinct orientations, a white border, and one white filled square, were created to function as "cues". Finally, an additional 65 images were collected from the web. From these, 11 images were further processed and used as the "theme of the game" in order to make the task appealing to the children.

Automated Working Memory Assessment (AWMA; Alloway, 2007): In addition to the Attentional Orienting Task, participants from the central-cue groups[2] were assessed with two visuo-spatial subscales, the Dot Matrix and the Spatial Recall from the AWMA, in order to estimate independent measures of VSTM and VWM capacity as it was predicted that individuals with lower VSTM / VWM capacity would benefit less from attention cues (see Fukuda & Vogel, 2009, 2011 for relevant adult data). The AWMA is a widely used computerized battery test that assesses the STM and WM capacity of children and young adults and provides standardized scores for individuals in the age range of 4 to 22 years old. It can also be used for screening WM problems in childhood and in early adulthood. The test includes verbal and non-verbal subscales assessing different aspects of STM and WM. The scoring can produce a raw score and a standardized score for all the subscales and a WM profile for each individual. The test demonstrates good internal consistency, i.e., the test-retest reliability coefficients range from 0.83 (Cronbach's Alpha) to 0.64. Its

[2] Due to time constraints in testing at schools, additional data on individual differences in VSTM and VWM capacity could only be collected from participants in the central-cue groups. However, see "statistical design and analyses" section for sufficient statistical power.

validity has been supported by the high positive correlation with the WISC-IV Working Memory Index.

AWMA – Dot Matrix: This subscale measures VSTM capacity. It is independent of participants' ability to read, speak, or write as it simply requires that participants view sequentially presented red dots on a 4x4 matrix and then, after they disappear, point to their screen location in exactly the same order.

AWMA – Spatial Recall: This subscale measures VWM capacity. Participants view two identical shapes, from which the shape on the right is flipped to be the mirror image of the shape on the left in half of the trials. Participants have to report whether the two shapes face towards the same or opposite direction, requiring them to mentally rotate the shape on the right. At the same time, the shape on the right is paired with a red dot whose serial position participants have to retain in memory. The task therefore requires participants to perform a series of mental rotations whilst retaining the changing location of a dot, the ordered locations of which are to be recalled at the end of the sequence by selecting among three possible locations presented on the screen. For both subscales the number of the red dots to-be-remembered is increased until performance falls below a two-thirds criterion which reveals the participants' VSTM / VWM capacity respectively.

Rationale for administering the AWMA with regards to examining relations with attentional orienting

Memory for spatial sequences measured by classic tasks such as the Corsi Block task is known to make extensive demands on attentional resources (Barrouillet et al., 2009; Rudkin, Pearson, & Logie, 2007; Vandierendonck, Kemps, Fastame, &

Szmalec, 2004). Both AWMA subscales are derivatives of the Corsi Block task and therefore their successful execution is assumed to rely on both spatial processing and attentional resources or the central executive of WM (Baddeley & Hitch, 1974). However, the two subscales may differ in the extent to which they draw on attentional resources since they vary in their cognitive demands: complex tasks tapping VWM capacity (e.g., the Spatial Recall subscale) require participants to maintain spatial sequences similar to simple VSTM capacity tasks (e.g., the Dot Matrix subscale) while also performing a concurrent task during retention such as mental rotation (Salway & Logie, 1995). Imposing a concurrent attentionally demanding task introduces interference between encoding and recall and this has recently helped delineating the role of attentional control in the encoding and maintenance of features in VSTM (Allen et al., 2006; Baddeley et al., 2011; Stevanovski & Jolicœur, 2007). More specifically, irrelevant items during retention have been found to interfere with memory, suggesting an attentional cost of avoiding interference and protecting representations during maintenance (Awh et al., 1998; Smyth & Scholey, 1994; Ueno, Allen, et al., 2011). Attentional orienting, thus, seems to be a critical underlying process for spatial memory performance and should be treated as more "than merely a correlated phenomenon" (Awh & Jonides, 2001 p.120). Furthermore, children's visuo-spatial memory capacity measured with the Corsi Block task has been shown to increase with age (Kemps, De Rammelaere, & Desmet, 2000; Logie & Pearson, 1997). Hence, examining how attentional orienting contributes to ability on these more classical VSTM / VWM tasks across development can elucidate further the contribution of attentional control to memory storage capacity.

Procedure

Children were tested in a quiet room within their school in Nicosia. Adults in the central-cue group were tested in the Brain and Cognition Laboratory (B&C) at the University of Oxford, whereas adults in the peripheral-cue group were tested in the Experimental Psychology Lab (EPL) at the University of Cyprus. All participants were individually tested. Participants sat at a comfortable distance from the screen and were introduced to the testing procedure. First, the examiner told the participants that they were going to play a game called "The Pinky and the Brain game" with two mice named Pinky and Brain that want to take over the world and needed the participant's help to achieve their goal. In order to do so, participants needed to help Pinky, a forgetful mouse, to spot old and new colours by responding yes/no. Every time they spotted the colours correctly, they would win a point. They were told that the game has four levels and at every level they would have to try and collect as many points as possible in order to conquer a continent. Once they conquered a continent, they would win a sticker of their choice. The ultimate goal was to conquer all four continents and win a "Science" certificate. Then, the experimenter explained the characteristics of the trial-types of the Attenional Orienting Task using examples presented on cards. Illustrations of the example cards are presented in Appendix B, Figure B1 and Figure B2 for the central-cue and peripheral-cue groups respectively. Participants were told that 4 identical pictures in different colours would first appear on the screen and after a little while, another coloured picture would appear. Their job was to search their memory and decide whether that last coloured picture was one of the four initial ones by pressing the mouse button. They were also told that

sometimes Brain, the clever mouse, would give them a cue which would sometimes point to (for central-cue groups) or mark (for peripheral-cue groups) the one coloured picture out of the four that might re-appear next. Sometimes the cue would appear before the four pictures and sometimes afterwards, but they would always know before the beginning of the block when the cue would appear. When no cue appeared, they would just see a white square presented centrally. The experimenter emphasized that participants should pay attention to the spatial cues, when available, as these would help them decide whether the probe item was presented in the preceding memory array.

Participants were also asked to respond as quickly and accurately as possible while focusing their gaze on the fixation point throughout the trial. Children placed the index finger of each hand on each mouse button while adults held the mouse in their right hand. The practice session lasted approximately 5 minutes and each test block around 6 minutes. Participants completed the whole task in approximately 35 minutes. After completing the Attentional Orienting Task, participants in the central-cue groups also completed the two subscales of the AWMA. The AWMA was administered following the standardized instructions that accompany the test. During the AWMA subscales participants were encouraged to perform as well as possible but were not given feedback about their performance, except in the practice sessions. The AWMA took approximately 30 minutes. Short breaks in-between the test blocks and the tasks were inserted. Children carried out the Attentional Orienting Task on a laptop computer and adults on a desktop computer. The AWMA subscales were presented on the laptop for all participants.

All children received stickers as rewards for the completion of the test blocks and a certificate of participation (Science certificate) at the end of the testing. Adults in the central-cue group were reimbursed with £15 for their time whereas adults in the peripheral-cue group participated voluntarily.

Statistical design and analyses

Experiment 1 followed a mixed design with the block (pre-cue, retro-cue) and the trial-type (cued, neutral) as the within-subject variables and the age-group (7-year-olds, 11-year-olds, and adults) and the cue-position (central, peripheral) as the between-subject variables. In general, studies examining cueing effects focus primarily on participants' speed to detect the targets. However, accuracy-based d-prime measures and median reaction times (RTs) may index distinct effects on how well stimuli are represented in memory and information is accessed respectively (Prinzmetal et al., 2005). For this reason, a sensitive discrimination measure (d-prime) and median RTs were computed for statistical analyses. To aid comparisons with previous findings (Cowan et al., 2005, 2011, 2010; Riggs et al., 2006, 2011), Cowan's *K* was also computed. D-prime scores reflect the degree to which participants can accurately report the presence or absence of the probe in the preceding memory array. As d-prime controls for the presence of a response bias, it was preferred over raw accuracy analyses[3]. D-prime scores were computed by using a p→z transform of the proportion of the trials that participants correctly reported as present (hit rate) and subtracting from it the p→z transform of the proportion of the trials that participants incorrectly reported as present (false alarm rate). The formula

[3] Analyses on raw accuracy scores were also carried out. Results were similar to those reported for d-prime, thus only d-prime results will be reported for brevity.

resulted in d-prime = z (hit rate) – z (false alarm rate). *K* scores reflect the number of stored items in memory (Cowan, 2001; Pashler, 1988) and their estimation in the Attentional Orienting Task presumably indexes the increase in memory capacity as a result of efficient allocation of attention. *K* was calculated using the formula: *K* = S (set size of the initial array) × (hit rate – false alarm rate). Extreme scores (e.g., perfect hit rate) were adjusted using the formulae recommended by Macmillan & Creelman (2005) [e.g., 1-(1/2N) where N is the number of trials in a condition]. RTs were computed for probe-present trials and for correct responses only because incorrect responses and absent trials maybe influenced by multiple non attentional processes (as discussed in Griffin & Nobre, 2003). In addition, criterion c (*c*) was also computed to investigate potential response biases across the age-groups. *c* was calculated in addition to d-prime because it is unaffected by changes in d-prime if d-prime assumptions are violated (Stanislaw & Todorov, 1999). *c* was calculated using the formula: $c = -0.5 \times [z(\text{hit rate}) + z(\text{false alarm rate})]$. Mean d-prime, *K*, *c*, and median RT scores were computed for each participant and each combination of the independent variables.

Separate mixed-design Analyses of Variance (ANOVAs) were performed for each dependent variable to test main effects and interactions in the 2 (block: pre-cue, retro-cue) x 2 (trial-type: cued, neutral) x 3 (age-group: 7-year-olds, 11-year-olds, adults) x 2 (cue-position: central, peripheral) design. The Greenhouse-Geisser correction was employed to deal with violations of sphericity when necessary. Bonferroni corrections were used to adjust comparisons of means required to clarify the nature of main effects or interactions[4]. In order to assess the size of cueing effects

[4] The Greenhouse-Geisser and the Bonferroni corrections have been applied when necessary in all experiments; however, these statements will appear only here for brevity.

independently of baseline age-related differences in the accuracy, storage capacity, and speed of memory performance, cueing benefits were also calculated by subtracting d-prime on neutral trials from d-prime on cued trials, *K* on neutral trials from *K* on cued trials, and median RT on cued trials from median RT on neutral trials respectively. To account for age-related differences in overall response speed, RT data were also scaled, dividing cueing benefits by RT on neutral trials.

To investigate the extent to which performance on the Attentional Orienting Task related to VSTM and VWM abilities, preliminary correlational analyses were followed by hierarchical regression models in which age in months, performance on neutral baseline trials, and performance on cued trials (d-prime and *K* on retro-cue trials) were assessed as predictors of raw scores on the Dot Matrix (indexing VSTM span) and Spatial Recall (indexing VWM span) subscales. D-prime and *K* were chosen here because traditional span measures are unspeeded and because RT is thought to index less well the precision of cued representations (Prinzmetal et al., 2005). Furthermore, preliminary partial correlations between median RTs and the two AWMA subscales indicated null results. The subsample of participants entered into the regression analyses (N = 55) afforded sufficient statistical power to investigate the role of three variables (age in months, d-prime/*K* on neutral trials, d-prime/*K* on cued trials) as predictors of VSTM and VWM span: given the R^2 values reported by Astle et al. (2012) in the closest experimental analogue to the current experiment (reporting large effect sizes for the same three predictors), a sample size of 55 individuals afforded a power of .96 (calculated using G-power 3, Faul, Erdfelder, Lang, & Buchner, 2007).

Results

D-prime

The analysis on d-prime scores revealed main effects of block [$F(1,110)=74.78$, $p<.001$, $\eta^2=.41$] reflecting higher accuracy in pre-cue compared to retro-cue blocks, of trial-type [$F(1,110)=356.30$, $p<.001$, $\eta^2=.76$] driven by higher accuracy in cued compared to neutral trials, of age-group [$F(2,110)=69.74$, $p<.001$, $\eta^2=.56$] showing higher scores for adults compared to children, and of cue-position [$F(1,110)=6.85$, $p=.01$, $\eta^2=.06$] documenting higher scores with central compared to peripheral cues. Also, significant interactions of block x trial-type [$F(1,110)=139.66$, $p<.001$, $\eta^2=.56$], block x age-group [$F(2,110)=7.23$, $p=.001$, $\eta^2=.12$], and cue-position x age-group [$F(2,110)=4.52$, $p=.01$, $\eta^2=.08$] were obtained. Most importantly, these were moderated by two higher-order significant interactions of block x trial-type x age-group [$F(2,110)=3.05$, $p=.05$, $\eta^2=.05$] and cue-position x block x trial-type [$F(1,110)=4.49$, $p=.04$, $\eta^2=.04$]. Mean d-prime scores are reported in Table 1.

Table 1. *Mean d-prime, K, and RT scores for central vs. peripheral cues, for pre-cue, retro-cue, and neutral trials for all age-groups. Standard deviations are reported in parentheses.*

	Central-cue				Peripheral-cue			
	Pre-cue block		Retro-cue block		Pre-cue Block		Retro-cue block	
	Cued	Neutral	Cued	Neutral	Cued	Neutral	Cued	Neutral
D-prime								
7-year-olds	2.37 (0.91)	0.72 (0.64)	0.95 (0.69)	0.68 (0.47)	2.51 (0.89)	0.75 (0.53)	0.98 (0.69)	0.76 (0.53)
11-year-olds	2.97 (0.91)	1.49 (0.69)	2.18 (0.76)	1.41 (0.65)	3.02 (0.78)	1.29 (0.70)	1.79 (0.89)	1.22 (0.67)
Adults	3.75 (0.47)	2.04 (0.80)	3.31 (0.52)	2.30 (0.81)	3.36 (0.73)	1.44 (0.68)	2.40 (0.57)	1.77 (0.76)
K								
7-year-olds	2.79 (0.86)	0.90 (0.71)	1.30 (0.95)	0.96 (0.63)	2.92 (0.75)	1.00 (0.62)	1.36 (0.86)	1.06 (0.72)
11-year-olds	3.17 (0.63)	1.95 (0.85)	2.65 (0.78)	1.84 (0.74)	3.32 (0.53)	1.76 (0.84)	2.26 (0.87)	1.62 (0.84)
Adults	3.70 (0.24)	2.55 (0.75)	3.53 (0.27)	2.71 (0.71)	3.46 (0.49)	1.90 (0.80)	2.88 (0.50)	2.25 (0.86)
RT (ms)								
7-year-olds	940.23 (225.62)	1402.23 (323.80)	1171.53 (306.89)	1467.88 (263.49)	951.23 (263.14)	1332.63 (402.57)	1157.73 (312.58)	1367.90 (449.34)
11-year-olds	641.08 (187.67)	899.83 (270.54)	656.75 (264.83)	918.88 (274.36)	699.20 (150.59)	902.78 (252.64)	714.93 (191.88)	965.53 (245.97)
Adults	581.23 (126.22)	773.53 (169.00)	551.47 (136.44)	769.67 (178.39)	530.69 (155.14)	797.98 (161.58)	516.93 (134.78)	824.50 (145.89)

Analyses of simple main effects for the interaction of block x trial-type x age-group suggested that there were developmental differences in attentional cueing benefits on VSTM. Table 2 presents means for this interaction. All age-groups performed better in cued than in neutral trials in both pre-cue ($p<.001$ for all age-groups) and retro-cue blocks ($p<.001$ for adults and 11-year-olds and $p=.03$ for 7-year-olds), highlighting benefits of attentional orienting for accurate recognition and, in *cued trials*, all age-groups performed better in the pre-cue than in the retro-cue block ($p<.001$ for all age-groups), suggesting that they benefited more from cues prior to encoding than during maintenance. Adults performed better than 7-year-olds and 11-year-olds, who in turn did better than the 7-year-olds in *cued trials* of both blocks ($p<.05$ for all age-group comparisons). Unsurprisingly, there were also baseline differences in memory for *neutral trials*, as adults performed better than both 7-year-olds and 11-year-olds, who in turn performed better than 7-year-olds on neutral trials of both blocks ($p<.05$ for all age-group comparisons). As the absolute level of performance by the youngest children was low, I tested whether this differed significantly from chance. In neutral trials, average accuracy on target present trials was $M=.55$ for pre-cue blocks and $M=.60$ for retro-cue blocks, values that differed significantly from chance ($p=.036$ and $p<.001$ respectively). In addition, average accuracy on retro-cue trials was $M=.67$, a value that also differed significantly from chance ($p<.001$).

Table 2. *D-prime scores for pre-cue, retro-cue, and neutral trials for all age-groups. Standard errors of the mean are reported in parentheses.*

	Pre-cue		Retro-cue	
	Cued	Neutral	Cued	Neutral
7-year-olds	2.44 (0.13)	0.73 (0.11)	0.97 (0.11)	0.72 (0.10)
11-year-olds	3.00 (0.13)	1.39 (0.11)	1.98 (0.11)	1.31 (0.10)
Adults	3.56 (0.14)	1.74 (0.11)	2.85 (0.12)	2.04 (0.11)

In order to investigate developmental differences in benefits associated with attention cues independently of baseline differences in memory in neutral trials across age-groups, difference scores were also calculated by subtracting the d-prime score for neutral trials from the d-prime score for cued trials (Figure 3). The analysis on difference scores revealed a main effect of block-benefit [$F(1,110)=139.66$, $p<.001$, $\eta^2=.56$] and a block-benefit x age-group interaction [$F(2,110)=3.05$, $p=.05$, $\eta^2=.05$]. Simple main effects for the interaction indicated that all age-groups benefited from pre-cues to a greater degree than from retro-cues (7-year-olds: $M=1.70$ and $M=.25$ respectively, $p<.001$; 11-year-olds: $M=1.61$ and $M=.67$ respectively, $p<.001$; adults: $M=1.81$ and $M=.82$ respectively, $p<.001$). The interaction was driven by the fact that, when the cue was presented in advance of encoding, all three age-groups benefited to the same degree ($p>.05$ for all age-group comparisons), but when the cue was presented during maintenance, adults and 11-year-olds benefited to a similar degree to each other ($p>.05$) and significantly more than the 7-year-olds ($p=.003$ and $p=.03$ respectively).

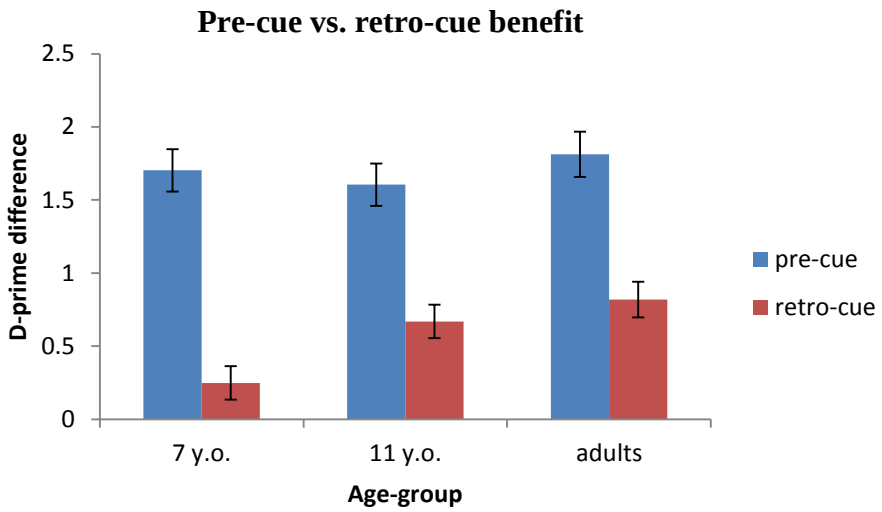


Figure 3. D-prime difference scores from neutral baseline, comparing pre-cue and retro-cue blocks for all age-groups. Error bars represent standard errors of the mean.

Given the poorer baseline memory capacity of younger children, cueing benefits were also assessed by analysing scaled d-prime difference scores [i.e., (cued-neutral)/neutral]. The analysis revealed a main effect of age on cueing benefits [$F(2,108)=3.26$, $p=.04$, $\eta^2=.06$] and an interaction of block-benefit x age-group [$F(2,108)=8.85$, $p<.001$, $\eta^2=.14$], driven by proportionally greater benefits with pre-cues than retro-cues for younger children (M=5.01 and M=-.23 respectively), whereas older children (M=.28 and M=.73 respectively) and adults (M=1.52 and M=.66 respectively) did not differ significantly in their benefits from both types of cues.

To return to the question of whether the physical characteristics of cues (i.e., the cue-position) drive attentional orienting effects, the cue-position x block x trial-type interaction was investigated through an analysis of simple main effects. Table 3 presents means for this interaction. No differences were found between central and peripheral cues in the *pre-cue block* ($p>.05$). When presented with either central or

peripheral cues, all participants performed better in cued than in neutral trials in both blocks ($p<.001$ for both pre-cue and retro-cue blocks) and, with either cue-position, central or peripheral, they performed better when the cue was presented prospectively than retrospectively ($p<.001$ for both central and peripheral cues). The interaction was driven by better performance for central cues compared to peripheral cues in the *retro-cue block* ($p=.002$). Difference scores confirmed that there were greater benefits stemming from the pre-cues than from the retro-cues regardless of the position of the cue ($M=1.61$ and $M=.69$ respectively for central cues, $p<.001$ and $M=1.80$ and $M=.47$ respectively for peripheral cues, $p<.001$). This finding was corroborated by the presence of a significant block-benefit x cue-position interaction [$F(1,110)=4.50$, $p=.04$, $\eta^2=.04$].

Table 3. *D-prime scores for central vs. peripheral cues, for pre-cue, retro-cue, and neutral trials across participants. Standard errors of the mean are reported in parentheses.*

	Central-cue position		Peripheral-cue position	
	Pre-cue	Retro-cue	Pre-cue	Retro-cue
Cued	3.03 (0.11)	2.15 (0.10)	2.96 (0.10)	1.72 (0.09)
Neutral	1.42 (0.09)	1.46 (0.09)	1.16 (0.09)	1.25 (0.08)

Post hoc comparisons were also carried out for the cue-position x age-group interaction to examine developmental differences regarding the effects of cue-position. These revealed that the interaction was driven by the adults performing significantly better when presented with central cues ($M=2.85$) than with peripheral cues ($M=2.24$, $p<.001$), while 7-year-olds and 11-year-olds performed similarly with

central and peripheral cues (7-year-olds: M=1.18 and M=1.25 respectively, p>.05; 11-year-olds: M=2.01 and M=1.83 respectively, p>.05). With both central and peripheral cues, adults performed significantly better than both 7-year-olds (p<.001 for central and peripheral cues) and 11-year-olds (p<.001 for central cues and p=.02 for peripheral cues), who in turn performed better than 7-year-olds (p<.001 for central cues and p=.001 for peripheral cues). Crucially, the interactions of cue-position x age-group [$F(2,110)=.10$, $p=.91$, $\eta^2=.002$] and cue-position x block-benefit x age-group [$F(2,110)=.43$, $p=.65$, $\eta^2=.008$] on d-prime benefit did not reach significance when differences in neutral trials were controlled for (Figure 4). This in turn suggested that benefits across age-groups were not differentially affected by the physical characteristics of the cue and were not poorer in children than adults for symbolic central cues, with either encoding (p>.05) or maintenance cues (p>.05).

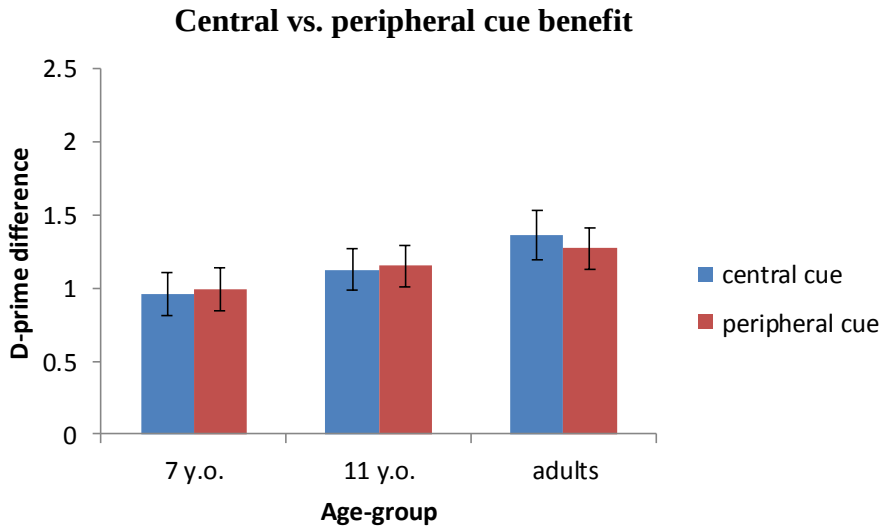


Figure 4. D-prime difference scores from neutral baseline, comparing central and peripheral cues across pre-cue and retro-cue blocks for all age-groups. Error bars represent standard errors of the mean.

K capacity measure

As in d-prime analysis, there were significant main effects of block [$F(1,110)=53.80$, $p<.001$, $\eta^2=.33$] driven by higher *K* scores in pre-cue compared to retro-cue blocks, of trial-type [$F(1,110)=303.55$, $p<.001$, $\eta^2=.73$] reflecting higher *K* scores in cued compared to neutral trials, of age-group [$F(2,110)=62.62$, $p<.001$, $\eta^2=.53$] indicating higher *K* scores for adults compared to children, and of cue-position [$F(1,110)=3.81$, $p=.05$, $\eta^2=.03$] documenting higher *K* scores with central compared to peripheral cues. Also, the block x trial-type [$F(1,110)=109.84$, $p<.001$, $\eta^2=.50$], block x age-group [$F(2,110)=11.45$, $p<.001$, $\eta^2=.17$], and cue-position x age-group [$F(2,110)=3.11$, $p=.05$, $\eta^2=.05$] interactions reached significance. Most importantly, the higher-order interactions of block x trial-type x age-group [$F(2,110)=11.89$, $p<.001$, $\eta^2=.18$] and cue-position x block x trial-type [$F(1,110)=4.75$, $p=.03$, $\eta^2=.04$] were significant. Mean *K* scores are reported in Table 1. Simple main effects for the 3-way interactions revealed an identical pattern of results to the d-prime analysis. Therefore, for the sake of brevity, they are not reported.

Criterion c

The analysis on *c* scores yielded significant main effects of block [$F(1,110)=18.66$, $p<.001$, $\eta^2=.15$] and trial-type [$F(1,110)=85.82$, $p<.001$, $\eta^2=.44$]. These were moderated by a significant block x trial-type interaction [$F(1,110)=25.37$, $p<.001$, $\eta^2=.19$] indicating that participants of all ages responded “yes” more often in cued trials (M= -.15 and M=.08 for pre-cue and retro-cue respectively) than in neutral trials (M=.20 and M=.18 for pre-cue and retro-cue respectively) in both

blocks ($p<.001$ for pre-cue block and $p=.002$ for retro-cue block). The interaction was driven by the participants of all ages responding "yes" more often in cued trials of the pre-cue block than of the retro-cue block ($p<.001$).

Importantly, the main effect of age-group did not reach significance [$F(2,110)=.15$, $p=.86$, $\eta^2=.003$] suggesting that there were no differences among the three age-groups in their tendency to respond yes or no. Also, there were no significant interactions of trial-type x age-group [$F(2,110)=.45$, $p=.64$, $\eta^2=.01$], cue-position x age-group [$F(2,110)=.19$, $p=.83$, $\eta^2=.003$], block x trial-type x age-group [$F(2,110)=.37$, $p=.70$, $\eta^2=.01$], and cue-position x block x age-group [$F(2,110)1.27$, $p=.28$, $\eta^2=.02$] confirming the absence of differential response bias across the age-groups. There was only a block x age-group interaction [$F(2,110)=6.43$, $p=.002$, $\eta^2=.11$]. Analyses of simple main effects indicated that the interaction was driven by the adults and 11-year-olds responding "yes" more often in the pre-cue block than in the retro-cue block (adults: $M= -.003$ and $M=.20$ respectively, $p<.001$; 11-year-olds: $M=.01$ and $M=.14$ respectively, $p=.002$) while this was not the case for 7-year-olds. Importantly, there were no age-group differences across the two blocks (7-year-olds: $M=.07$ and $M=.06$ for pre-cue and retro-cue respectively, $p>.05$ for all age-group comparisons) confirming that the age-groups did not differ from each other in their tendency to respond yes or no. These findings suggest that the d-prime results reflect participants' ability to make use of the cue and not responding biases. For this reason and again in the interest of brevity, *c* will not be reported further.

Median RTs

The analysis of median RTs revealed significant main effects of block [$F(1,110)=16.97$, $p<.001$, $\eta^2=.13$] documenting faster speed in pre-cue compared to retro-cue blocks, of trial-type [$F(1,110)=393.79$, $p<.001$, $\eta^2=.78$] showing faster speed in cued compared to neutral trials, and of age-group [$F(1,110)=64.80$, $p<.001$, $\eta^2=.54$] driven by faster scores for adults compared to children. In addition, the block x age-group [$F(2,110)=10.97$, $p<.001$, $\eta^2=.17$] and the trial-type x age-group [$F(2,110)=5.05$, $p=.008$, $\eta^2=.08$] interactions were highly significant. The block x trial-type [$F(1,110)=3.75$, $p=.055$, $\eta^2=.03$] interaction was marginally significant. Most importantly, effects were moderated by a highly significant 3-way interaction of block x trial-type x age-group [$F(2,110)=12.34$, $p<.001$, $\eta^2=.18$], bolstering the similar effect for d-prime and *K*. Finally, there was a marginally significant interaction of cue-position x trial-type x age-group [$F(2,110)=3.00$, $p=.05$, $\eta^2=.05$]. Median RTs are reported in Table 1.

Analyses of simple main effects for the block x trial-type x age-group interaction (see Table 4 for the means of this interaction) revealed that all participants were significantly faster in cued trials than in neutral trials, both in pre-cue ($p<.001$ for all age-groups) and retro-cue blocks ($p<.001$ for all age-groups). In *cued trials*, 7-year-olds performed faster in the pre-cue than in the retro-cue block ($p<.001$), whereas 11-year-olds and adults were equally fast across blocks ($p>.05$ for both adults and 11-year-olds). Performance on neutral trials did not differ across blocks ($p>.05$ for all age-groups). Adults were faster than both 7-year-olds ($p<.001$ for both pre-cue and retro-cue blocks) and 11-year-olds ($p=.04$ and $p=.02$ for pre-cue and retro-cue blocks respectively), who in turn were faster than 7-year-olds ($p<.001$

for both pre-cue and retro-cue blocks) in *cued trials* of both blocks. However, there were again age-related differences in baseline neutral trials: in *neutral trials* of both blocks 11-year-olds were as fast as adults ($p>.05$ in both pre-cue and retro-cue blocks) but both age-groups were faster than the 7-year-olds ($p<.001$ with both adults and 11-year-olds).

Table 4. *RT scores for pre-cue, retro-cue, and neutral trials for all age-groups. Standard errors of the mean are reported in parentheses.*

	Pre-cue		Retro-cue	
	Cued	Neutral	Cued	Neutral
7-year-olds	945.73 (30.48)	1367.43 (44.20)	1164.63 (37.85)	1417.89 (44.23)
11-year-olds	670.14 (30.48)	901.30 (44.20)	685.84 (37.85)	942.20 (44.23)
Adults	555.96 (32.58)	785.76 (47.25)	534.20 (40.46)	797.08 (47.28)

In order to interpret interaction effects including age independently of baseline differences in neutral trials across age-groups, cueing benefits were again calculated by subtracting the median RT for cued trials from the median RT for neutral trials. The analysis on difference scores showed a significant main effect of age-group [$F(2,110)=5.05$, $p=.008$, $\eta^2=.08$] and a significant interaction of block-benefit x age-group [$F(2,110)=12.34$, $p<.001$, $\eta^2=.18$]. The block-benefit x age-group interaction was driven by the 7-year-olds drawing significantly greater RT benefits from pre-cues ($M=421.70$) than from retro-cues ($M=253.26$, $p<.001$) whereas adults and 11-year-olds benefited equally from pre-cues and retro-cues (adults: $M=231.16$ and $M=256.23$ respectively, $p>.05$; 11-year-olds: $M=229.79$ and $M=262.89$ respectively, $p>.05$).

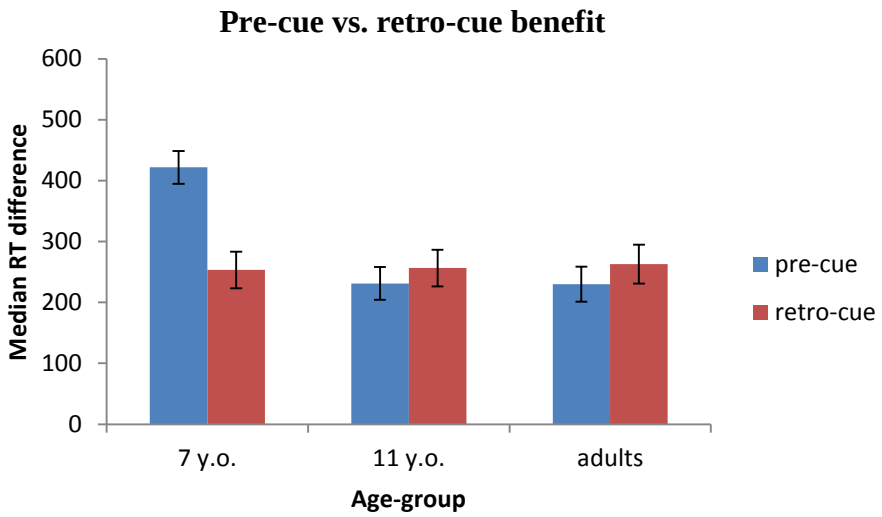


Figure 5. Median RT difference scores from neutral baseline, comparing pre-cue and retro-cue blocks for all age-groups. Error bars represent standard errors of the mean.

Nevertheless, age-related differences and similarities in RT benefits may still depend on overall slowing in responses by the younger children (Salthouse, 1996). In other words, large RT pre-cue benefits in younger children may yet pertain to a similar proportion of their baseline neutral RTs, which are slower than for older participants. Overall slowing was therefore taken into account by also considering RT differences as proportions of neutral RTs [i.e., (neutral-cued)/neutral]. Critically, the main effect of age on scaled cue benefits remained significant [$F(2,110)=4.23$, $p=.02$, $\eta^2=.07$], and so did the block-benefit x age-group interaction [$F(2,110)=16.36$, $p<.001$, $\eta^2=.23$]. Analyses of simple main effects showed that the interaction effect depended on the youngest children drawing significantly greater RT benefits from pre-cues ($M=.30$) than from retro-cues ($M=.16$, $p<.001$) and significantly smaller retro-cueing benefits than the older children ($M=.27$, $p=.005$) and adults ($M=.33$, $p<.001$), who did not differ from each other as earlier and did not differ in the extent

to which they benefited from pre-cues (M=.24 and M=.28 for 11-year-olds and adults respectively, p>.05) or retro-cues (p>.05).

Given the aim of understanding the effects of cue-position, the cue-position x trial-type x age-group interaction was also explored, despite being statistically only marginal (p=.05). Table 5 presents the means for this interaction. All age-groups reported probe presence faster in cued than in neutral trials with both central (p<.001) and peripheral cues (p<.001). However, adults and 11-year-olds performed significantly faster than 7-year-olds in both cued and neutral trials with both central and peripheral cues (p<.001 for all comparisons). When presented with a peripheral cue (but in none of the other conditions), adults performed significantly faster than 11-year-olds (p=.01). Critically, no significant differences between central and peripheral cues were obtained in any age-group. This was corroborated by the lack of a significant main effect of cue-position [$F(1,110)=.36$, $p=.98$, $\eta^2=.000$].

Table 5. *RT scores for central vs. peripheral cues, for cued and neutral trials for all age-groups. Standard errors of the mean are reported in parentheses.*

	Central-cue position		Peripheral-cue position	
	Cued	Neutral	Cued	Neutral
7-year-olds	1055.88 (45.60)	1435.05 (58.89)	1054.48 (45.60)	1350.26 (58.89)
11-year-olds	648.91 (45.60)	909.35 (58.89)	707.06 (45.60)	934.15 (58.89)
Adults	566.35 (52.65)	771.60 (67.10)	523.81 (44.50)	811.24 (57.47)

For difference scores, the cue-position x age-group interaction effect was only marginally significant [$F(2,110)=2.99$, $p=.05$, $\eta^2=.05$] and driven by the fact that 7-year-olds (M=379.18) benefited more in speed than 11-year-olds (M=260.44,

p=.04) and adults (M=205.25, p=.003) when given a central cue, while all age-groups benefited to the same degree when given a peripheral cue (7-year-olds: M=295.79; 11-year-olds: M=227.09; adults: M=287.43, p>.05 for all age-group comparisons).

With scaled RTs, the cue-position x age-group interaction reached statistical significance [$F(2,110)=4.75$, $p=.01$, $\eta^2=.08$], with adults benefiting from peripheral cues (M=.35) to a greater degree than the two other age-groups (11-year-olds: M=.23, p=.003, 7-year-olds: M=.20, p<.001).

Relations between attentional cueing benefits and VSTM / VWM capacity

Next, I assessed whether individual differences in attentional orienting related to performance on validated VSTM / VWM span tasks for all participants. Age was considered as a continuous variable (age in months), rather than a categorical one, to evaluate fully the relative contribution of age and individual differences in predicting memory capacity. Preliminary partial correlations controlling for chronological age across measures of attentional orienting and memory span performance (raw scores from the two AWMA subscales) are presented in Table 6 and Table 7 for d-prime and *K* respectively. In summary, performance following retro-cues in *d-prime* and *K* related significantly to VSTM span (as indexed by the Dot Matrix subscale) and VWM span (as indexed by the Spatial Recall subscale). As detailed in the Methods section, these measures share spatial requirements and attentional demands, but Spatial Recall requires additional attentional resources by imposing a concurrent mental rotation task. The relation between d-prime and *K* on retro-cue trials and VWM span held even when the variability associated with neutral trials (effectively

measuring baseline performance of how accurately participants could remember whether the probe item was part of the memory array) was taken into account in multiple ways.

Tables 6 and 7. *Relations between chronological age (age in months), attentional control measures (d-prime scores, denoted by "d'" in Table 6; K scores in Table 7) and raw scores for VSTM span (Dot Matrix, AWMA) and VWM span (Spatial Recall, AWMA). Values above the diagonal indicate partial correlations across measures controlling for chronological age in months, whereas values below the diagonal indicate partial correlations between d-prime and K on cued trials and AWMA subscales, controlling for both chronological age and d-prime or K on neutral trials. "Pre-neutral" refers to neutral trials in pre-cue blocks and "retro-neutral" refers to neutral trials in retro-cue blocks.*

Table 6. *Correlation table for d-prime.*

	d' pre-cues	*d*' retro-neutral	*d*' retro-cues	Dot Matrix	Spatial Recall
d' pre-neutral	.355**	.630***	.557***	.398**	.305*
d' pre-cues		.128	.491***	.276*	.318*
d' retro-neutral			.550***	.316*	.255[a]
d' retro-cues				.386**	.366**
Dot Matrix	.157		.268*		
Spatial Recall	.236		.279*		

[a] *p=.06, *p<.05, **p<.01, ***p<.001.*

Table 7. *Correlation table for K.*

	K pre-cues	*K* retro-neutral	*K* retro-cues	Dot Matrix	Spatial Recall
K pre-neutral	.363**	.667***	.618***	.412**	.329*
K pre-cues		.099	.562***	.272*	.295*
K retro-neutral			.570***	.355**	.273*
K retro-cues				.428**	.386**
Dot Matrix	.144		.294*		
Spatial Recall	.199		.291*		

**p<.05, **p<.01, ***p<.001.*

As preliminary partial correlations highlighted relations between specific experimental variables (d-prime and *K* on retro-cues, d-prime and *K* on neutral trials) and visuo-spatial memory span (AWMA) scores, hierarchical regression analyses were carried out to test the extent to which they would account for individual differences in memory span, over and above differences in age. First, scores on retro-cue trials and those on neutral trials were entered simultaneously as predictors, to assess the amount of shared variance they predicted in VSTM and VWM span (indexed by the Dot Matrix and Spatial Recall subscales respectively), together with the extent to which each emerged as a significant predictor. Model statistics and coefficients for the predictor variables in d-prime and *K* are reported in Table 8 and Table 9 respectively.

The regression models were statistically significant for both AWMA subscales [D-prime: F change (2,51)=5.01, p=.01 for Dot Matrix; F change (2,51)=4.08, p=.02 for Spatial Recall; *K*: F change (2,51)=6.43, p=.003 for Dot Matrix; F change (2,51)=4.62, p=.01 for Spatial Recall]. Predictors in the *d-prime*

regression model jointly explained 69.5% of the total variance in Dot Matrix [R^2=.70, adjusted R^2=.68] and 63.6% of the total variance in Spatial Recall [R^2=.64, adjusted R^2=.62], with the two predictors in retro-cue and neutral trials explaining a further 6% in Dot Matrix and a further 5.8% in Spatial Recall after controlling for age. As seen in Table 8, in both AWMA subscales, the β was significant for retro-cue trials (although marginally for Dot Matrix; β=.27, p=.05 for Dot Matrix; β=.31, p=.04 for Spatial Recall), but not for neutral trials (β=.12, p>.05 for Dot Matrix; β=.07, p>.05 for Spatial Recall).

Table 8. *Hierarchical regression model statistics predicting scores on the Dot Matrix (indexing VSTM) and on the Spatial Recall (indexing VWM) subscales of the AWMA for d-prime. Despite significant correlations across variables, collinearity statistics warranted the use of multiple regression (with tolerance values greater than .320 and VIF smaller than 3.1).*

D-prime	Dot Matrix (DM)				Spatial Recall (SR)			
	R^2 Change	*p*	*β*	*p*	*R^2 Change*	*p*	*β*	*p*
Model 1[a]	.64	<.001			.58	<.001		
Age			.80	<.001			.76	<.001
Model 2[b]	**.06**	**.01**			**.06**	**.02**		
Age			.53	<.001			.50	<.001
D-prime retro-neutral			.12	.34			.07	.62
D-prime retro-cue			**.27**	**.05**			**.31**	**.04**

Predictors in the *K* regression model jointly explained 70.8% of the total variance in Dot Matrix [R^2=.71, adjusted R^2=.69] and 64.3% of the total variance in Spatial Recall [R^2=.64, adjusted R^2=.62], with the two predictors in retro-cue and neutral trials explaining a further 7.4% in Dot Matrix and a further 6.5% in Spatial Recall after controlling for age. As seen in Table 9, in both AWMA subscales, the β was significant for retro-cue trials (β=.27, p=.03 for Dot Matrix; β=.30, p=.03 for Spatial Recall), but not for neutral trials (β=.13, p>.05 for Dot Matrix; β=.07, p>.05 for Spatial Recall).

Table 9. *Hierarchical regression model statistics predicting scores on the Dot Matrix (indexing VSTM) and on the Spatial Recall (indexing VWM) subscales of the AWMA for K.*

K	Dot Matrix (DM)				Spatial Recall (SR)			
	R^2 *Change*	*p*	*β*	*p*	R^2 *Change*	*p*	*β*	*p*
Model 1[a]	.64	<.001			.58	<.001		
Age			.80	<.001			.76	<.001
Model 2[b]	**.07**	**.003**			**.07**	**.01**		
Age			.53	<.001			.52	<.001
K retro-neutral			.13	.29			.07	.62
K retro-cue			**.27**	**.03**			**.30**	**.03**

In addition, I tested whether d-prime and *K* in retro-cue trials predicted unique variance in VSTM and VWM (AWMA) spans having controlled for d-prime and *K* in neutral trials respectively at an earlier modelling step. This is a conservative approach because it excludes from the regression any attentional processes that are also required by maintaining information in VSTM when no cues are provided. In

essence, it focuses selectively on attentional processes related to visuo-spatial orienting benefits. The results from d-prime and *K* analyses are summarized in Table 10 and Table 11 respectively. When controlling for performance on d-prime in neutral trials, d-prime in retro-cue trials significantly predicted an additional 3.1% of unique variance in Spatial Recall subscale [F change (1,51)=4.32, p=.04], but only 2.4% of variance in Dot Matrix subscale, a marginal effect [F change (1,51)=3.95, p=.05]. In addition, for Spatial Recall, d-prime in neutral trials did not uniquely contribute to variance when entered before retro-cue trials (p=.06), whereas it predicted 3.6% of variance in Dot Matrix (p=.02).

Table 10. *Hierarchical regression model statistics predicting scores on the Dot Matrix (indexing VSTM) and on the Spatial Recall (indexing VWM) subscales of the AWMA for d-prime.*

D-prime	Dot Matrix (DM)				Spatial Recall (SR)			
	R^2 *Change*	*p*	*β*	*p*	R^2 *Change*	*p*	*β*	*p*
Model 1[a]	.64	<.001			.58	<.001		
Age			.80	<.001			.76	<.001
Model 2[b]	**.04**	**.02**			**.03**	**.06**		
Age			.64	<.001			.62	<.001
D-prime retro-neutral			.25	.02			.22	.06
Model 3[c]	**.02**	**.05**			**.03**	**.04**		
Age			.53	<.001			.50	<.001
D-prime retro-neutral			.12	.34			.07	.62
D-prime retro-cue			**.27**	**.05**			**.31**	**.04**

When controlling for performance on *K* in neutral trials, *K* on retro-cue trials significantly predicted an additional 3.3% of unique variance in Spatial Recall subscale [F change (1,51)=4.73, p=.03], but only 2.8% of variance in Dot Matrix subscale [F change (1,51)=4.82, p=.03]. In addition, for Spatial Recall, *K* in neutral trials uniquely contributed to variance when entered before *K* in retro-cue trials only marginally (p=.05), whereas it predicted 4.6% of variance in Dot Matrix (p=.008). The results from the regression analyses collectively indicate that while scores in retro-cue and neutral trials are correlated and they predict shared variance for Dot Matrix and Spatial Recall subscales, they also differ in how they uniquely predict performance on the two tasks.

Table 11. *Hierarchical regression model statistics predicting scores on the Dot Matrix (indexing VSTM) and on the Spatial Recall (indexing VWM) subscales of the AWMA for K.*

K	Dot Matrix (DM)				Spatial Recall (SR)			
	R^2 *Change*	*p*	*β*	*p*	R^2 *Change*	*p*	*β*	*p*
Model 1[a]	.64	<.001			.58	<.001		
Age			.80	<.001			.76	<.001
Model 2[b]	**.05**	**.008**			**.03**	**.05**		
Age			.61	<.001			.61	<.001
D-prime retro-neutral			.28	.008			.24	.05
Model 3[c]	**.03**	**.03**			**.03**	**.03**		
Age			.53	<.001			.52	<.001
K retro-neutral			.13	.29			.07	.62
K retro-cue			**.27**	**.03**			**.30**	**.03**

Discussion

In Experiment 1, attention cues resulted in benefits both prior to encoding and during maintenance, suggesting that deploying attentional control can facilitate the accurate and fast retrieval of information from VSTM. This result extends the findings of Astle et al. (2012) by documenting benefits for both central and peripheral cues.

Central and peripheral cues did not yield reliable developmental differences in memory benefits, either in terms of accuracy or speed, with the effects of cue position being driven by better performance with central compared to peripheral retro-cues. Despite the lack of an interaction involving age group, this was the case for the adults and 11-year-olds but not for the 7-year olds. This could be the case because peripheral retro-cues could act as a backward mask during the maintenance period and partly interfere with probe recognition, in a way that central cues could not (see Ueno et al., 2011 for interference during maintenance). Similar "masking" results were obtained for adults and 11-year-olds in another experiment that employed a "star" instead of a "border" as peripheral cue (see Experiment 1B, Appendix C). This finding is in agreement with the finding of Berryhill et al. (2011, see Experiment 1), the only study so far that has manipulated the nature of the retro-cue to examine its influence on adults' VSTM. Berryhill et al. found greater retro-cue effects for a centrally-presented arrow compared to a peripherally-presented dash at the location of the probe. In the present study, the lack of interactions involving age argues against *developmental differences* in attentional orienting being driven by the physical or symbolic characteristics of cues, at least when in service of VSTM, and

with children as young as 7 years of age. Rather, they reflect children's improving attentional control during maintenance.

This is further supported by cues prior to encoding which resulted in stronger benefits compared to those resulting from cues when maintaining information for all age groups, perhaps because these cues offer the opportunity to select and prioritize a single item, amongst the four in the memory array, for encoding and retention until test. Importantly, these benefits were similar across development, despite baseline differences in memory ability across age groups. Indeed, storage capacity, measured with *K* estimates in neutral trials, similarly to those reported with a different procedure and in a condition when attention could not be allocated preferentially (see Cowan et al., 2010, 50% condition), showed a monotonic increase across development replicating recent studies (Cowan et al., 2011, 2010; Riggs et al., 2006; Simmering, 2012). Critically though, *K* increased significantly in all age groups when provided with visuo-spatial attention cues and especially for the youngest children it was more than double when cues preceded encoding than when they did not.

Importantly, *developmental differences* emerged in the extent to which cues during maintenance helped participants. That is, the youngest children did not benefit from these cues as much as older children and adults, confirming the differential developmental trajectories by which attention cues facilitate encoding and maintenance in VSTM but also that these trajectories are not constrained by cues' physical or symbolic characteristics. The differential prospective and retrospective cueing benefits in d-prime and *K* across the age groups were bolstered by similar effects on reaction time. Overall, the pattern of benefits here shows that, despite

limited VSTM capacity and poor performance for 7-year-olds (cf. Cowan et al., 2011, 2010), visuo-spatial selective attention plays a critical role in VSTM encoding and maintenance from early childhood in line with adult research proposing that attended locations facilitate object retrieval from VSTM (Treisman & Zhang, 2006). Maintenance differences across the age groups could be driven by multiple non-mutually exclusive factors: dramatic developmental changes in attentional control itself have been clearly recorded (e.g., Akhtar & Enns, 1989; Brodeur & Enns, 1997; Brodeur, Trick, & Enns, 1997), but so have differences in the passive decay of information from memory (e.g., Cowan, Nugent, Elliott, & Saults, 2000) and the interference across the memoranda (e.g., Lewandowsky, Geiger, Morrell, & Oberauer, 2010 for a recent overview of interference-based accounts in adults), points to which I return in later chapters.

Furthermore, the ability to use visuo-spatial orienting cues during the maintenance period related to individual differences in spatial VSTM / VWM span on validated measures used to assess these constructs in childhood, over and above basic memory performance. This is consistent with previous developmental results (Astle et al., 2012) as well as with the extensive literature from cognitive neuroscience (e.g., Fukuda & Vogel, 2009; Vogel & Machizawa, 2004; Vogel et al., 2005). But, what are the cognitive processes that may underpin this relation? Both span measures employed here are derivatives of the Corsi block task and hence had a visuo-spatial emphasis by requiring memory for sequential dot locations (Barrouillet et al., 2009; Rudkin et al., 2007; Salway & Logie, 1995; Vandierendonck et al., 2004). Yet, they differed in terms of cognitive demands and specifically in the extent to which they drew on attentional resources: the Spatial Recall task required

participants to maintain spatial sequences, similar to the Dot Matrix task, while also performing a concurrent task during retention which introduced interference. The contributions of retro-cueing effects being similar to both span measures suggest that the relation between active maintenance and voluntary attentional refreshment exists whether there is a concurrent processing task or not and independently of switching between primary and secondary tasks. Thus, these findings are informative for the current debates on theoretical models of WM and on the precise cognitive processes supporting maintenance, i.e., competition for the limited cognitive resources between processing and storage (e.g., Case, Kurland, & Goldberg, 1982; Daneman & Carpenter, 1980) vs. simple switching between processing and storage rather than resource sharing as proposed by the former account (Towse & Hitch, 1995; Towse et al., 1998) vs. activation of memory traces via refreshment in order to protect items from time-related decay (e.g., Barrouillet et al., 2004, 2012) vs. representation-based interference of the memoranda (e.g., Oberauer & Kliegl, 2006; Oberauer & Lewandowsky, 2008). Although the current data do not allow for robust conclusions as to which WM model makes valid predictions about the mechanisms underlying maintenance and potentially explains developmental differences, results here demonstrate the importance of top-down attentional control in understanding age differences in VSTM / VWM. Nevertheless, these accounts are explored further in Chapter 5.

The strongest relations emerged between the experimental measures of attentional orienting and the Spatial Recall task indicating that controlled attention mechanisms contributed most towards avoiding interference and thus protecting visual representations during maintenance. This supports my suggestion that

voluntary visuo-spatial attentional mechanisms, indexed by retro-cues, are critical for selective maintenance from early childhood. While previous studies showed that children's visuo-spatial memory capacity measured with the Corsi block task increases with age (Logie & Pearson, 1997), results here demonstrate that maximizing VSTM / VWM capacity is intrinsically tied to actively biasing locations and objects in space to effectively maintain information and to a greater degree when under interference, extending results from adults (Awh et al., 1998; Smyth & Scholey, 1994; Ueno, Allen, et al., 2011) to the developmental domain; individual differences in the ability to engage this active process is what retro-cued trials may capture best. These results along with the smaller attentional benefits for younger compared to older children are also consistent with the suggestion by Barrouillet et al. (2009) that attentional refreshment mechanisms may influence complex verbal span differentially from 5 to 14 years of age. Notably, these mechanisms have not been investigated in the visual modality.

Finally, unlike in the study of Astle et al. (2012), 11-year-olds in the current experiment broadly aligned themselves with adults. Their performance may have been superior in the experiment reported here because cues were fully predictive in nature, in contrast to the 75% of cue validity in Astle et al.'s study (2012). This possibility might also explain adults' results, as unlike adults in other studies (Astle et al., 2012; Griffin & Nobre, 2003), adults' accuracy in the current experiment benefited more from orienting prior to encoding than during maintenance. If this is the case, then two questions arise: could it be that the benefits derived from the attentional orienting in service of memory observed so far are automatic rather than voluntary in nature? Even more critically, could reflexive mechanisms underpin

attentional orienting benefits in young children, whereas similar effects are driven by voluntary processes in adults? While endogenously guiding attention is typically associated with centrally presented cues and reflexive shifts of attention with peripheral cues, a number of studies have also shown that central cues can reflexively allocate attention (Hommel et al., 2001; Ranzini, Dehaene, Piazza, & Hubbard, 2009; Ristic et al., 2002; Ristic & Kingstone, 2006; Stevens, West, Al-Aidroos, Weger, & Pratt, 2008; Tipples, 2002) and that peripheral cues engage both voluntary and reflexive orienting when they are spatially predictive (Olk, Cameron, & Kingstone, 2008) both in adults and in children (Iarocci et al., 2009; Ristic & Kingstone, 2009), although these effects have rarely been investigated in service of memory. It is to a manipulation of cue validity that I now turn.

Chapter 3: Development of attentional orienting and VSTM II: Effects of cue validity

Manipulations of cue validity can provide insight into the voluntary or automatic nature of attentional orienting. Critically, they can elucidate similarities and/or differences in attentional deployment across development. The difference between valid and neutral trials indicates the magnitude of an orienting benefit whereas the difference between invalid and neutral trials indicates the magnitude of an orienting cost. Across the adult and child literatures investigating these mechanisms in service of perception, findings demonstrated faster responses for valid than invalid trials for all ages but greater orienting costs for younger than older individuals (Akhtar & Enns, 1989; Enns & Brodeur, 1989; Schul et al., 2003; Wainwright & Bryson, 2002), revealing thus developmental differences in the observed effect of spatial re-orienting. However, findings regarding the magnitude of benefits across ages are more inconsistent and seem to depend on cue validity, ranging from equal benefits across ages with high validity cues to smaller benefits for children than adults with low validity cues (Akhtar & Enns, 1989; Enns & Brodeur, 1989; Pearson & Lane, 1990; see also Schul et al., 2003 and Wainwright & Bryson, 2002 for further discussion).

In addition to providing information about attentional orienting in service of perception, manipulations of cue validity can be extremely useful in furthering our understanding about mechanisms of VSTM. For example, in Cowan et al. 's study (2010), both children and adults were highly sensitive to changes in validity, with *K* dropping significantly when the consistency with which changes occurred in the

attended feature dropped from 100% to 50%. Furthermore, the slope of the change was steeper for adults compared to the youngest children when three items had to be attended, suggesting that older individuals benefited more from valid cues, especially at the limits of their memory capacity. Similarly, Matsukura et al. (2007) employed infrequently presented invalid central cues during the maintenance period to study how adults prioritise cued information and the fate of unattended stimuli which later appeared as target stimuli. Results showed that invalid central cues presented during maintenance reduced adults' accuracy of memory retrieval compared to valid cues. Astle et al. (2011) extended Matsukura et al.'s results by manipulating both cue validity and memory load size and demonstrating that adults use retro-cues strategically; that is, when they operate within capacity limits, adults use valid retro-cues to prioritize how they initiate their search of information in memory. In contrast, when the to-be-remembered information exceeds capacity limits, adults use valid retro-cues to discard the uncued items. However, these and other studies (e.g., Griffin & Nobre, 2003; Schmidt et al., 2002) that used invalid cue trials focused on examining whether retrospective spatial orienting can reliably modulate and improve VSTM retrieval rather than on assessing whether such biases are automatic in nature.

To date, only Berryhill et al. (2012, see Experiment 3) examined the extent to which maintenance effects are under endogenous control. In this experiment, participants were presented with 4 coloured discs followed by an arrow cue that they had to attend or ignore depending on the instructions. Three conditions were included: an "attend" condition with fully informative retro-cues, an "ignore mixed" condition with 25% informative retro-cues, and an "ignore inaccurate" condition

with fully uninformative retro-cues. Participants were advised to attend the cue in the "attend" condition and were explicitly informed that it would always be accurate. They were also instructed to ignore the cue in the other two conditions because it would not be accurate. Berryhill et al. hypothesized that if retrospective orienting is under endogenous control then participants would be able to ignore the cues and therefore memory retrieval would not be compromised by the invalid trials. Results showed no cue benefits in the "ignore inaccurate" condition and a non-significant trend for a cue benefit in the "ignore mixed" condition that nonetheless diminished over time, prompting Berryhill et al. to suggest that endogenous control drives, although not entirely, the orienting effects during maintenance. However, the experiment did not address these questions in a developmental context and did not manipulate cue position (i.e., central vs. peripheral). In the present experiment, in which cues are not always informative, cue position may play a differentially larger role than what we have witnessed in Chapter 2.

Experiment 2: Endogenous vs. exogenous orienting processes during VSTM maintenance

Results from Chapter 2 showed no substantial differences in the way central and peripheral cues modulate VSTM retrieval in children and adults when they reliably predict the target's location, whereas developmental differences were particularly evident when cues oriented attention during the maintenance period. In order to investigate further the argument concerning the same vs. different attentional mechanisms for voluntary vs. automatic orienting in service of memory, in

Experiment 2 I reduced the predictive validity of cues and explicitly pointed out the low validity to participants of all ages. I hypothesized that if overall cueing benefits and any of the developmental differences demonstrated in Experiment 1 (Chapter 2) depend on automatic orienting processes rather than controlled voluntary orienting, then, regardless of cue position, benefits should be obtained even when cues have very low validity. If, on the contrary, voluntary allocation of attention drives the effects, cueing benefits should be drastically reduced compared to Experiment 1. In contrast to Experiment 1 (Chapter 2), only spatial retro-cues were employed here since this type of cues produced the age-related differences in Experiment 1 and because individual differences in retro-cueing benefits uniquely related to VSTM / VWM span.

Experiment 2 addressed these questions by examining (1) whether cues in different positions result in automatic or reflexive allocation of attention in representations held in VSTM and (2) whether these allocation mechanisms change across ages.

Methods

Participants

Thirty-four children (15 boys and 19 girls) aged 6-7 year old (M=6.47 years old, SD=.51; “7-year-olds” henceforth), 36 children (16 boys and 20 girls) aged 10-12 years old (M=10.92 years old, SD=.77; “11-year-olds” henceforth) and 19 adults (4 males and 15 females) aged 19 to 30 years old (M=24.95, SD=3.37) participated in this experiment. Adults were recruited from the University of Oxford.

Measures

Attentional Orienting Task: All parameters were the same as Experiment 1 except in three main respects. First, all cued trials were presented retrospectively, to investigate the developmental differences demonstrated in Chapter 2. Therefore, there were only retro-cue and neutral trials and the memory array was always presented after the fixation point. Second, retro-cues could be valid or invalid. Third, instead of manipulating cue-position across participants, all participants completed two blocks with centrally presented cues ("central blocks") and two blocks with peripherally presented cues ("peripheral blocks"), whose order alternated across blocks and was counterbalanced across participants (see Figure 6).

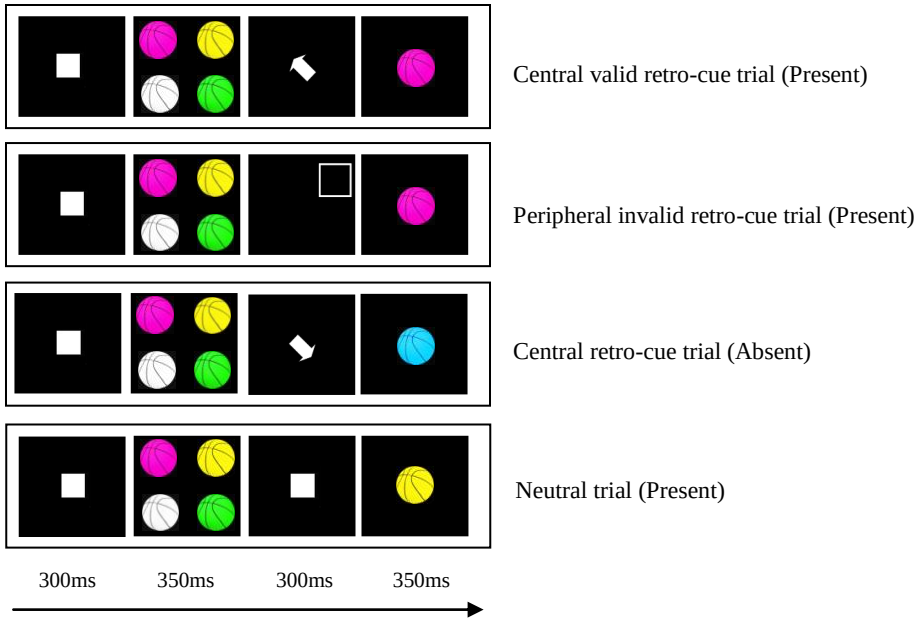


Figure 6. Schematic illustration of the task and the trial-types. Dimensions of items in relation to space are bigger for display purposes.

As with Experiment 1, each test block contained 48 trials, totalling 192 test trials, of which 128 (66.6%) were probe-present trials and 64 (33.3%) were probe-absent trials. Of the probe-present trials, 96 were cued (equally likely to point to one of the four possible spatial locations; half of all cued trials used central cues and half used peripheral cues) and 32 were neutral trials. If a cue was presented in probe-present trials, it indicated the location of the probe in the memory array 50% of the time. That is, of cued probe-present trials, half were validly cued (i.e., the probe appeared at the cued location), totalling 48 validly cued trials over the four blocks, and half were invalidly cued (i.e., the probe appeared at one of the other three locations), totalling 48 invalidly cued trials. Therefore, on probe-present trials, cues were 50% likely to indicate the location of the probe in the memory array, a significant decrease in their validity compared to the 100% validity of Experiment 1. Of note, retro-cues were still moderately predictive of probe location in probe-present trials (50% at cued location vs. 16.6% at each of the remaining uncued locations). A lower validity would have been achieved with cues 25% likely to indicate the location of the probe amongst the 4 possible in the memory array. I settled on the current level of validity to reach a balance between a substantial reduction in validity compared to Experiment 1 and a reliable number of trials for d-prime, *K*, and median RT calculations. Probe-absent trials contained an equal split of cued (32) and neutral trials (32) to avoid cues indexing "present" trials. All timing parameters were identical to Experiment 1 (see Figure 2).

Procedure

The procedure was nearly identical to Experiment 1 (Chapter 2). The only difference was the nature of the task-specific instructions participants received. Participants were told that sometimes a cue, either a white arrow or a white border, would appear after the four pictures and that they would always be informed prior to the beginning of the block about the type of cue that would appear. When no cue would appear, they would just see a white filled square presented centrally. Importantly, they were informed that occasionally the cue would be helpful but other times it would trick them by pointing towards or marking a different spatial location than the one the final picture had occupied in the memory array. Participants were thus recommended to ignore the cue if they could. Illustrations of the example cards are presented in Appendix B, Figure B3. The task was completed in approximately 20 minutes. Adults participated voluntarily and were tested at the Attention, Brain and Cognitive Development (ABCD) Lab at the Department of Experimental Psychology at the University of Oxford.

Statistical design and analyses

A mixed-design ANOVA was performed on d-prime, *K*, and median RT scores testing the within-subjects factors of cue-position (central, peripheral) and trial-type (valid cue, invalid cue, neutral) and the between-subjects factor of age-group (7-year-olds, 11-year-olds, adults). In addition, to compare the effects obtained in Experiment 1 (Chapter 2) with the effects obtained in this experiment (Chapter 3), I conducted two separate ANOVAs on valid retro-cue and retro-neutral trials[5] with

[5]"Retro-neutral" trials refer to neutral trials in retro-cue blocks in Experiment 1 (Chapter 2) and all neutral trials in Experiment 2 (Chapter 3).

the "Experiment" (Experiment 1: 100% central valid vs. Experiment 2: 50% central valid in the first ANOVA; Experiment 1: 100% peripheral valid vs. Experiment 2: 50% peripheral valid in the second ANOVA) and the age-group as between-subject variables. In short, the first ANOVA was on central-cue blocks only (i.e., Experiment 1 central cues vs. Experiment 2 central cues) and the second one on peripheral-cue blocks only (i.e., Experiment 1 peripheral cues vs. Experiment 2 peripheral cues).

Results

D-prime

D-prime scores revealed significant main effects of trial-type [$F(1.81,155.68)=3.67$, $p=.03$, $\eta^2=.04$] and age-group [$F(2,86)=83.44$, $p<.001$, $\eta^2=.66$]. The means for d-prime scores are reported in Table 12. Participants performed significantly better in trials with valid retro-cues (M=1.49) compared to invalid retro-cues (M=1.37, p=.02). However, cueing benefits compared to neutral trials were much reduced compared to Experiment 1 (see Figure 7). Indeed, there were no significant differences between valid cued and neutral trials (M=1.37, p>.05) or between invalid cued and neutral trials (p>.05). Unsurprisingly, adults (M=2.36) performed significantly better than 7-year-olds (M=.44, p<.001) and 11-year-olds (M=1.44, p<.001), who in turn discriminated significantly better than 7-year-olds (p<.001). None of the other main effects or interactions reached statistical significance (p>.05 for all effects). As in Experiment 1, because the absolute level of performance by the youngest children was low, I tested whether it differed significantly from chance. In neutral trials, average accuracy on target present trials was M=.57 for central blocks and M=.60 for peripheral blocks, values that differed

significantly from chance (p=.01 and p=.004 respectively). In addition, average accuracy on retro-cue trials was M=.58 for both valid and invalid trials in central blocks and M=.61 and M=.58 for valid and invalid trials in peripheral blocks respectively, values that also differed significantly from chance (p≤.01 in all instances).

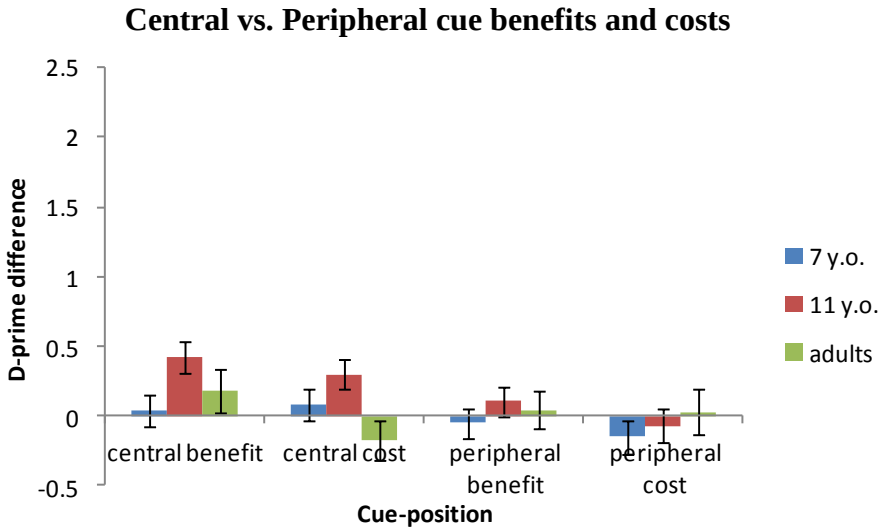


Figure 7. D-prime difference scores from neutral baseline, comparing valid and invalid cues across central and peripheral blocks for all age-groups. Benefit scores indicate the difference between valid and neutral trials and cost scores indicate the difference between invalid and neutral trials. Error bars represent standard errors of the mean.

Table 12. *D-prime, K, and RT scores for valid, invalid, and neutral trials, in central and peripheral blocks for all age-groups. Standard deviations are reported in parentheses.*

	Central block			Peripheral Block		
	Valid	Invalid	Neutral	Valid	Invalid	Neutral
D-prime						
7-year-olds	0.41	0.45	0.37	0.48	0.38	0.53
	(0.54)	(0.65)	(0.52)	(0.54)	(0.56)	(0.60)
11-year-olds	1.59	1.47	1.18	1.55	1.37	1.44
	(0.74)	(0.64)	(0.67)	(0.73)	(0.85)	(0.60)
Adults	2.52	2.18	2.35	2.38	2.37	2.34
	(0.72)	(0.87)	(0.74)	(0.60)	(0.79)	(0.83)
K						
7-year-olds	0.58	0.60	0.53	0.70	0.57	0.72
	(0.75)	(0.86)	(0.76)	(0.72)	(0.74)	(0.85)
11-year-olds	2.12	1.99	1.61	2.02	1.79	1.93
	(0.85)	(0.79)	(0.87)	(0.83)	(1.01)	(0.66)
Adults	2.98	2.64	2.86	2.86	2.83	2.82
	(0.51)	(0.77)	(0.67)	(0.51)	(0.64)	(0.71)
RT (ms)						
7-year-olds	1185.49	1177.63	1183.31	1198.97	1267.97	1199.87
	(305.08)	(277.03)	(270.11)	(325.72)	(351.26)	(344.59)
11-year-olds	923.58	917.06	937.99	916.06	965.32	971.50
	(317.23)	(265.26)	(290.74)	(294.52)	(252.54)	(303.72)
Adults	644.29	719.97	704.53	656.58	716.29	696.58
	(181.25)	(171.00)	(136.04)	(178.87)	(139.45)	(144.71)

Next, I examined possible age differences in response to changes in percentage validity for each cue-position separately. To do so, I contrasted directly the d-prime scores on validly cued and neutral trials for Experiment 1 vs. 2 (central cue-position) and for Experiment 1 vs. 2 (peripheral cue-position). Both comparisons resulted in statistically significant interactions of Experiment x trial-type [$F(1,138)=15.67$, $p<.001$, $\eta^2=.10$ for central cue; $F(1,144)=15.27$, $p<.001$, $\eta^2=.10$ for peripheral cue], suggesting that cueing benefits differed depending on cue validity (100% vs. 50%).The d-prime analysis on difference scores (retro-cue – neutral trials) for both ANOVAs showed a significant reduction in cue benefits in Experiment 2 compared to 1: there was a statistically significant main effect of Experiment (Experiment 1 central cue benefit: M=.69 and Experiment 2 central cue benefit: M=.21, p<.001; Experiment 1 peripheral cue benefit: M=.47 and Experiment 2 peripheral cue benefit: M=.03, p<.001). The Experiment x age-group interactions did not reach significance in any of the two ANOVAs [$F(2,138)=2.05$, $p=.13$, $\eta^2=.03$ for central cue benefit; $F(2,144)=.62$, $p=.54$, $\eta^2=.01$ for peripheral cue benefit] suggesting that the age-groups responded similarly to changes in cue validity for both central and peripheral cues.

K capacity measure

Results mirrored those in the d-prime analysis. *K* scores revealed significant main effects of trial-type [$F(1.83,157.20)=3.44$, $p=.04$, $\eta^2=.04$] and age-group [$F(2,86)=88.60$, $p<.001$, $\eta^2=.67$ respectively]. The means for *K* scores are reported in Table 12. Participants had higher *K* scores in trials with valid retro-cues (M=1.88) compared to invalid retro-cues (M=1.73, p=.02). Again, there were no significant

differences between valid cued and neutral trials (M=1.75, p>.05) or between invalid cued and neutral trials (p>.05). Figure 8 illustrates the benefits and costs from central and peripheral cues. Unsurprisingly, adults (M=2.83) had higher *K* scores than 7-year-olds (M=.62, p<.001) and 11-year-olds (M=1.91, p<.001), who in turn had higher *K* scores than 7-year-olds (p<.001). None of the other main effects or interactions reached statistical significance (p>.05 for all effects).

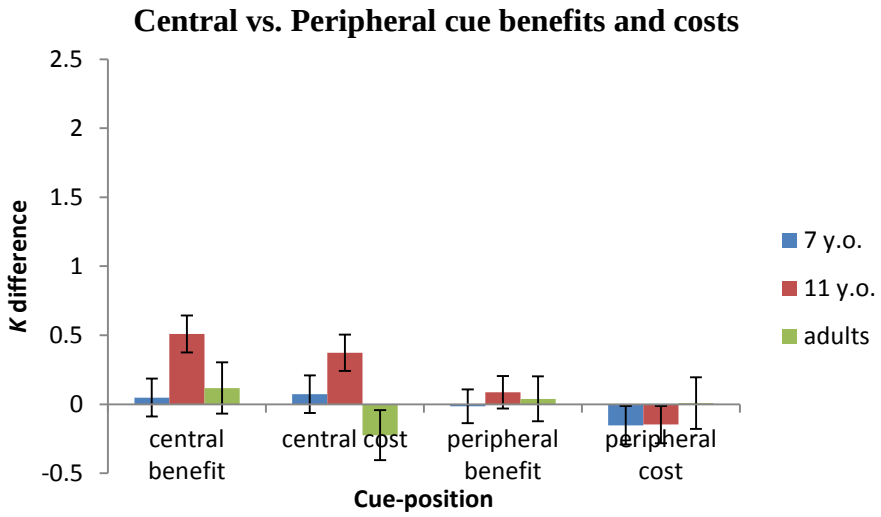


Figure 8. *K* difference scores from neutral baseline, comparing valid and invalid cues across central and peripheral blocks for all age-groups. Benefit scores indicate the difference between valid and neutral trials and cost scores indicate the difference between invalid and neutral trials. Error bars represent standard errors of the mean.

Again, I contrasted the central and peripheral cue benefits for Experiment 1 (Chapter 2) vs. Experiment 2 (Chapter 3). The *K* analysis on difference scores showed a significant reduction in cue benefits in Experiment 2 compared to Experiment 1: there was a significant main effect of Experiment (Experiment 1 central cue benefit: M=.66 and Experiment 2 central cue benefit: M=.23, p=.002;

Experiment 1 peripheral cue benefit: M=.53 and Experiment 2 peripheral cue benefit: M=.04, p<.001). No Experiment x age-group interactions were present [F(2,138)=.86, p=.43, η^2=.01 for central cue benefit; F(2,144)=.48, p=.62, η^2=.01 for peripheral cue benefit].

Median RTs

A similar pattern of results was obtained for median RTs, with significant main effects of trial-type [F(2,172)=3.91, p=.02, η^2=.04] and age-group [F(2,86)=27.12, p<.001, η^2=.39]. The means for RT scores are reported in Table 12. Participants were faster in valid cued trials (M=920.83) compared to invalid cued trials (M=960.71, p<.05), though cueing benefits, i.e., the difference between valid cued and neutral (M=948.96) trials, and costs, i.e., the difference between invalid cued and neutral trials, were not significant (p>.05 for both benefits and costs). Figure 9 illustrates the benefits and costs from central and peripheral cues. As in d-prime and *K*, adults (M=689.71) were faster than 7-year-olds (M=1202.21, p<.001) and 11-year-olds (M=938.58, p=.002), who in turn were faster than 7-year-olds (p<.001). None of the other main effects or interactions reached statistical significance (p>.05 for all effects).

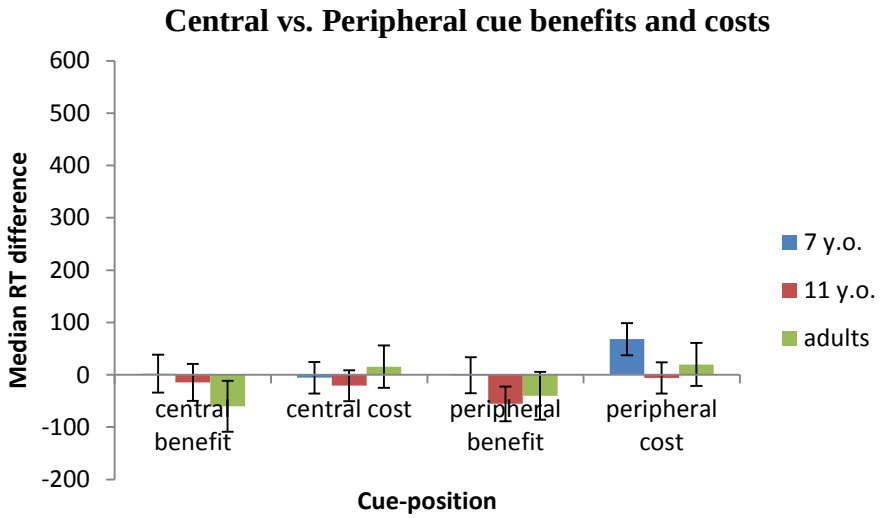


Figure 9. Median RT difference scores from neutral baseline, comparing valid and invalid cues across central and peripheral blocks for all age-groups. Benefit scores indicate the difference between valid and neutral trials and cost scores indicate the difference between invalid and neutral trials. Error bars represent standard errors of the mean.

As before, I also contrasted the benefits conferred by central and peripheral cues (retro-cue – neutral trials) between Experiment 1 and 2. Again, there was a significant reduction in cue benefits in Experiment 2 compared to Experiment 1 for both central and peripheral cues: there was a main effect of Experiment (Experiment 1 central cue benefit: M=258.89 and Experiment 2 central cue benefit: M=24.15, $p<.001$; Experiment 1 peripheral cue benefit: M=256.12 and Experiment 2 peripheral cue benefit: M=32.11, $p<.001$). There were no interactions between Experiment and age-group in either ANOVA [$F(2,138)=1.18$, $p=.31$, $\eta^2=.02$ for central cue benefit; $F(2,144)=.43$, $p=.65$, $\eta^2=.01$ for peripheral cue benefit].

Discussion

A key finding of Experiment 2 is that, beyond differences in overall accuracy, storage capacity, and speed, there were no significant age-related differences in cueing effects. This contrasts with the marked differences in cueing effects between young children and the other two age groups found in Experiment 1 (Chapter 2). In Experiment 2, I reduced cue validity by introducing trials with invalid cues, and informed participants of this, and as a result improvements in accuracy and response times for probes at validly cued locations (compared to neutral trials) were eliminated. The current findings therefore suggest that attentional benefits depend largely on voluntary rather than automatic orienting processes, and confirm that the specific physical or symbolic characteristics of orienting cues (central or peripheral) do not result in developmental differences, at least not when in service of memory and in children as young as 7 years of age. The reliability with which cues predict target locations is a much stronger distinguishing factor in understanding attentional orienting mechanisms engendered by spatial cues, both in adults and in children (consistent with Iarocci et al., 2009; Ristic & Kingstone, 2009). To the best of my knowledge, this is the first study that assessed this in service of VSTM and across development.

Valid cues nonetheless resulted in a small but significant residual advantage compared to invalid cues, even when orienting cues predicted the location of targets in memory with low probability. Based on the results from Berryhill et al.'s study (2012), this may be because the cues used here were not completely unpredictive of the target location, although they were much less informative than in Experiment 1.

These effects deserve further investigation using parametric manipulations of cue validity across development: although the greater proportion of attentional cueing benefits hinge on voluntary orienting, automatic orienting may still play a small role in biasing where participants begin to search their memory, as indexed by the difference between validly and invalidly cued locations in large memory arrays (Astle et al., 2011), and these strategic search mechanisms may change over developmental time. The voluntary or automatic nature of attentional refreshment mechanisms is a topical question for recent developmental studies of memory maintenance (e.g., Barrouillet et al., 2009; Tam et al., 2010), and the current findings strongly point to the fact that, even children as young as 7 years of age can voluntarily allocate attention to refresh or prioritise items in VSTM as well as that they can largely resist automatic effects of cues when they are not informative. The extent to which children would use cues spontaneously had they not been informed of the value of the cues should also be investigated in future.

Given that the physical characteristics of the cues and their symbolic nature cannot explain developmental differences in benefits from the cues during maintenance as demonstrated in Chapter 2, and that children as young as 7 years old can voluntarily guide their attention to selectively maintain and/or ignore competing information in VSTM as demonstrated in Chapter 3[6], it remains unclear why the youngest children's accuracy did not benefit from retro-cues compared to neutral baseline performance in Experiment 1 as much as 7-year-olds'accuracy in the study

[6] This statement highlights the difference in findings for the 7-year-olds across Experiments 1 and 2. While 7-year-olds benefited from cues during maintenance when they were explicitly told to pay attention to the cues in Experiment 1, they showed no reliable retro-cue effects in Experiment 2 when they were explicitly asked to ignore the cues. Taken together, these two results demonstrate that 7-year-olds can follow experimental instructions either to voluntarily guide their attention to the spatial location indicated by the retro-cues or to volitionally ignore the cues.

by Astle et al. (2012) and why in general young children do not benefit from these cues as much as older children and adults. One possibility for the latter is that the size of the memory array was beyond VSTM capacity limits for the youngest children. If the load of the-to-be-remembered items exceeded storage capacity for the 7-year-olds, it is possible that there was nothing to select from by the time the retro-cue appeared. Indeed, Cowan et al. (2010) showed that 7-year-olds exhibit equivalent filtering abilities to older individuals unless their capacity is overloaded. If this is the case, then we should expect to see attention effects from cues during maintenance when the memory load is within capacity limits but not beyond.

Furthermore, in the adult literature, it has been proposed that cues during maintenance enhance the active maintenance of relevant items and/or suppress the activation of irrelevant items (Lepsien & Nobre, 2006, 2007), protect the representation of the selected item from decay or interference during the retention interval (Makovski & Jiang, 2007; Makovski et al., 2008; Matsukura et al., 2007), and provide direct retrieval routes to items in memory by prioritizing the comparison process of the selected item with the probe (Astle et al., 2011). Based on these proposals, at least two more possible accounts can be suggested. First, for younger children, information encoded in VSTM may be decaying at a faster rate (e.g., Cowan et al., 2000) so that when a beneficial cue eventually appears in the maintenance period, the quality of the representations on which it can operate is degraded to a greater extent. This account may explain the smaller retro-cue benefits for 7-year-olds in Experiment 1 compared to those of Astle et al. (2012, Experiment 1). Indeed, Astle et al. (2012) employed a shorter retention interval period to the one

used in Experiment 1, and thus the presence of iconic traces may account for the larger retro-cueing benefits observed for 7-year-olds in the their study.

Second, the memoranda may be interfering with each other to a greater degree (Lewandowsky et al., 2010) resulting in more fragile internal representations by the time the retro-cue appears, even when no concurrent secondary processing task is required. The to-be-remembered items used by Astle et al. were very different from the current items: the array included 4 pictures that were perceptually highly dissimilar from each other, referred to highly familiar objects, and could be easily verbalized. In contrast, current arrays included 4 identical items that only differed in colour. These differential characteristics of the memoranda might also account for the finding that unlike adults in other studies (Astle et al., 2012; Griffin & Nobre, 2003), adults' accuracy here benefited more from orienting prior to encoding than during maintenance. I assess the memory load and decay accounts in the next two chapters, in Experiments 3 and 4, Chapters 4 and 5 respectively. I return to the characteristics of the memoranda in Experiment 5, Chapter 6.

Chapter 4: Orienting of attention in early childhood I: Effects of memory load

Findings from many studies with adult populations strongly advocate the presence of a highly limited VSTM capacity of about 4 items, with memory performance declining when the load of visual information exceeds this number (Alvarez & Cavanagh, 2004; Awh, Barton, & Vogel, 2007; Barton, Ester, & Awh, 2009; Bays, Catalao, & Husain, 2009; Bays & Husain, 2008; Cowan, 2001; Fukuda, Awh, & Vogel, 2010; Luck & Vogel, 1997; Rouder et al., 2008; Todd & Marois, 2004; Vogel, Woodman, & Luck, 2001; Zhang & Luck, 2008, 2011). Also, studies have shown that the effect of increasing load with up to 4 items is attenuated when spatial orienting or selection can take place on representations held internally in VSTM (Kuo, Stokes, et al., 2011; Lepsien et al., 2005). This indicates that attentional control is critical during the maintenance period for enhancing memory performance when the total number of items is within capacity limits (but see Sligte et al., 2008, for evidence that attentional cueing can also improve memory with much larger memory arrays). For example, Nobre, Griffin, and Rao (2008) compared adults' performance following spatially informative retro-cues with performance following neutral cues after encoding an array of varied load sizes (1, 2, and 4 items). Results revealed an interaction between the type of cue and the memory load size in both accuracy and latency; the interaction was driven by better performance following retro-cues than neutral cues in the load-2 and load-4 arrays, but not reliably in the load-1. Also, the benefits of retro-cues were accentuated as the load increased from 1 item to 2 items and from 2 items to 4 items.

However, recent load manipulations have not always yielded benefits from cues during maintenance when the total number of items exceed VSTM capacity limits, demonstrating that young adults do not always rely on retro-cues to enhance memory recognition. Astle et al. (2011, see Experiment 3) presented participants with a memory array of coloured crosses that varied in load sizes (2, 4, and 8 items) followed by either spatial retro-cues or neutral cues. Results showed that orienting attention internally modulated item maintenance, resulting in cueing benefits, but only when the load of items was just within capacity limits, i.e., 4 items. With 8 items in the array, participants did not benefit from retro-cues compared to the neutral cues. Furthermore, their overall storage capacity estimates did not exceed 4 items, suggesting that in the load-8 condition they did not store items in VSTM beyond the 4-item limit. Surprisingly, in contrast to previous findings (Nobre et al., 2008), Astle et al. found no cue benefits even with 2 items in the array, suggesting that when the load of information to be held in VSTM is low, individuals do not necessarily use the retro-cue.

Experiment 3: Top-down biases in early childhood when VSTM capacity is overloaded

Results from Experiment 1 (Chapter 2) showed that 7-year-olds are able to use cues presented *prior to encoding* information equally well to 11-year-olds and adults in order to facilitate memory efficiency, presumably because these cues reduced the load of information for encoding, whereas developmental differences were clearly evident in participants' ability to use cues presented *during the*

maintenance of information. These differences could not be explained by the symbolic nature of the cues as demonstrated in Experiment 1 (Chapter 2) or by the youngest children's inability to voluntarily guide their attention to selectively maintain and/or ignore competing information in VSTM as demonstrated in Experiment 2 (Chapter 3). Building on the adult findings described above (Astle et al., 2011), an alternative account for the smaller retro-cue benefits in 7-year-olds compared to the other two age groups is that a memory array of 4 items exceeded young children's capacity limits, resulting simply in a smaller number of items being stored in VSTM compared to the older participants, and therefore less information to be selectively refreshed by retro-cues. Indeed, developmental studies have already documented the smaller storage capacity for younger children (approximately 3 items) compared to older children and adults (approximately 4-5 items; Cowan et al., 2005; Riggs et al., 2006) and the diminished attentional filtering abilities for 7-year-olds compared to 12-year-olds and adults when the 7-year-olds' capacity was overloaded with visual information but not when the load of information was low (Cowan et al., 2010). In order to investigate further this hypothesis, in Experiment 3 I reduced the number of memory array items for the 7-year-olds to 2 items and compared their performance to that with memory arrays of 4 items.

I hypothesized that if smaller cueing benefits during maintenance for the 7-year-olds compared to older children and adults depend simply on less information having been encoded in VSTM because of lower storage capacity, then such benefits should be obtained when the memory load of visual information is within capacity limits (i.e., 2 items) but not beyond (i.e., 4 items). As in Experiment 1, both spatial pre-cues and retro-cues were employed to allow for direct comparisons across trial-

types (pre-cue vs. retro-cue) and for better understanding how the attentional processes that these cues enable (attentional orienting prior to encoding in VSTM vs. attentional orienting during maintenance in VSTM) interact with storage capacity in early childhood. The spatial cues employed here were central symbolic arrows to avoid possible masking effects[7] similar to those observed for adults in the peripheral-cue group in Experiment 1.

Methods

Participants

Twenty-one children (7 boys and 14 girls) aged 6 and 7 years old (M = 6.52 years old, SD = .51, "7-year-olds" henceforth) participated in Experiment 3 and completed the Attentional Orienting Task with 2 items in the array (2-item task). Their data were analysed in combination with those of 7-year-olds in the central-cue group in Experiment 1, who completed the Attentional Orienting Task with 4 items in the array (4-item task). As a result, data from 41 children (15 boys and 26 girls) between 6 and 7 years old (M=6.56 years old, SD=.50; "7-year-olds" henceforth) contributed to these analyses. Children who completed the 2-item task were labelled as the "load-2 group" and children who completed the 4-item task were labelled as the "load-4 group".

Measures

Attentional Orienting Task: The task used was identical to the 4-item task used for the central-cue group in Experiment 1 except that participants in the load-2

[7] Indeed, an additional experiment with peripheral cues (e.g., a star) showed masking effects for cues during maintenance. This experiment is presented in Appendix C (Experiment 1B).

group in Experiment 3 were presented with two items in the array instead of four (see Figure 10).

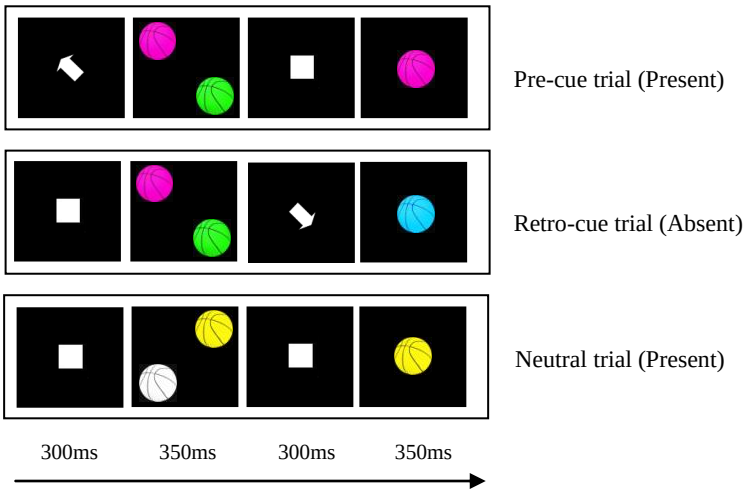


Figure 10. Schematic illustration of the 2-item task and the 3 trial-types. Dimensions of items in relation to space are bigger for display purposes.

AWMA – Dot Matrix and *Spatial Recall:* The two AWMA subscales (the Dot Matrix and the Spatial Recall, measuring VSTM and VWM span respectively) administered in Experiment 1, were also administered to the load-2 group in Experiment 3.

Procedure

The procedure was identical to that of central-cue group in Experiment 1 except for a difference in the task instructions that participants in the load-2 group received. Participants were told that 2 identical pictures in different colours would first appear on the screen and after a little while, another coloured picture would appear. Their job was to search their memory and decide whether that last coloured

picture was one of the two initial ones and to click the mouse buttons accordingly. Illustrations of the example cards are presented in Appendix B, Figure B4. The AWMA subscales (Dot Matrix and Spatial Recall) were administered to the load-2 group following the same instructions and procedure as in Experiment 1.

Statistical design and analyses

Three mixed-design ANOVAs were performed separately on d-prime, *K*, and median RT scores with the block (pre-cue, retro-cue) and the trial-type (cued, neutral) as the within-subject variables and the memory load (2 items, 4 items) as the between-subject variable. In order to investigate the extent to which performance on the Attentional Orienting Task related to VSTM and VWM abilities, bivariate and partial correlational analyses, controlling for performance on neutral baseline trials, were carried out on performance on cued trials (d-prime and *K* on pre-cue and retro-cue trials) and on raw scores on the Dot Matrix (indexing VSTM span) and Spatial Recall (indexing VWM span) subscales for each load separately.

Results

D-prime

The analysis on the d-prime scores yielded significant main effects of memory load [$F(1,39)=6.51$, $p=.02$, $\eta^2=.14$], block [$F(1,39)=27.51$, $p<.001$, $\eta^2=.41$], and trial-type [$F(1,39)=24.72$, $p<.001$, $\eta^2=.39$], as well as significant interactions of memory load x block [$F(1,39)=14.83$, $p<.001$, $\eta^2=.28$], memory load x trial-type [$F(1,39)=18.99$, $p<.001$, $\eta^2=.33$], and block x trial-type [$F(1,39)=20.90$, $p<.001$,

η^2=.35]. Most importantly, the analysis yielded a highly significant three-way interaction of memory load x block x trial-type [F(1,39)=27.80, p<.001, η^2=.42]. Mean d-prime scores are reported in Table 13.

Analyses of simple main effects for the three-way interaction revealed that with *4 items* in the array, 7-year-olds performed significantly better in cued than in neutral trials in the pre-cue block (p<.001), but not in the retro-cue block (p=.08, note that the trend was in the same direction as the significant effect in the pre-cue block), whereas with *2 items* in the array, 7-year-olds performed equally well in cued and neutral trials, both in pre-cue (p>.05) and retro-cue (p>.05) blocks. Furthermore, with *4 items* in the array, 7-year-olds performed significantly better in the pre-cue block than in the retro-cue block in cued trials (p<.001), but not in neutral trials (p>.05), whereas with *2 items* in the array 7-year-olds performed equally well across blocks both in cued (p>.05) and neutral trials (p>.05). Importantly, in *cued trials of the pre-cue block*, 7-year-olds performed equally well with 2 and 4 items in the array (p>.05), suggesting that pre-cues equated encoding requirements across the two conditions. In contrast, 7-year-olds performed significantly better with 2 items than with 4 items in the array in *cued trials of the retro-cue block* (p=.004) and in *neutral trials* of both pre-cue (p=.001) and retro-cue (p<.001) blocks.

In order to investigate differences in cueing benefits associated with memory load independently of baseline differences in memory in neutral trials, difference scores were also calculated (Figure 11). The analysis on difference scores yielded main effects of memory load [F(1,39)=18.99, p<.001, η^2=.33] and block-benefit [F(1,39)=20.90, p<.001, η^2=.35] as well as a significant interaction of memory load x block-benefit [F(1,39)=27.80, p<.001, η^2=.42]. Simple main effects for the

interaction indicated that 7-year-olds benefited from pre-cues to a greater degree when the array contained 4 items (M=1.65) than 2 items (M=.01, p<.001), whereas they benefited from retro-cues to a similar degree across arrays with 4 items (M=.28) and 2 items (M=.11, p>.05). With *4 items*, 7-year-olds benefited from pre-cues to a greater degree than from retro-cues (p<.001), whereas with *2 items*, 7-year-olds benefited equally from pre-cues and retro-cues (p>.05).

Table 13. D-*prime, K, and RT scores for load-2 vs. load-4, for pre-cue, retro-cue, and neutral trials. Standard deviations are reported in parentheses.*

	Pre-cue block		Retro-cue block	
	Cued	Neutral	Cued	Neutral
D-prime				
Load-2	1.92 (1.12)	1.90 (1.30)	1.86 (1.15)	1.74 (1.12)
Load-4	2.37 (0.91)	0.72 (0.64)	0.95 (0.69)	0.68 (0.47)
K				
Load-2	1.15 (0.63)	1.12 (0.69)	1.12 (0.63)	1.07 (0.68)
Load-4	2.79 (0.86)	0.90 (0.71)	1.30 (0.95)	0.96 (0.63)
RT (ms)				
Load-2	1234.43 (381.96)	1331.71 (496.39)	1245.24 (300.64)	1196.64 (300.40)
Load-4	940.23 (225.62)	1402.23 (323.80)	1171.53 (306.89)	1467.88 (263.49)

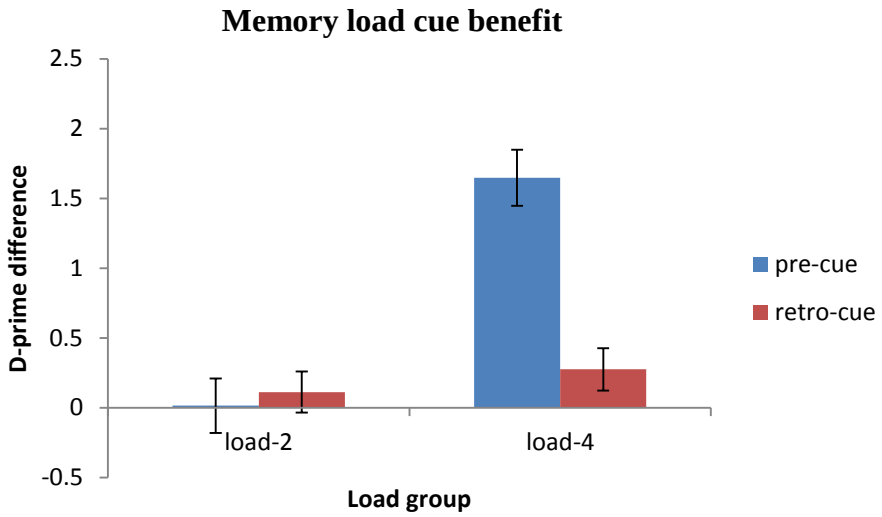


Figure 11. D-prime difference scores from neutral baseline, comparing pre-cue and retro-cue blocks for load-2 and load-4 groups. Error bars represent standard errors of the mean.

K capacity measure

The analysis on *K* scores yielded a marginal main effect of memory load [$F(1,39)=4.04$, $p=.05$, $\eta^2=.09$] and significant main effects of block [$F(1,39)=24.35$, $p<.001$, $\eta^2=.41$] and trial-type [$F(1,39)=38.32$, $p<.001$, $\eta^2=.50$]. In addition, the memory load x block [$F(1,39)=19.21$, $p<.001$, $\eta^2=.33$], the memory load x trial-type [$F(1,39)=32.89$, $p<.001$, $\eta^2=.46$], and the block x trial-type [$F(1,39)=47.28$, $p<.001$, $\eta^2=.55$] interactions reached significance. Importantly, the three-way interaction of memory load x block x trial-type [$F(1,39)=48.20$, $p<.001$, $\eta^2=.55$] was highly significant. Mean *K* scores are reported in Table 13.

Analyses of simple main effects for the three-way interaction revealed that with *4 items* in the array, 7-year-olds had higher *K* scores in cued than in neutral trials, both in pre-cue ($p<.001$) and retro-cue ($p=.03$) blocks, whereas with *2 items* in the array, young children had equal *K* scores between cued and neutral trials, both in

pre-cue ($p>.05$) and retro-cue ($p>.05$) blocks, indicating the presence of benefits in storage capacity from pre-cues and retro-cues with 4 items but not with 2 items in the array. Furthermore, with *4 items* in the array, 7-year-olds had higher *K* scores in the pre-cue block than in the retro-cue block in cued trials ($p<.001$), but not in neutral trials ($p>.05$), whereas with *2 items* in the array, young children had equal *K* scores across blocks both in cued ($p>.05$) and neutral trials ($p>.05$), suggesting the presence of greater benefits in storage capacity from cues prior to encoding than during maintenance with 4 items but not with 2 items in the array. Finally, in *cued trials of the pre-cue block*, 7-year-olds had higher *K* scores with 4 items than with 2 items in the array ($p<.001$). In contrast, *K* scores were equal between 4 items and 2 items in the array in *cued trials of the retro-cue block* and in *neutral trials* of both pre-cue and retro-cue blocks ($p>.05$ for all cases).

In order to verify cueing benefits in storage capacity independently of baseline differences in neutral trials, difference scores were also calculated (Figure 12). The analysis on difference scores yielded main effects of memory load [$F(1,39)=32.89$, $p<.001$, $\eta^2=.46$] and block-benefit [$F(1,39)=47.28$, $p<.001$, $\eta^2=.55$], as well as a significant interaction of memory load x block-benefit [$F(1,39)=48.20$, $p<.001$, $\eta^2=.55$]. Simple main effects for the interaction indicated greater pre-cue benefits in arrays with 4 items ($M=1.88$) than with 2 items ($M=.04$, $p<.001$) and, with 4 items in the array, greater pre-cue than retro-cue ($M=.34$, $p<.001$) benefits. There were no significant differences in retro-cue benefits between arrays of 4 items and 2 items ($M=.05$, $p>.05$) or between pre-cue and retro-cue benefits with 2 items in the array ($p>.05$).

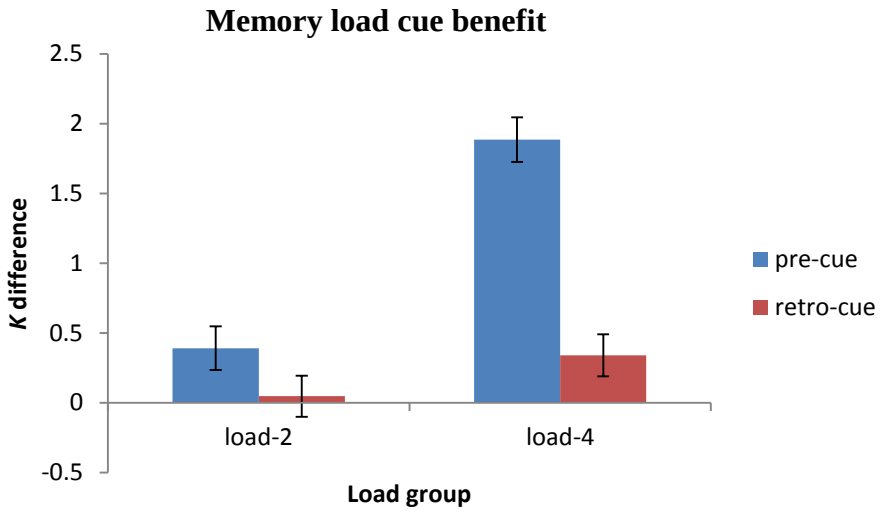


Figure 12. *K* difference scores from neutral baseline, comparing pre-cue and retro-cue blocks for load-2 and load-4 groups. Error bars represent standard errors of the mean.

Median RTs

The analysis on the RT scores yielded a significant main effect of trial-type [$F(1,39)=75.72$, $p<.001$, $\eta^2=.66$] and significant interactions of memory load x block [$F(1,39)=9.87$, $p=.003$, $\eta^2=.20$], memory load x trial-type [$F(1,39)=58.55$, $p<.001$, $\eta^2=.60$], and block x trial-type [$F(1,39)=12.53$, $p=.001$, $\eta^2=.24$]. The main effect of memory load [$F(1,39)=.005$, $p=.95$, $\eta^2=.000$] and the interaction of memory load x block x trial-type [$F(1,39)=.05$, $p=.82$, $\eta^2=.001$] did not reach significance. Median RT scores are reported in Table 13.

Simple main effects analyses for the memory load x block interaction revealed that with *4 items* in the array, 7-year-olds performed significantly faster in the pre-cue block (M=1171.23) than in the retro-cue block (M=1319.70, p=.004), whereas with *2 items* in the array, young children performed equally fast across blocks (M=1283.07 for pre-cue and M=1220.94 for retro-cue block, p>.05).

Performance with 4 items in the array did not differ significantly in speed from performance with 2 items in the array, either in pre-cue ($p>.05$) or in retro-cue blocks ($p>05$). Simple main effects analyses for the memory load x trial-type interaction revealed that with *4 items* in the array, 7-year-olds performed significantly faster in cued ($M=1055.88$) than in neutral trials ($M=1435.05$, $p<.001$), whereas with *2 items* in the array, young children performed equally fast between cued ($M=1239.83$) and neutral trials ($M=1264.18$, $p>.05$). Young children performed marginally faster in cued trials with 4 items in the array than in cued trials with 2 items in the array ($p=.05$), whereas performance on neutral trials did not differ across memory loads ($p>.05$). Finally, simple main effects analyses for the block x trial-type interaction revealed that 7-year-olds performed faster in cued than in neutral trials, both in pre-cue ($M=1087.33$ for cued trials and $M=1366.97$ for neutral trials, $p<.001$) and retro-cue blocks ($M=1208.38$ for cued trials and $M=1332.26$ for neutral trials, $p<.001$). The interaction was driven by faster performance in cued trials of the pre-cue block than of the retro-cue block ($p=.001$), whereas performance on neutral trials did not differ across blocks ($p>.05$).

A separate analysis of difference scores (Figure 13) corroborated these results by revealing greater cueing benefits in speed compared to the neutral baseline for memory arrays with 4 items ($M=379.18$) than with 2 items ($M=24.35$, $p<.001$) that led to a significant main effect of memory load [$F(1,39)=58.55$, $p<.001$, $\eta^2=.60$], and greater benefits in speed from pre-cues ($M=279.64$) than from retro-cues ($M=123.88$, $p=.001$) that led to a significant main effect of block-benefit [$F(1,39)=12.53$, $p=.001$, $\eta^2=.24$]. The memory load x block-benefit interaction did not reach significance [$F(1,39)=.05$, $p=.82$, $\eta^2=.00$].

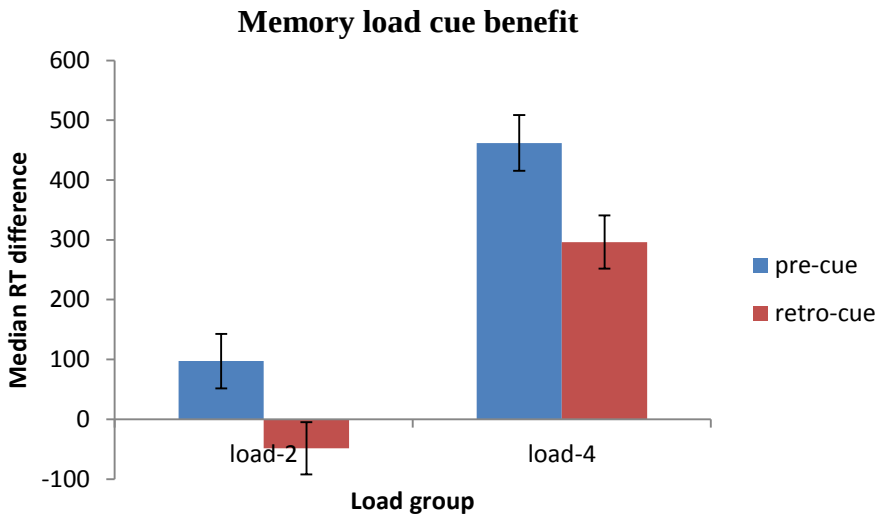


Figure 13. Median RT difference scores from neutral baseline, comparing pre-cue and retro-cue blocks for load-2 and load-4 groups. Error bars represent standard errors of the mean.

Relations between attentional cueing benefits and VSTM / VWM capacity

Next, I assessed whether individual differences in attentional orienting related to performance on validated VSTM / VWM span tasks for each load group separately. Bivariate and partial correlations controlling for neutral baseline performance across measures of attentional orienting and memory span performance (raw scores from the two AWMA subscales) are presented in Tables 14-17 for both d-prime and *K* and for both load-2 and load-4 groups. In summary, with *2 items* in the array, performance following pre-cues and retro-cues in d-prime and *K* related significantly to VSTM span (as indexed by the Dot Matrix subscale) and VWM span (as indexed by the Spatial Recall subscale), whereas with *4 items* in the array, only performance following retro-cues consistently related to VSTM span (as indexed by the Dot Matrix subscale) across d-prime and *K* scores. Importantly, when the

variability associated with neutral trials (effectively measuring baseline performance of how accurately participants could remember whether the probe item was part of the memory array) was taken into account, the relation between d-prime and *K* on retro-cue trials and VSTM span held only for arrays with *4 items*. These results indicate that when the load of the to-be-remembered visual information is within storage capacity limits, young children rely mainly on storage availability and recruit broad attentional resources that relate to the storage of information (if we accept that attentional resources are required even for simple storage of information when no cues are provided). Critically, when memory load is beyond capacity limits, 7-year-olds recruit top-down attentional control processes during the maintenance period to help them retain the information in VSTM and the more refined this ability to recruit these processes is, the better memory performance a child will have.

Tables 14 - 17. *Relations between attentional control measures (d-prime scores, denoted by "d'" in Tables 14 and 16; K scores in Tables 15 and 17) and raw scores for VSTM span (Dot Matrix, AWMA) and VWM span (Spatial Recall, AWMA). Values above the diagonal indicate bivariate correlations across measures, whereas values below the diagonal indicate partial correlations between d-prime and K on cued trials and AWMA subscales, controlling for d-prime and K on neutral trials. "Pre-neutral" refers to neutral trials in pre-cue blocks and "retro-neutral" refers to neutral trials in retro-cue blocks.*

Table 14. *Correlation table for d-prime load-2.*

	d' pre-cues	*d*' retro-neutral	*d*' retro-cues	Dot Matrix	Spatial Recall
d' pre-neutral	.802***	.919***	.799***	.622**	.556**
d' pre-cues		.834***	.816***	.525*	.439*
d' retro-neutral			.809***	.671**	.561**
d' retro-cues				.556**	.560**
Dot Matrix	.054		.031		
Spatial Recall	-.015		.219		

**p<.05, **p<.01, ***p<.001.*

Table 15. *Correlation table for K load-2.*

	K pre-cues	*K* retro-neutral	*K* retro-cues	Dot Matrix	Spatial Recall
K pre-neutral	.904***	.931***	.840***	.605**	.544*
K pre-cues		.897***	.836***	.517*	.459*
K retro-neutral			.868***	.653**	.541*
K retro-cues				.564**	.524*
Dot Matrix	-.089		-.007		
Spatial Recall	-.092		.130		

**p<.05, **p<.01, ***p<.001.*

Table 16. *Correlation table for d-prime load-4.*

	d' pre-cues	*d*' retro-neutral	*d*' retro-cues	Dot Matrix	Spatial Recall
d' pre-neutral	.196	.230	.355	.449*	.173*
d' pre-cues		-.180	.538*	.306	.312
d' retro-neutral			.406[a]	.295	.320
d' retro-cues				.607**	.360
Dot Matrix	.248		.558*		
Spatial Recall	.288		.266		

[a] *p=.076, *p<.05, **p<.01, ***p<.001.*

Table 17. *Correlation table for K load-4.*

	K pre-cues	*K* retro-neutral	*K* retro-cues	Dot Matrix	Spatial Recall
K pre-neutral	.238	.284	.406[a]	.371	.224
K pre-cues		-.191	.601**	.385	.303
K retro-neutral			.404[b]	.314	.307
K retro-cues				.629**	.357
Dot Matrix	.329		.579**		
Spatial Recall	.264		.267		

[a] *p=.075,* [b] *p=.077,*p<.05, **p<.01, ***p<.001.*

Discussion

Experiment 3 demonstrated that attentional orienting in early childhood, both prior to encoding and during maintenance, depends heavily on the number of items that young children are required to encode and maintain in VSTM, supporting the hypothesis that the memory load modulates cueing benefits. Surprisingly though, certain results were at odds with what was expected, especially those relating to the maintenance of information. Children performed equally well across cued and neutral trials both in terms of accuracy and speed when the memory load was within capacity limits and demonstrated no reliable benefits from cues presented either prior to encoding or during maintenance of memory arrays with 2 items. In contrast, differences across cued and neutral trials were clearly evidenced when the load exceeded capacity limits, but these benefits were largest and, for one of the dependent measures (d-prime) only significant following cues presented prior to encoding of visual information. These pre-cue benefits accentuated as the memory

load increased from 2 items to 4 items and attenuated the deleterious effects of increasing load. This result confirms that young children successfully recruit top-down attentional control processes for the selective encoding of information into VSTM in the face of increased visual competition in order to reduce the amount of information to be later maintained, accounting for the absence of developmental differences in cueing benefits during VSTM encoding in Experiment 1. Furthermore, the greater ability of 7-year-olds to *prioritize* a single item (amongst the four in the memory array) for *encoding and retention* until test compared to their ability to *selectively and actively maintain* a single item (amongst the four in the memory array) until test and when the memory load exceeds their capacity demonstrates that pre-cues and retro-cues are behaviourally dissociated and that the attentional processes that these cues support are *fractionated* at different time-points in development.

The null results of cueing benefits when the memory load was within capacity limits in Experiment 3 indicate that 7-year-olds did not use any cues, either for encoding or for maintaining the information, because they could easily retain in memory 2 items and decide whether the probe was in the array without any help. This finding is in agreement with the results by Astle et al. (2011) who found no cue benefits for adults when maintaining 2 items in VSTM. The suggestion that children relied simply on their storage capacity when the memory load was low is also supported by the correlation results, which revealed that once the basic storage ability (indexed by the neutral baseline performance) was taken into account, then the cueing benefits no longer predicted VSTM span. This does not mean that attentional processes do not play a role in basic storage capacity. Rather, it is

possible that young children use attention cues strategically in a similar manner to adults (see Astle et al., 2011). For example, once the memory array appears, 7-year-olds might make a judgment as to whether the number of items calls for recruitment of top-down attentional control. If the load exceeds capacity, then they can selectively encode into VSTM only one item out of four. If it does not, then they may attempt to retain both items in memory until the probe appears. This account is compatible with the findings of greater cueing benefits in speed in 4-item arrays compared to 2-item arrays.

It remains to be determined why young children fail to show reliable and consistent maintenance benefits (cf. Experiment 1 vs. Experiment 3) when load is beyond their capacity limits. Understanding the process underlying this limitation in early childhood is critical because, in contrast with what happened when memory load was low, the ability to use visuo-spatial orienting cues during the maintenance period when the load exceeded capacity limits related to individual differences in spatial VSTM span, over and above basic memory performance. This result demonstrates that even in early childhood the more refined the ability to use attention cues during the maintenance of information is, the greater the VSTM span is, highlighting again the important role of maintenance processes in VSTM from early in development. However, it leaves unanswered why young children as a group failed to benefit from these cues reliably.

One potential constraining factor that was briefly introduced in Chapter 3 is that, for younger children, information encoded in VSTM may be decaying at a faster rate (e.g., Cowan et al., 2000) so that when the retro-cue eventually appears, the quality of the representations on which it can operate is degraded to a greater extent.

Such an account could also explain Cowan et al.'s results (2010) with regards to inefficient attention for 7-year-olds compared to older children and adults when overloading VSTM / VWM capacity. Cowan et al. (2011) attributed those results to a simple increase in capacity by presenting the memory items to 7-year-olds sequentially and ruling out encoding limitations; however, they did not assess the contribution of visuo-spatial biases and their temporal parameters to maintenance in VSTM. I examine the hypothesis of faster decay of information in the next chapter in Experiment 4.

Chapter 5: Orienting of attention in early childhood II: Effects of time-based decay

Theories of cognitive development have long proposed that temporal factors play a critical role in WM capacity in childhood. In a very influential study, Case, Kurland, and Goldberg (1982) found a linear relation between memory span increase, measured with a counting span task, and the speed with which 6- to 12-years-old children counted objects. According to Case et al., this result suggested that, compared to younger children, older children were characterised by faster processing speed that allowed them to use more of their remaining cognitive resources for storage. In a follow-up manipulation, Case et al. asked adults to perform a modified version of the children's counting span, in which they increased the concurrent task's difficulty, thus slowing adults' counting speed. They found that once adults' counting speed was equated to the counting speed of 6-year-olds, their span was reduced to match that of the 6-year-olds. These findings were replicated in an experiment using a word span task. On the basis of these findings, Case et al. proposed that processing and storage compete for a shared central processing resource that remains constant in size across the lifespan and that the observed increase in complex span performance across development is attributed to *processing efficiency*, indexed by task difficulty and the required processing speed, rather than to an increase in storage capacity (see also Case, 1985). Case et al.'s *resource-sharing* theory (also referred to as processing speed-storage capacity trade-off) was later rejected because it confounded the difficulty of the concurrent task with the overall duration of the concurrent task (Towse & Hitch, 1995). However, in spurring

criticisms, this study set the stage for accounts that have modelled and investigated time-based decay as a critical factor for changes in WM capacity.

For example, Hitch and colleagues proposed a *task-switching* model according to which, during a complex span task, children switch between processing information and storing the items to-be-recalled, instead of acting simultaneously on both processing and storage as suggested by the resource-sharing theory. In a series of studies, Hitch et al. challenged Case et al.'s theory by manipulating the concurrent task's difficulty while controlling for completion time and thus the retention interval duration (Towse & Hitch, 1995). In a complementary fashion, they also manipulated the retention interval duration while controlling for processing difficulty in counting, reading, and operation span tasks (Towse et al., 1998). They found that longer delays in the retention interval, during which 6- to 11-years-old children performed a concurrent counting task, were related to a decrease in memory span. Importantly, processing difficulty did not affect participants' memory span indicating that the temporal interval, but not the cognitive demands during maintenance, moderated memory span in childhood. According to the task-switching model, during concurrent processing young children do not try to maintain the items to-be-recalled. Therefore, the greater the duration of the processing is, the longer children switch away from remembering the items to-be-recalled. Hitch and colleagues argue that it is precisely these long intervals that lead to the loss of the memory traces of the items to-be-recalled (Hitch et al., 2001; Towse, Hitch, & Hutton, 2002). While this time-based forgetting proposal can explain to a large extent young children's poor complex span performance compared to older children, Hitch and colleagues highlighted the model's limitations in providing a comprehensive account for age-

related changes in WM span across the lifespan (e.g., see Towse et al., 2000 in adults; see also Towse, Hitch, & Hutton, 1999 for further suggestions stemming from child results but pertaining to adults). Notably, distinct age groups have not been contrasted directly within this time-based decay framework. Also, Hitch and colleagues have not ruled out the possibility that, in addition to decay, other processes such as interference or temporal distinctiveness (e.g., Neath & Crowder, 1990) may also be responsible for memory loss (Towse & Hitch, 1995; Towse, Hitch, & Horton, 2007; Towse et al., 1998).

More recently, Barrouillet and colleagues (Barrouillet et al., 2004; Barrouillet & Camos, 2001; Barrouillet et al., 2012, 2009; Gaillard et al., 2011; Portrat, Camos, & Barrouillet, 2009) systematically investigated how limitations both in time and in attentional resources explain developmental differences in WM span, proposing the *time-based resource-sharing* (TBRS) model. According to this model, concurrent processing and maintenance of items in a complex span task depend on a shared limited resource, that is *attention* (broadly similar to Cowan's notion of focus of attention; Cowan, 1999); when concurrent processing is in the focus of attention, maintenance processes are not and therefore item traces decay (similar to Towse & Hitch, 1995), unless they are refreshed via a rapid and nonstop switch of attention towards them during concurrent processing. According to Barrouillet et al., older children are more efficient in refreshing decaying memory traces by switching attention quickly to maintenance activities during processing pauses and the efficiency of this refreshment process continues to improve until late adolescence. Furthermore, the faster execution of the concurrent processing task prolongs the available interval for refreshing the stored items, resulting in better item

maintenance. Barrouillet et al. argue that while this refreshing activity operates as a rehearsal mechanism (e.g., Raye et al., 2007, 2002), it does not necessarily imply verbal rehearsal operations (e.g., Baddeley & Logie, 1999). Rather, even for verbal material, it takes the form of a non-articulatory "attentional focusing" mechanism, in which the target item to-be-recalled is selected via a "memory scanning" procedure operating across the items stored in verbal STM (Cowan, 1992).

In summary, the two dominant time-based models differ from each other in how they conceptualise decay to operate on stored items: the task-switching model proposed by Towse and Hitch (1995) states that memory traces decay passively with time because there is no attempt for maintenance activity. As a result, traces decay more as the length of the processing task becomes longer. In contrast, the TBRS model states that an active maintenance process takes place via attentional refreshment and the longer this refreshment is prohibited by concurrent processing (not because of the total length of processing but because it occupies attention) the more the memory traces decay. Recently, Camos and Barrouillet (2011) suggested that there are developmental changes at 6 years of age from passive to active maintenance. This suggests that up until 6 years of age (although the exact age boundary may depend on specific task demands) the task-switching model proposed by Hitch et al. can explain WM span better than the TBRS model and Camos and Barrouillet concluded that WM span develops in 2 stages, merging this way the two models. Despite their differences, the two time-based accounts provided strong evidence that the decay of memory traces is a significant predictor of WM span in childhood and suggest that the duration of the maintenance interval is a factor that should be considered when attempting to understand developmental differences in

memory performance. It should be noted that both accounts were developed and tested mainly with *verbally- and sequentially- encoded* material.

In addition to providing information about the processes underlying retention in dual tasks, manipulations of temporal demands during maintenance have also been extremely useful in understanding mechanisms of VSTM capacity in tasks during which participants are required to maintain *visual items encoded simultaneously* (e.g., Zhang & Luck, 2009). These tasks are a closer analogue to the experiments in the current thesis, although their temporal parameters have been manipulated to a greater extent in adults and less so for children. In his now classical study, Sperling (1960), for example, found that when adults were presented with an auditory cue directing attention to one row of letters immediately after the encoding of a memory array consisting of three rows of letters, they could report almost all letters from that row. This result indicated that representations remained accessible shortly after stimulus offset; however, when participants were presented with a cue much later following array offset (e.g., 1000ms), their performance decreased significantly and did not differ from the condition in which no cue was provided and participants had to report all encoded letters. This finding suggested that representations degraded by the time the cue appeared (see also Averbach & Coriell, 1961). These radical results along with those from a number of studies that followed (e.g., Neisser, 1967; Pashler, 1988; Phillips, 1974) established that visual memory is divided into iconic memory (IM), a high-capacity system whose representations are susceptible to rapid decay, and VSTM, a limited-capacity system whose representations are more durable than IM (see also Dick, 1974 for a review). However, in contrast to Sperling' s findings, later studies demonstrated that adults (Griffin & Nobre, 2003; Lepsien et al., 2005;

Makovski et al., 2008; Matsukura & Hollingworth, 2011; Matsukura et al., 2007; Nobre et al., 2008) and 10-year-olds (Astle et al., 2012) can benefit from cues following a memory array (i.e., retro-cues) even when these are presented well beyond iconic limits, indicating that from middle childhood spatial biases can be applied to both short- and longer-lived internal representations. Critically though, studies that have manipulated the length of the maintenance interval prior to retro-cue presentation systematically showed that longer delays in the presentation of a retro-cue result in poorer memory performance compared to shorter delays (Astle et al., 2011; Becker, Pashler, & Anstis, 2000; Kuo, Yeh, Chen, & D'Esposito, 2011; Sligte et al., 2008; Sligte, Vandenbroucke, Scholte, & Lamme, 2010), supporting the conclusion that memory traces decay as a function of time. For example, Astle et al. (2012) manipulated the interval between the memory array and the onset of the retro-cue to be either short or long in order to examine whether retro-cue benefits operated on transient iconic traces or on more durable VSTM representations. In their first experiment, the array – retro-cue interval was short (500ms on average), suggesting that the selection of a memory item via internal attentional orienting could have been facilitated by visual after-effects, i.e., iconic memory. Results from their second experiment, using array – cue intervals that were either short (700ms) or long (2700ms), showed that retro-cue effects held across intervals and that both 10-year-olds and adults were sensitive to this manipulation, with accuracy and response times dropping after long delays. As Astle et al. did not test 7-year-olds in Experiment 2, it is not clear whether the smaller retro-cue benefits for 7-year-olds as assessed in Experiment 1 (Chapter 2), in the current thesis, which adopted clear VSTM

parameters and those of Astle et al. (2012, Experiment 1) with iconic parameters were due to a difference in the duration of the interval preceding the retro-cue.

Experiment 4: Attentional orienting during maintenance: Are attentional benefits evidenced in early childhood?

Studies examining temporal parameters in early childhood have shown that duration delays in the maintenance period have a detrimental effect on children's verbal WM span, though a lack of consensus exists on how these delays affect maintenance. On the one hand, it could be that these delays reflect the time for which a concurrent task inhibits the attentional refreshment of the memory representations (e.g., Barrouillet et al., 2009). On the other hand, maintenance delays may determine the passive decay of memory traces during the execution of concurrent tasks (e.g., Towse & Hitch, 1995). One shortcoming of these studies is that they have employed secondary tasks that introduced additional interference or distraction during the period in which children were required to maintain the information in memory. While these secondary tasks were employed to block rehearsal mechanisms, nevertheless they might engage interfering processes that load STM differentially across age groups, thus potentially obscuring the presence and if such, the precise role, of maintenance activities in early childhood. It should be noted that these experiments focused on verbal STM capacity, and time-based decay as a factor in accounting for developmental differences in VSTM capacity remains understudied.

Based on the existing time-based accounts, the present experiment examined why 7-year-olds in Experiment 1 (Chapter 2) benefited little, albeit significantly,

from cues during maintenance. One possibility, based on the TBRS model, is that 7-year-olds have a less developed ability to use attentional mechanisms to actively maintain the information to-be-probed in VSTM. An alternative possibility, based on the model proposed by Towse & Hitch (1995), is that encoded representations decay faster in young children compared to older children and adults (when the number of encoded representations exceeds 7-year-olds' VSTM capacity), so that more degraded representations are available to selectively refresh when they are given the opportunity to do so. To the best of my knowledge, no previous study has examined pure time-based effects in situations with no interference from a concurrent task during the maintenance of visual items in 7-year-olds.

In order to investigate whether the temporal decay accounts for 7-year-olds' poor performance on retro-cue trials in Experiment 1 (Chapter 2), I manipulated the duration of the maintenance interval between the memory array and the retro-cue as well as shortened the duration of the retention interval between retro-cue and probe. I hypothesized that if young children benefitted little from retro-cues in Experiments 1 and 3 because memory representations had already decayed before they could apply a spatial bias, then bigger benefits should be obtained when cues are presented shortly after the memory array, i.e., within an interval adopting IM parameters, than when they are presented long after the memory array, i.e., within an interval adopting VSTM parameters. By shortening the cue – probe interval, I aimed to examine whether the retention interval following the selection of an item (via retro-cues) also matters. It could be the case, for example, that 7-year-olds are able to orient their attention internally to select one item even long after the array offset, but the selected item passively decays as a function of time as Towse et al. (1998) proposed. If this is

the case, then cue benefits could also be obtained in a condition where the retro-cue appears long after the array offset (i.e., long array – cue interval adopting VSTM parameters; in contrast to the hypothesis above), provided the probe appears shortly after selection (i.e., short cue – probe interval). In Experiment 1 and 3, all inter-stimulus intervals (ISIs) adopted VSTM parameters[8] and the youngest children did not always show reliable cueing benefits during maintenance. In contrast to Experiment 1, only spatial retro-cues were employed here since 7-year-olds showed clear benefits from cues presented prior to encoding.

Methods

Participants

Thirty-five new children (13 boys and 22 girls) aged between 6 and 8 years old (M = 7.06 years old, SD = .68, "7-year-olds" henceforth) participated in Experiment 4.

Measures

Attentional Orienting Task: Experiment 4 differed from the task used in Experiment 1: a) by including only retro-cue blocks that were then divided into two blocks that differed in latency (explained next), b) by manipulating the array – cue interval [i.e., the inter-stimulus interval (ISI) between the array and the retro-cue] to short (adopting IM temporal parameters) vs. long (adopting VSTM temporal parameters), and c) by shortening the cue – probe interval [i.e., the ISI between the retro-cue and the probe]. More precisely, the task contained 2 test blocks in which

[8] As a reminder, in Experiment 1 (Chapter 2) both the array – cue interval and the cue – probe interval varied between 800-1200ms.

the array – cue interval was shorter compared to Experiment 1 and used the short temporal parameters presented in Figure 14 (“iconic memory blocks” henceforth) and 2 test blocks that shared similar temporal parameters in the array – cue interval with those used in the retro-cue blocks in Experiment 1 (“VSTM blocks” henceforth). There were only 2 trial-types, retro-cue and neutral, that were randomly presented within a block.

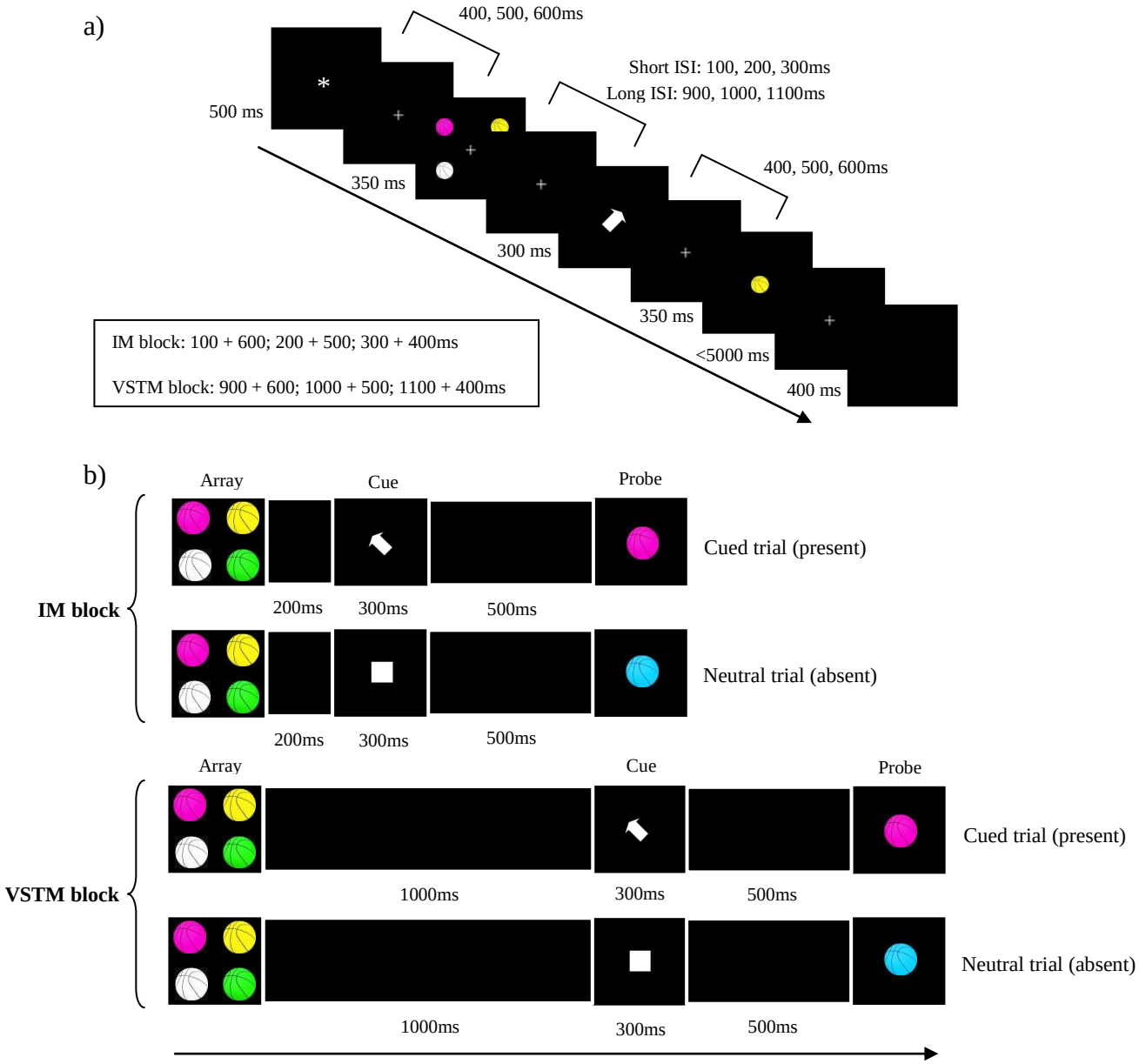


Figure 14. a). Schematic illustration of the sequence of events and their temporal parameters on each test trial. ISI timings within each block were yoked to obtain a constant array to probe latency as explained in the text box. ***b)*** Key temporal parameters across trials and blocks from memory array onset. Reported time in ms represents the average length of the specific inter-stimulus interval.

Each trial began with an asterisk (500ms) signalling the start of a new trial followed by a fixation point that remained visible throughout the trial. After a randomly varied fixation interval (500ms on average), the memory array was presented for 350ms, followed by another variable fixation interval. The duration of this second fixation interval (array – cue) depended on the block of the experiment. In the IM blocks, the interval was on average 200ms whereas in the VSTM blocks, the interval was on average 1000ms. Subsequently, a cue appeared for 300ms: in retro-cue trials, an arrow directed participants' attention to the mental representation of one of the already encoded items whereas in neutral trials, an uninformative filled square appeared. Finally, after a variable fixation interval (500ms on average), the probe appeared for 350ms, followed by a fixation point that remained on the screen until a response was made or until a maximum of 5000ms elapsed. Then, a blank screen was presented for 400ms until the next trial begun.

The timing parameters of the array – cue interval in the IM blocks ensured that the duration of the interval from the array onset to the retro-cue onset fell within the limits that Sperling (1960) classified as iconic, e.g., ~800ms [350ms (array) + 100ms/200ms/300ms (fixation interval until the cue onset) = 450ms/550ms/650ms]. Therefore, the attentional orienting in the IM blocks is believed to operate on transient iconic representations.

Furthermore, the fixation intervals selected for this experiment allowed assessing children's baseline memory recognition at the time the retro-cue appeared in VSTM blocks. This is because in IM blocks, the probe appeared at the same time at which the retro-cue appeared in the VSTM blocks, that is, at 1000ms on average after the memory array offset (see Figure 14b). As a result, performance on neutral

trials in the IM blocks allows drawing an inference on whether children's baseline memory recall is simply very poor at the time-point when the VSTM retro-cue appears. In addition, if, in contrast to Experiments 1 and 3, this experiment shows reliable and greater retro-cueing benefits in VSTM blocks, this would suggest that the cue – probe interval is also important. Finally, given that the cue – probe interval was identical across the two blocks in the present experiment, it is possible to meaningfully compare the retro-cue effects across the VSTM and IM blocks.

Practice blocks, feedback, recording procedures, and experimental trial numbers were identical to Experiment 1.

Procedure

The procedure was identical to that of the central-cue group in Experiment 1 (Chapter 2) unless stated differently. Participants received the same instructions as in Experiment 1 except that the cue was always presented after the four pictures (i.e., no pre-cues were employed here). Illustrations of the example cards are presented in Appendix B, Figure B5. There were two 5-minute VSTM test blocks and two 3-minute IM test blocks that alternated throughout the task and were counterbalanced across participants. The whole task was completed in approximately 20 minutes. All children received stickers as rewards for the completion of the test blocks and a certificate of participation at the end of the testing.

Statistical design and analyses

Two-way repeated-measures ANOVAs were performed on d-prime, *K*, and median RT scores with the block (IM, VSTM) and the trial-type (cued, neutral) as

the within-subject variables. Cueing benefits were also calculated in order to assess the size of cueing effects independently of baseline time-related differences in the accuracy, storage capacity, and speed of memory performance.

Results

Table 18. *D-prime, K, and RT scores for iconic memory (IM) vs. visual short-term memory (VSTM), for retro-cue and neutral trials. Standard deviations are reported in parentheses.*

	IM block		VSTM block	
	Cued	Neutral	Cued	Neutral
D-prime				
	1.22 (1.02)	0.84 (0.75)	0.71 (0.70)	0.49 (0.54)
K				
	1.55 (1.17)	1.16 (0.94)	0.99 (0.88)	0.69 (0.77)
RT (ms)				
	1113.87	1415.54	1142.99	1264.73
	(299.45)	(386.88)	(299.82)	(370.39)

D-prime

The analysis on d-prime scores yielded a main effect of block [$F(1,34)=25.11$, $p<.001$, $\eta^2=.43$] with significantly better performance in the IM block (M=1.03) than in the VSTM block (M=.60) suggesting that overall memory was greater with shorter maintenance intervals and a main effect of trial-type [$F(1,34)=8.09$, $p=.007$, $\eta^2=.19$] with significantly better performance in cued (M=.96) than in neutral trials (M=.67) suggesting cue benefits across blocks. The block x trial-type interaction did not reach significance [$F(1,34)=.97$, $p=.33$, $\eta^2=.03$].

As seen in Figure 15, cueing benefits computed as the difference between cued and neutral trials did not differ reliably across IM (M=.38) and VSTM (M=.22) blocks. The means for d-prime scores are reported in Table 18.

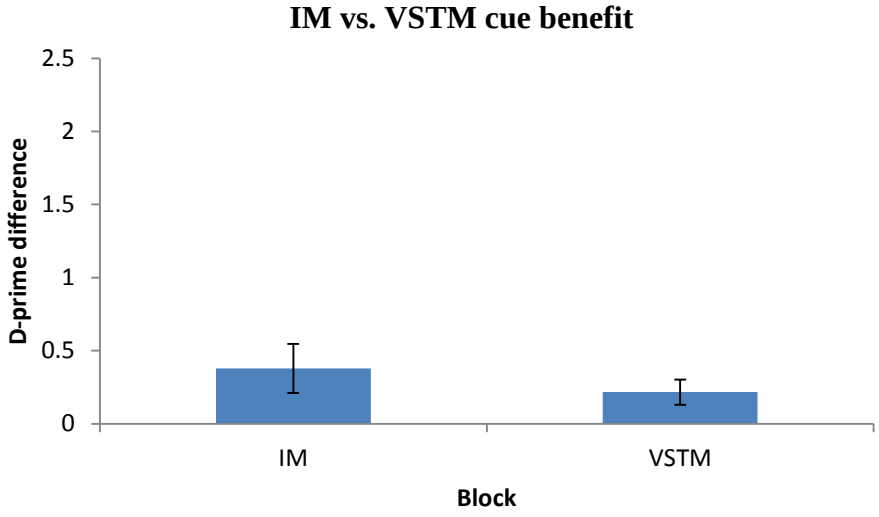


Figure 15. D-prime difference scores from neutral baseline, comparing retro-cues across IM and VSTM blocks. Error bars represent standard errors of the mean.

K capacity measure

Results mirrored those in the d-prime analysis. *K* scores yielded a main effect of block [$F(1,34)=25.09$, $p<.001$, $\eta^2=.43$] with significantly higher *K* scores in the IM block (M=1.35) than in the VSTM block (M=.84) and a main effect of trial-type [$F(1,34)=7.08$, $p=.01$, $\eta^2=.17$] with significantly higher *K* scores in cued (M=1.27) than in neutral trials (M=.92). The block x trial-type interaction did not reach significance [$F(1,34)=.17$, $p=.69$, $\eta^2=.01$]. Figure 16 illustrates cueing benefits compared to neutral trials (M=.39 and M=.31 for IM and VSTM respectively). The means for *K* scores are reported in Table 18.

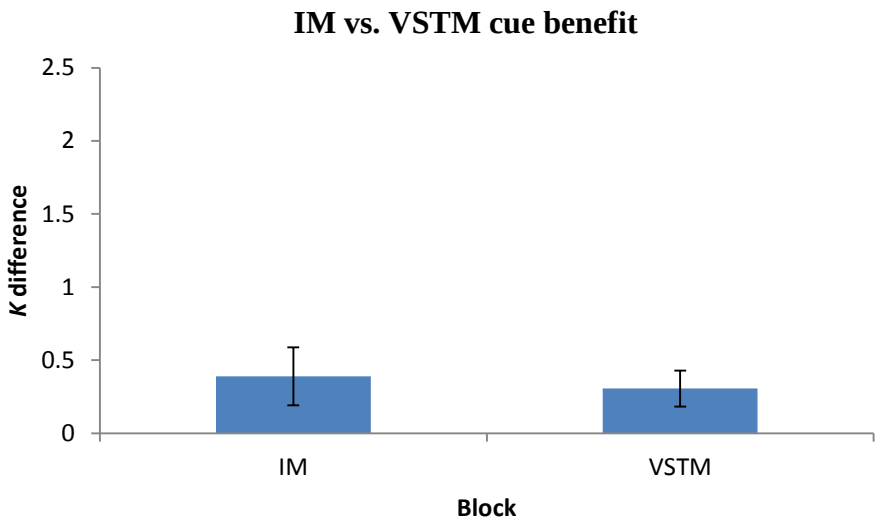


Figure 16. *K* difference scores from neutral baseline, comparing retro-cues across IM and VSTM blocks. Error bars represent standard errors of the mean.

Median RTs

The ANOVA on the RTs revealed a main effect of trial-type [$F(1,34)=39.94$, $p<.001$, $\eta^2=.49$] and a significant interaction of block x trial-type [$F(1,34)=11.57$, $p=.002$, $\eta^2=.25$]. The means for median RT scores are reported in Table 18.

Analyses of simple main effects for the interaction indicated faster responses for cued than neutral trials, both in the IM ($p<.001$) and the VSTM blocks ($p=.005$). The interaction was driven by faster responses in neutral trials of the VSTM block than neutral trials of the IM block ($p=.007$). Performance on cued trials did not differ across blocks ($p>.05$). A separate analysis of difference scores (Figure 17) revealed that 7-year-olds benefited in speed from retro-cues in the IM block ($M=301.67$) to a greater degree than from retro-cues in the VSTM ($M=121.74$) block [$t(34)= -3.40$, $p=.002$]. In order to examine whether larger RT benefits for the IM block were

driven by overall slowing in responses[9], a second analysis was then performed on cue benefits. This showed that the effect on scaled cue benefits remained significant [t(34)= -3.11, p=.004] with bigger benefits in IM block (M=.19) than in the VSTM block (M=.07).

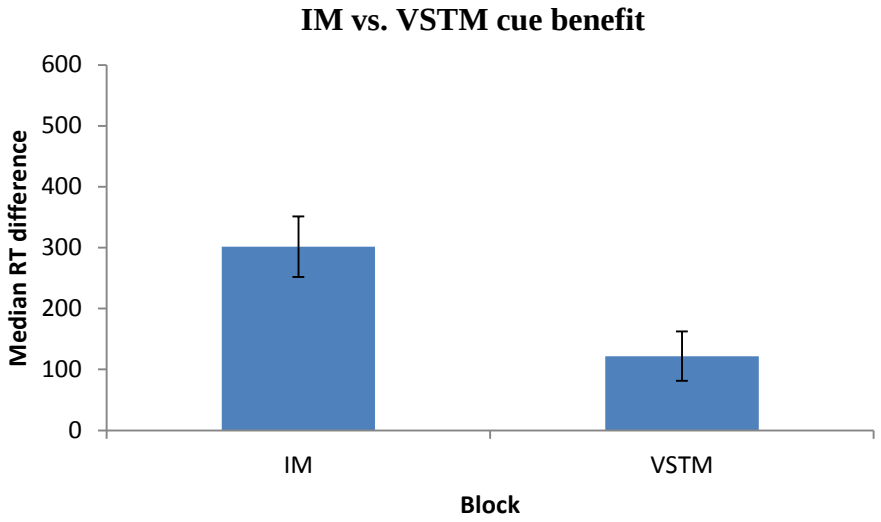


Figure 17. Median RT difference scores from neutral baseline, comparing retro-cues across IM and VSTM blocks. Error bars represent standard errors of the mean.

Discussion

A key finding in Experiment 4 is that 7-year-olds benefited reliably from cues presented during the maintenance period although these again were small. This contrasts with the less reliable cueing benefits during maintenance for this age group in Experiment 3 (where there was only a trend towards significance). In Experiment 4, I manipulated the duration of the period during which 7-year-olds had to maintain all encoded items until cue presentation as well as shortened the period during which

[9] This analysis treated RT differences as proportions of neutral RTs [i.e., (neutral-cued)/neutral].

7-year-olds had to retain the selected representation until response. As a result, improvements in accuracy and response times for probes at cued locations were observed. Importantly, 7-year-olds performed better when retro-cues were presented shortly after the memory array and thus operated on transient iconic traces rather than on VSTM representations. Also, their performance on baseline neutral trials became poorer when longer delays were imposed during maintenance (array – cue interval). Together with the findings of Experiment 3 (Chapter 4), the current findings suggest that orienting attention in early childhood depends heavily on temporal parameters during the maintenance period and confirm that memory traces decay as a function of time (consistent with Cowan et al., 2000; Towse & Hitch, 1995; Towse et al., 1998). Complementing Experiment 2 (Chapter 3), which focused on the reliability of cues predicting target location, the present experiment provided evidence that temporal parameters are an important factor in understanding attentional orienting mechanisms engendered by spatial cues in young children.

A notable finding of the current experiment was that despite the fact that accuracy-based performance was overall poorer with increasing maintenance delays, the benefits drawn by 7-year-olds from retro-cues across the IM and VSTM blocks did not differ significantly. This finding is also reported by Astle et al. (2011). As in the present study, Astle et al. (2011) found that performance was better when retro-cues appeared after a short than a long delay. However, retro-cue benefits, computed by taking into account performance on neutral trials, were equivalent following short and long delay. Nonetheless, response times in the present experiment revealed a different pattern of results: children benefited from cues to a greater degree (compared to baseline neutral trials) when these were presented within an iconic

interval than within a VSTM interval suggesting that accuracy and RT measures index distinct effects on how well information is represented in memory and how fast it is accessed respectively (Prinzmetal et al., 2005).

Another important finding of Experiment 4 is that 7-year-olds benefited from retro-cues more reliably than elsewhere (see Experiment 3, Chapter 4), in which retro-cues were also presented long after the memory array. As Experiments 1 and 3 involved longer cue – probe interval durations (1000ms on average), the difference across experiments suggests that the length of the retention period following the selection of an item via the retro-cue until response is also important for memory. Results here suggested that young children can orient their attention internally to select one item even at longer delays as indexed by the better performance in cued than in neutral trials in the VSTM block (though the representation is not as robust as when the cue appears at shorter delays). However, the representation of the selected item is still subject to decay with time so that when the probe finally appears, after a further maintenance period, the selected representation is weaker. These time-based effects on the maintenance of memory representations were also evidenced in the poorer recognition on baseline neutral trials with long than short delays for probe presentation even in the absence of imposed distraction; these pure time-based effects are in agreement with recent adult findings (Ricker & Cowan, 2010). Overall, these results support the predictions of time-based forgetting during maintenance and suggest that a greater degree of decay in young children compared to older children and adults may account at least in part for their smaller ability to benefit from cues presented during maintenance. The current findings would therefore need to be followed up by a direct comparison between 7-year-olds, older children and adults,

using IM and VSTM parameters as well as manipulations of cue – probe intervals. The findings already extend previous developmental results (Barrouillet et al., 2009; Camos & Barrouillet, 2011; Portrat et al., 2009; Towse & Hitch, 1995; Towse et al., 1998) in the visual domain using a paradigm that involves no concurrent interfering tasks. Importantly, these results emphasize that constraining factors during maintenance should be taken into account when examining developmental differences in VSTM capacity (Cowan et al., 2011, 2010).

In summary, the presence of reliable cueing benefits in VSTM trials in the present experiment suggests that the small or only marginal benefits in Experiments 1 and 3 should not be attributed solely to 7-year-olds' inability to orient attention internally to selectively maintain one item but also to a greater item fragility, compared to older individuals, caused by delay. This seems to be especially the case when items exceed 7-year-olds' VSTM capacity, as results from Experiment 3 (Chapter 4) showed that 7-year-olds do not rely on attention cues to maintain information when the memory load is well within their VSTM capacity.

As suggested by early studies, IM is a high-capacity system which is nonetheless prone to decay (Averbach & Coriell, 1961; Phillips, 1974; Sperling, 1960). Information registered in IM is lost briefly after its presentation unless it is transferred to VSTM, where its representation becomes more durable. Attention is assumed to be heavily involved in transferring selected information from the iconic to the visual short-term state of memory even though the mechanisms underlying this transfer are still not well understood even in adults (Sligte et al., 2008, 2010). It may well be that older individuals are more efficient in using attention mechanisms to transfer a larger number of items from iconic to VSTM before they decay and in

using top-down attentional control to selectively maintain an already transferred-to-VSTM internal representation. Greater accuracy and speed when cues are presented shortly after the memory array, compared to much later, could depend on multiple factors, e.g., more efficient re-activation of the representation to be probed before it decays (Lepsien & Nobre, 2006, 2007), facilitation in its transfer to VSTM and protection from decay during maintenance (Makovski & Jiang, 2007; Makovski et al., 2008; Matsukura et al., 2007). All of these potential processes by which cues may operate, for these young children in particular, are to be placed in the context of clear decay of the to-be-maintained information. These results are in agreement with recent adult findings demonstrating that retro-cues, presented shortly after a memory array whose load exceeded adults' VSTM capacity (8 items), boosted significantly performance (Astle et al., 2011). Importantly, this was not the case when the cue was presented long after the array offset. Similarly, Sligte et al. (2008) demonstrated that by presenting an "iconic" cue shortly after the memory array boosted adults' memory capacity significantly more than by presenting a "retro-cue" long after the memory array even with set sizes of 32 items.

Taking into account the results from Experiment 3 (Chapter 4), the effects of array – cue delay and cueing deserve further investigation using parametric manipulations of memory load and maintenance delays across development: with 2 items in the array (Experiment 3), 7-year-olds did not show any retro-cue benefits possibly because they could retain all items in VSTM until responses were required, whereas with 4 items in the array (Experiment 4), 7-year-olds performed better when retro-cues operated on iconic traces. Voluntary orienting may play a critical role in biasing information in situations in which memory arrays contain a load of items that

is just within VSTM capacity limits (i.e., 3 items) and when maintenance of the encoded information is required for a long period of time. Such an investigation would have implications for current theoretical models of WM in childhood (Baddeley & Hitch, 2000; Barrouillet et al., 2009; Gaillard et al., 2011; Towse et al., 2002). For example, memory traces decay as a function of time even in the absence of concurrent interference and the number of simultaneously encoded items seem to influence a) the extent to which time will have an effect on their maintenance and b) the necessity to recruit top-down attention during maintenance, albeit less successfully than older individuals when items exceed 7-year-olds' VSTM capacity.

A further aspect to be examined is whether, and if so, the degree to which memoranda interfere with each other (Lewandowsky et al., 2010) affects the rate of degradation and the fragility of internal representations by the time the retro-cue appears. Indeed, Ricker and Cowan (2010) found differential effects on the maintenance of visual unconventional stimuli and familiar English letters and proposed that some nonverbal information cannot go through attentional refreshment. Also, the to-be-remembered items used by Astle et al. (2012) included items that were perceptually highly dissimilar from each other, referred to as highly familiar objects, and could be easily verbalized. These differential characteristics of the memoranda might account for the finding that even with shorter delays, 7-year-olds in Experiment 4 benefited from retro-cues to a smaller degree than 7-year-olds in the Astle et al. experiment and, unlike adults in other studies (Astle et al., 2012; Griffin & Nobre, 2003), adults' accuracy benefited more from orienting prior to encoding than during maintenance in Experiment 1 (Chapter 2). It is to these characteristics of the memoranda that I turn in Chapter 6.

Chapter 6: Development of attentional orienting and VSTM III: Verbalisability of the memoranda

Visuo-spatial memory improves significantly over childhood (Alloway et al., 2006; Gathercole, 1999; Kwon et al., 2002; Logie & Pearson, 1997) and it has been suggested that qualitative changes in the ability to use mnemonic strategies, such as phonological recoding of visuo-spatial material and subvocal rehearsal of the object names, and factors such as knowledge of the identity of the objects to-be-remembered, expand VSTM capacity (Cowan & Alloway, 2009; Gathercole, 1999; Hitch, 2006; Pickering et al., 2001; Pickering, 2001). Adults are largely engaged in subvocal rehearsal for retaining visual material. This is evidenced by phonological similarity and word length effects in immediate recall following the encoding of nameable drawings and visually presented words (Schiano & Watkins, 1981) and by visual similarity effects when rehearsal is disrupted by articulatory suppression (Logie, 1995; Walker, Hitch, & Duroe, 1993). In contrast, children do not rehearse visually presented material before the age of 7-8, rather young children spontaneously rely on visual codes to maintain information (Gathercole & Hitch, 1993; Gathercole, 1998; Hitch & Halliday, 1983).

Developmental evidence for this stems from a great number of studies that examined immediate serial recall of nameable pictorial items in young and older children (Ford & Silber, 1994; Halliday, Hitch, Lennon, & Pettipher, 1990; Hitch, Halliday, Schaafstal, & Heffernan, 1991; Hitch, Halliday, Schaafstal, & Schraagen, 1988; Hitch, Woodin, & Baker, 1989; Hitch & Halliday, 1983; Hitch et al., 1989; Longoni & Scalisi, 1994; Palmer, 2000a; Walker, Hitch, Doyle, & Porter, 1994). For

example, Hitch et al. (1988) presented 5- to 6-year-olds and 10- to 11-year-olds with series of nameable drawings of familiar objects while manipulating visual similarity and word length. Results showed that young children recalled poorly the visually similar items but were unaffected by word length whereas the opposite pattern held for the older children. These findings prompted Hitch et al. to suggest that young children encoded and retained pictorial items in visual form whereas older children recoded these items into verbal form and then retained them via subvocal rehearsal.

Yet, young children were found to rely on verbal codes when required to retain non-visual material such as auditory and spoken items (Gathercole et al., 1994; Hitch et al., 1988; Hitch et al., 1989; Hulme, Silvester, Smith, & Muir, 1986; Hulme et al., 1984), revealing thus that the ability for verbal encoding is functional in early childhood. However encoding and maintenance are modality-dependent until late childhood. For example, in one study Hitch, Halliday, et al. (1989) found word length effects in memory for spoken words in children as young as 4 years of age, but these effects were eliminated with line drawings for children below 8 years of age. In another study, Hitch et al. (1991) found word length effects and phonological similarity effects in young children when they asked them to label line drawings of familiar objects at presentation but not when then they asked them to remain silent. Finally, Johnston and Conning (1990) obtained similar results for a group of young children who were trained to verbally rehearse visually presented objects, overtly or covertly, but not for the untrained controlled group. Also, the overtly trained group showed a significantly larger effect of phonological similarity than the covertly trained group. While the former result by Hitch, Halliday, et al. (1989) corroborated the earlier findings that only the older children converted pictorial drawings into

verbal codes, the latter results by Hitch et al. (1991) and Johnston and Conning (1990) showed that under instruction or training young children were able to convert visual forms to verbal codes and more so when encoding involved speech.

Likewise, older children were found to rely on visual encoding and maintenance when phonological recoding was prohibited (Hitch et al., 1989). By incorporating articulatory suppression conditions during the serial presentation of familiar pictorial objects, Hitch, Woodin, et al. (1989) found visual similarity effects in 11-year-olds, whereas Halliday et al. (1990) eliminated previously shown word length and phonological similarity effects in 11-year-olds' recall. These findings showed that children in late childhood exhibit the same pattern of results with adults, who demonstrate a pervasive tendency to recode familiar pictorial material into verbal form unless they are prevented from doing so (Brandimonte, Hitch, & Bishop, 1992; Schiano & Watkins, 1981). It seems, thus, that visual codes are not entirely lost over development (Della Sala, Logie, Marchetti, & Wynn, 1991; Logie, Della Sala, Wynn, & Baddeley, 2000; Saito, Logie, Morita, & Law, 2008; Walker et al., 1993). Rather, phonological codes dominate and mask the use of visual codes in tasks requiring encoding and maintenance of pictorial nameable objects, but do not replace them. These findings collectively suggest an increase in the number of available codes that can be used during maintenance instead of a dichotomous switch in coding strategy (Hitch et al., 1989; Hitch, 2006; Palmer, 2000a).

In the adult literature, early influential cognitive theories incorporated the notion of a "recoding" strategy in order to explain improvements in memory performance and the developmental changes in phonological recoding reported so far have been interpreted within these theoretical frameworks. For example, the dual

coding theory (Paivio, 1971) proposes two cognitive systems, one dedicated to imagery that processes and represents non-verbal objects, and one dedicated to language that processes and represents verbal items. Dual coding allows adults to create both visual and verbal memory traces for non-verbal objects, leading to an additive benefit in recall; that is, representing an object in both systems is superior to representing the same object in only one system (Paivio & Csapo, 1975; see also Kosslyn, 1978 for a similar "representational-development" hypothesis). Similarly, according to the multicomponent model of WM (Baddeley, 1986, 1990; Baddeley & Hitch, 1974; Baddeley & Logie, 1999; Logie, 1995), sensory items gain automatic access to one of the two domain-specific slave systems, the visuo-spatial sketchpad or the phonological loop, depending on the presentation modality (visual vs. auditory). In this model, visually-presented material (pictorial objects or written words) can also undergo an optional recoding process and be stored as verbal representations in the phonological loop. It is now believed that changes in VSTM across age groups reflect to a great extent changes in the ability to represent visuo-spatial objects in more than one modality. More specifically, children above 7-8 years of age, like adults, use dual coding to represent and maintain visuo-spatial material whereas younger children spontaneously rely on the available perceptual codes (Hitch, 2006; Palmer, 2000a; Pickering, 2001). The developmental changes in using phonological recoding have been associated with literacy competence (Fastenau, Conant, & Lauer, 1998; Palmer, 2000b), production deficiency and development of metacognitive skills (Goswami, 2008), development of higher executive functions (Luciana & Nelson, 1998), development of visual inhibition processes within the central executive (Palmer, 2000a), and maturation of the neural

cortices involved in phonological recoding (Kwon et al., 2002). However, changes in the ability to use phonological recoding alone cannot account for all developmental differences in VSTM (Pickering, 2001), considering evidence that not all visuo-spatial material can be retained verbally (Farmer, Berman, & Fletcher, 1986; Kemps et al., 2000; Pickering et al., 2001; Ricker, Cowan, & Morey, 2010; Vandierendonck et al., 2004). For example, in the Corsi block task adults are generally unaffected by articulatory suppression (e.g., Farmer et al., 1986) which suggests that they do not retain the spatial locations in memory verbally.

Also, as discussed in earlier chapters, top-down cognitive mechanisms, such as internal attentional orienting (Astle et al., 2012; Griffin & Nobre, 2003; Nobre et al., 2004), attentional refreshment (Barrouillet et al., 2009; Raye et al., 2007; Tam et al., 2010), and attention-based spatial rehearsal (Awh et al., 1998), have been proposed to contribute to the maintenance of visuo-spatial material. Yet, changes in attentional control alone cannot explain developmental differences in VSTM capacity (Astle & Scerif, 2011). It is plausible then that developmental differences in VSTM performance are better explained by the interaction of the two processes; that is, by older individuals' developed ability to strategically use dual coding at the time of presentation of visual items on one hand, which has an additive benefit on retaining enhanced visual representations internally (Paivio, 1971), and by their refined ability to apply spatial biases to maintain a selected internal representation on the other hand. Support for the interaction between attentional control and the type of encoding comes from a study by Johnson, Raye, Mitchell, Greene, and Anderson (2003) showing that the distribution of hemodynamic brain activity in frontal areas of the brain during attentional refreshment of line drawings of familiar nameable

objects, abstract patterns, and written words varied as a function of stimulus type. A possible interpretation of this result is that the type of stimulus that is refreshed determines the recruitment of segregated neural circuits to facilitate on-going cognition.

Experiment 5: Mnemonic strategies for maintaining verbalisable vs. abstract items in VSTM

The nature of the internal memory codes is deemed critical for understanding developmental changes in VSTM (Cowan & Kail, 1996). Experiments 1 to 4 (Chapters 2 to 5 respectively) demonstrated that the ability to orient attention internally in order to spatially bias maintenance relates significantly to VSTM capacity (see Experiments 1 and 3). Other studies in the literature examining mnemonic strategies across development indicated that the ability to strategically recode and maintain memory traces of serially presented pictorial information in two cognitive systems, visual and verbal, instead of only the system corresponding to the nature of the presented material, improves VSTM performance (Hitch et al., 1989; Hitch et al., 1989; Palmer, 2000a). Experiment 5 aimed at investigating whether attentional control modulates VSTM maintenance differentially depending on the type of items that needs to operate on and if so, whether this pattern of attentional biases changes across development. More specifically, Experiment 5 examined whether developmental differences in VSTM for pictorial material presented simultaneously through vision can be accounted for by older individuals' ability to encode objects both visually and verbally. Maintaining two codes would presumably

enhance retrieval, so that when the cue appears during the maintenance period they can access and re-activate the representation of the selected item more reliably. If this is the case, then young children may be less able to access and selectively refresh a representation held in VSTM because they rely only on unitary visual codes. In order to investigate further this hypothesis, in Experiment 5 I contrasted memory recognition for highly familiar and easily to verbalise items that are traditionally learned very early in life (i.e., animals) with that for novel meaningless shapes that are difficult to label.

I hypothesized that if adults and older children pervasively convert visual pictorial material to verbal codes to facilitate maintenance of information until response, in addition to the greater ability to use cues during maintenance, they should perform significantly better than younger children in a cued condition that contains familiar, nameable items than in a cued condition that contains unfamiliar, abstract items. If young children are perceptually bound and spontaneously rely only on visual codes for visually presented material, despite the availability of verbal codes, then they should perform similarly across conditions with nameable and abstract items. Conversely, if participants across age groups rely on visual features and the only factor that influences performance is the ability to recruit attentional control during maintenance, then all participants should perform equally across stimulus types. Nonetheless, older participants should perform better in cued trials than young children because of better attentional control (Astle et al., 2012; see also Experiment 1) and in neutral trials because of larger storage capacity (cf. Cowan et al., 2011, 2010).

Finally, in order to examine whether subvocal rehearsal of visuo-spatial material during maintenance drives developmental differences in VSTM over and above the ability to recruit top-down attention during maintenance, subvocal rehearsal was prevented across both item conditions by making items much more difficult to rehearse verbally. Even though the usual practice for disrupting subvocal rehearsal for nameable items is via articulatory suppression, I refrained from adopting this process in order to maintain consistency with the design of the previous experiments and to avoid a potential increase of attentional demands during maintenance (Morey & Cowan, 2004) that could interfere with retro-cuing effects. Instead, I opted for presenting objects with long names (all 3-syllabic words in Greek, the language of participants in this experiment). As previous studies suggested that rehearsal speed is about 400ms per monosyllabic word in serial presentation (Hulme, Maughan, & Brown, 1991; Tam et al., 2010; Thorn & Gathercole, 2001), it would be practically impossible to rehearse the simultaneously presented nameable array items in the short available time. Indeed, other studies, using paradigms similar to the one employed here, have verified that the brief simultaneous presentation of a memory array prevents the verbal rehearsal of visuo-spatial material even without enforcing articulatory suppression (Cowan et al., 2005; Vogel et al., 2001). Also, the experiment adopted a further alternative practice to articulatory suppression, that is, the use of difficult-to-verbalise items in what I shall call from now the "abstract" condition.

I hypothesized that if adults and 11-year-olds performed better than 7-year-olds in Experiments 1 and 2 (Chapters 2 and 3 respectively) simply because they verbally rehearsed all 4 items and not because of older individuals' refined

attentional control, then age group differences should be reduced or eliminated entirely across conditions with nameable but long and abstract items and across different trial-types (cued and neutral) in this experiment. If differences between the two item types are still observed, then these would be more likely to be attributed to the semantic nature of the memory codes that participants can form during stimulus presentation for the nameable items, rather than to subvocal rehearsal. Indeed, one notable difference between the dual coding theory and the WM model is the meaning they attribute to verbal codes: the dual coding theory emphasizes the semantic aspect of the items to-be-remembered, drawing thus on long-term memory (LTM), whereas the WM model emphasizes the phonological aspect of the items to-be-remembered, drawing thus on STM and the phonological loop (although a more recent version of the WM model added the episodic buffer which provides a gateway to semantic and LTM representations). For example, memory codes may be boosted for one set of material over the other by a priori knowledge of the identity of the items-to-be-remembered, a factor that has already been suggested to contribute to memory performance (Cowan & Alloway, 2009) but has been studied substantially less in the visual compared to the verbal domain (Pickering, 2001).

Methods

Participants

Twenty children (10 boys and 10 girls) aged 6 and 7 years old (M = 6.50 years old, SD = .51; “7-year-olds” henceforth), 20 children (9 boys and 11 girls) aged 10 and 11 years old (M = 10.5 years old, SD = .51; “11-year-olds” henceforth), and 20 adults (8 males and 12 females) between 21 and 27 years old (M = 23.90 years

old, SD = 1.86) participated in this experiment. Adults were recruited from the University of Cyprus.

Measures

Attentional Orienting Task: This experiment aimed at examining the effects of the memoranda on the maintenance of visual items and its interaction with cueing effects. For this reason, the task used in Experiment 5 differed from earlier tasks mainly in the extent to which it manipulated the items in the memory array. The task is presented schematically in Figure 18.

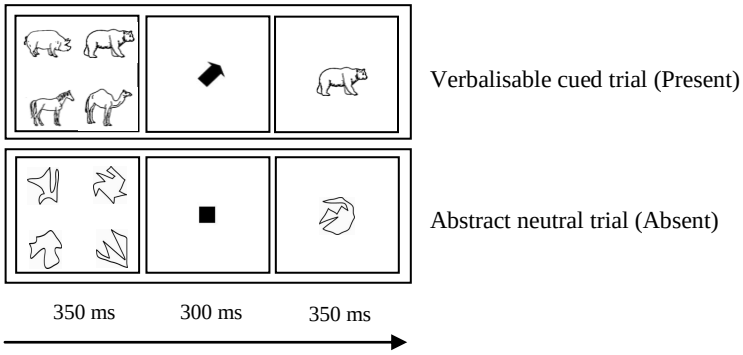


Figure 18. Schematic illustration of the task and the 2 trial-types. Dimensions of items in relation to space are bigger for display purposes.

In each trial participants viewed briefly a memory array of 4 peripheral items, followed by a single central probe item after a variable delay (see Figure 20) and were instructed to indicate whether the probe was present in the memory array by pressing the mouse buttons. Memory arrays were always followed by central cues that were informative (100% valid) or uninformative in nature depending on the trial-

type: retro-cue or neutral. Memory array items were black and white line drawings of animals (easily to label items, "verbalisable" items henceforth) or meaningless contour shapes (difficult to label items, "abstract" items henceforth) and were presented on a white background. The items in the verbalisable block were drawn from a set of eight animals: bear, camel, horse, kangaroo, pig, rabbit, frog, and turtle (see Figure 19a). The items in the abstract block were drawn from a set of eight meaningless contour shapes (see Figure 19b). The parameters taken into account for selecting the items across the two blocks are described in detail in the next section (see Adaptation of stimuli for the Attentional Orienting Task). Spatial cues were black arrows and neutral cues were black filled squares. Items subtended the same visual angles as those in the experiments described in the earlier chapters (see Experiment 1 for specific dimensions). Figure 20 illustrates a sample trial with the used temporal parameters.

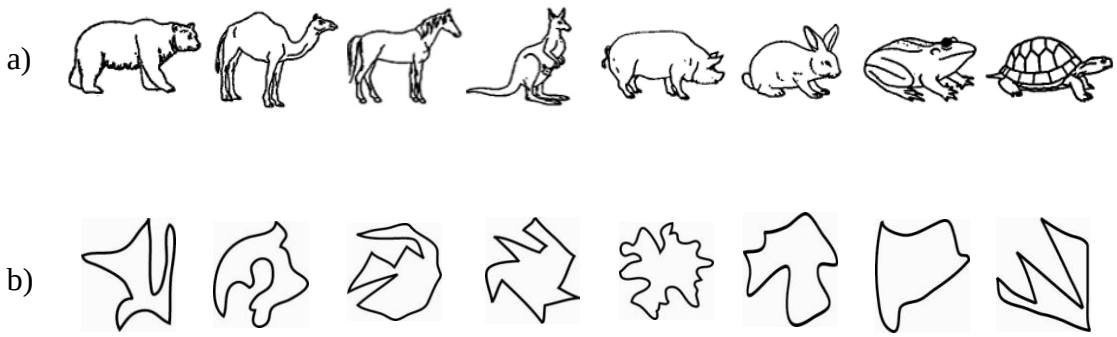


Figure 19. a). Schematic illustration of the 8 items in the verbalisable blocks. ***b)*** Schematic illustration of the 8 items in the abstract blocks.

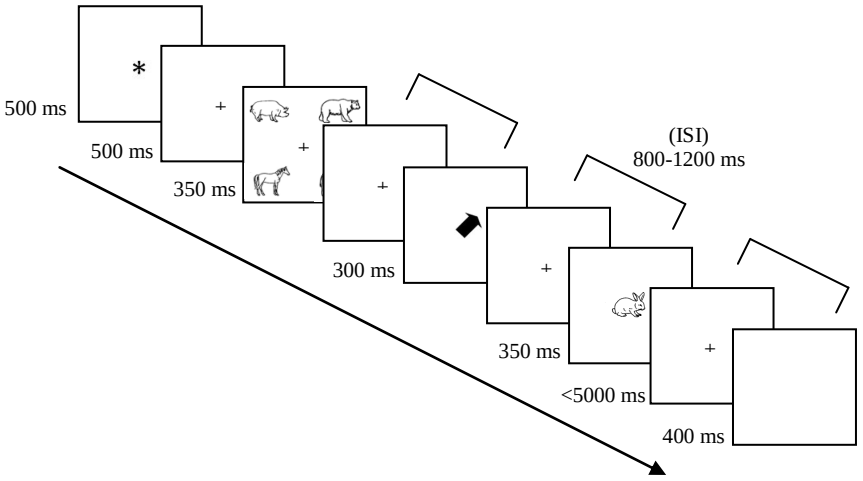


Figure 20. Schematic illustration of the sequence of events and their temporal parameters on each test trial.

As for other experiments, the task consisted of two practice blocks of 6 trials each so that participants could familiarize themselves with the task[10], followed by 4 test blocks of 48 trials each, totaling 192 experimental trials: 128 (66.6%) probe-present and 64 (33.3%) probe-absent trials. The first practice block was a slower version of the test blocks to ensure that participants understood the task, whereas the second practice block employed the timing parameters of the test blocks. Half of all test trials (50%) were cued (equally likely to point to one of the four possible spatial locations) and the other half (50%) were neutral. Of the probe-present trials over the four blocks, 64 were retro-cue and 64 were neutral trials. Of the probe-absent trials, 32 were retro-cue trials and 32 were neutral trials. These trials were presented over 2 "verbalisable" blocks, containing the animals, and 2 "abstract" blocks, containing the shapes, to prevent children from being confused by a continuous change of items

[10] Note that all practice items were different than those presented in the test blocks to rule out the possibility that participants would name aloud the items during the slow practice presentation and then use those labels for subvocal rehearsal during testing.

across trials and to be consistent with the design of the previous experiments. Test blocks alternated throughout the task and were counterbalanced across participants. Cued and neutral trials occurred randomly within each test block.

Adaptation of stimuli for the Attentional Orienting Task

Verbalisable items were taken from the set of black and white line drawings of Snodgrass and Vanderwart (1980) whereas abstract items were taken from the contour shapes developed by Endo, Saiki, Nakao, & Saito (2003). Verbalisable items were controlled for word length[11], age of acquisition[12], word frequency[13], and picture familiarity, measured by their means in the standardised set (Dimitropoulou, Duñabeitia, Blitsas, & Carreiras, 2009), to ensure the use of age-appropriate items as these can influence memory processes differentially across age groups (Cycowicz, Friedman, Rothstein, & Snodgrass, 1997). Also, verbalisable items belonged to the same category to avoid introducing categorical membership as a possible confounding factor (Awh et al., 2007). Finally, both verbalisable and abstract items were matched in visual perceptual complexity[14] to ensure that encoding processes operated on stimuli containing similar amounts of perceptual pictorial detail because previous studies showed that object complexity influences VSTM capacity (Alvarez & Cavanagh, 2004). Therefore, any differences in performance across items and across age groups would be attributed to the internal memory codes (dual or unitary) used for maintenance rather than to encoding differences in the perceptual features.

[11] All items constituted 3-syllable words in the Modern Greek language to prevent subvocal rehearsal as much as possible and reduce word length effects across age groups (Hitch et al., 1988; Hitch et al., 1989; Hulme et al., 1986).
[12] All animals are learned by 3 years of age in the Greek and Greek-Cypriot population.
[13] Selected animals were high-frequency words indicating high familiarity across age groups.
[14] Complexity parameters for the abstract items were provided by Endo et al. (2003).

Pilot testing for the abstract shapes with 10 adults indicated that these shapes were difficult to label. Subsequently, all images were resized to equal dimensions using the Adobe Photoshop software. Five additional images, a black arrow in 4 distinct orientations and one black filled square, were created to function as "cues". Finally, an additional 22 images were collected from the web and were further processed and used as the "theme of the game" in order to make the task appealing to the children.

AWMA – Dot Matrix and *Spatial Recall:* The two AWMA subscales (the Dot Matrix and the Spatial Recall, measuring VSTM and VWM span respectively) administered in Experiments 1 and 3 (Chapters 2 and 4 respectively), were also administered in Experiment 5.

AWMA – Digit Recall[15]: Digit Recall is a measure of verbal STM capacity. In this subscale, participants listen to a sequence of digits and are then required to recall the sequence aloud in exactly the same order.

AWMA – Backward Digit Recall: The Backward Digit Recall is an index of verbal WM capacity. As with Digit Recall, participants listen to a sequence of digits but this time they are required to recall the sequence aloud in a backward order. For both verbal subscales the number of the digits to-be-remembered is increased until performance falls below a two-thirds criterion which is taken as a measure of participants' verbal STM / WM capacity respectively.

[15] Greek versions of the Digit Recall and Backward Digit Recall subscales were administered to all participants. These were provided by Dr. Elvira Masoura based at the Aristotle University of Thessaloniki, Greece. The Greek versions have not been standardized but they have been used extensively for research purposes by Dr. Masoura. The subscales have been developed very carefully to match the English digits in length. Given that only the raw scores of all AWMA subscales have been used for statistical analyses, the lack of standardized scores for the two verbal subscales does not affect the analyses or the results of the experiment.

Similar to Experiment 1 (Chapter 2), I aimed to examine how attentional orienting contributes to ability measured by more classical STM / WM tasks across development. However, in this experiment, I examined these relations across both visual and verbal span tasks and for different types of items that participants need to maintain in memory [i.e., items that generate different internal codes: dual (visual and verbal) vs. unitary codes (visual)]. I hypothesized that performance in verbalisable blocks of the Attentional Orienting Task would relate to both visual and verbal STM / WM span tasks, presumably because encoding and maintenance of familiar and nameable items rely on dual coding, whereas performance in abstract blocks of the Attentional Orienting Task would relate to VSTM / VWM span tasks, presumably because encoding and maintenance of novel and difficult to label items rely on unitary visual codes only.

Procedure

Children were tested in a quiet room within their school in Nicosia and adults were tested at the EPL at the University of Cyprus. All participants were individually tested. Participants carried out the Attentional Orienting Task and subsequently they completed the four subscales of the AWMA. All measures were presented on a laptop computer for all participants. Short breaks in-between the test blocks and the tasks were inserted.

Participants sat at a comfortable distance from the screen and were introduced to the testing procedure. First, the examiner told the participants that they were going to play a game called “Treasure hunt” with a pirate (named “Jack” in the case of male participants and “Monica” in the case of female participants) who wants to

recover various hidden treasures that were buried in four different islands and needed the participant's help to achieve his/her goal. In order to do so, participants needed to spot old and new animals/shapes (depending on the block) by responding yes/no. Every time they spotted the animals/shapes correctly, they won a point. They were told that the game has four levels and at every level they would have to try to earn as many points as possible in order to collect the hidden treasures, i.e., crowns in the first block, gems in the second block, money/gold in the third block, and a chest full of treasures in the last block. Once they collected the treasures in an island, they won a sticker of their choice. The ultimate goal was to collect all treasures from all islands and win a "Science" certificate. This new game ensured that children were engaged in the task and tried to perform as well as possible. Then, the experimenter explained the characteristics of the trial-types of the Attenional Orienting Task using examples presented on cards. Illustrations of the example cards are presented in Appendix B, Figure B6. Participants were told that 4 pictures of animals or shapes would first appear on the screen and after a little while, another picture, animal or shape depending on the items in the preceding array, would appear. Their job was to search their memory and indicate by pressing the mouse button whether that last picture was one of the four initial ones. They were told that they would always know before the beginning of the block whether they would see animals or shapes in the array. They were also told that sometimes after the array they would be given a cue (a black arrow), which would sometimes point to the one picture out of the four that might re-appear next. When no cue appeared, they saw a black square presented centrally. The experimenter emphasized that participants should pay attention to the spatial cues,

when available, as these would help them decide whether the probe item was present in the preceding memory array.

The practice session lasted approximately 5 minutes and each test block around 6 minutes. Participants completed the whole task in approximately 35 minutes. Once children completed the task, they were given a post-test in which they were presented with a card illustrating the 8 test animals and were asked to name them. This ensured animal familiarity and name agreement for all children, especially the 7-year-olds[16]. While common practice in the field is to give children a pre-test to confirm item familiarity (Halliday et al., 1990; Hitch et al., 1991, 1989; Palmer, 2000a; Tam et al., 2010), here familiarity was tested at the end of the task to avoid priming the children to label the items during the task. Also, all participants were asked to remain silent while performing the testing blocks to prevent covert labelling at encoding which could enhance representations for verbalisable items (e.g., Hitch et al., 1991; Johnston & Conning, 1990) but not for abstract items. Therefore, converting visual material to verbal codes, if any, would be mentally spontaneous and under situations where subvocal rehearsal was deemed highly unlikely. At debriefing at the end of the experiment, all participants reported that they did not rehearse the items due to the short presentation time. However, they reported that they encoded verbalisable items more easily.

The AWMA was administered following the standardized instructions that accompany the test. During the AWMA subscales participants were encouraged to perform as well as possible but were not given feedback about their performance, except in the practice sessions. The AWMA took approximately 45 minutes. All

[16] There was 100% familiarity and name agreement across 7-year-olds and 11-year-olds.

children received stickers as rewards for the completion of the test blocks and a certificate of participation at the end of the testing. Adults participated voluntarily.

Statistical design and analyses

Separate mixed-design ANOVAs were performed on d-prime, *K*, and median RT scores with the block (verbalisable, abstract) and the trial-type (cued, neutral) as the within-subject variables and the age-group (7-year-olds, 11-year-olds, and adults) as the between-subject variable. Difference scores were also calculated to assess the size of cueing effects in accuracy and latency. In order to investigate the extent to which performance on the Attentional Orienting Task related to visual and verbal STM and WM abilities, correlational analyses were carried out to assess whether age in months, performance on neutral baseline trials, and performance on cued trials related to raw scores on the Dot Matrix (indexing VSTM span), Spatial Recall (indexing VWM span), Digit Recall (indexing verbal STM span), and Backward Digit Recall (indexing verbal WM span) subscales. As in Experiment 1, d-prime and *K* were chosen here because traditional span measures are unspeeded and because RT is thought to index less well the precision of cued representations (Prinzmetal et al., 2005).

Results

D-prime

The analysis on d-prime scores revealed significant main effects of block [$F(1,57)=39.72$, $p<.001$, $\eta^2=.41$], trial-type [$F(1,57)=124.90$, $p<.001$, $\eta^2=.69$], and

age-group [$F(2,57)=30.67$, $p<.001$, $\eta^2=.52$]. In addition, it yielded significant interactions of block x trial-type [$F(1,57)=10.09$, $p=.002$, $\eta^2=.15$], block x age-group [$F(2,57)=3.87$, $p=.03$, $\eta^2=.12$], and trial-type x age-group [$F(2,57)=7.46$, $p=.001$, $\eta^2=.21$]. The 3-way interaction of block x trial-type x age-group did not reach significance [$F(2,57)=.17$, $p=.85$, $\eta^2=.006$]. Mean d-prime scores are reported in Table 19.

Table 19. *D-prime, K, and RT scores for verbalisable vs. abstract items, for retro-cue and neutral trials for all age-groups. Standard deviations are reported in parentheses.*

	Verbalisable block		Abstract block	
	Cued	Neutral	Cued	Neutral
D-prime				
7-year-olds	0.59 (0.53)	0.09 (0.49)	0.27 (0.44)	0.04 (0.34)
11-year-olds	1.64 (0.59)	0.76 (0.56)	0.81 (0.48)	0.35 (0.36)
Adults	1.66 (0.62)	0.59 (0.42)	1.11 (0.50)	0.36 (0.56)
K				
7-year-olds	0.86 (0.74)	0.18 (0.64)	0.40 (0.62)	0.04 (0.48)
11-year-olds	2.20 (0.68)	1.06 (0.69)	1.15 (0.69)	0.51 (0.51)
Adults	2.17 (0.61)	0.86 (0.60)	1.59 (0.67)	0.54 (0.81)
RT (ms)				
7-year-olds	1221.33 (312.05)	1518.03 (425.01)	1347.18 (350.58)	1592.15 (609.20)
11-year-olds	735.13 (175.82)	961.60 (218.61)	878.08 (233.38)	1081.90 (319.01)
Adults	601.63 (163.48)	887.28 (286.64)	670.38 (198.78)	942.50 (226.46)

Analyses of simple main effects for the block x trial-type interaction showed significantly better performance in the verbalisable block than in the abstract block, both in cued (M=1.30 for verbalisable block and M=.73 for abstract block, $p<.001$) and neutral trials (M=.48 for verbalisable block and M=.25 for abstract block,

p=.008), and significantly better performance in cued than in neutral trials, both in verbalisable (p<.001) and abstract blocks (p<.001). The interaction was driven by greater differences between the two blocks in cued than in neutral trials (see also Difference Score analyses in the next page). Simple main effects for the block x age-group interaction showed that adults and 11-year-olds performed significantly better in the verbalisable than in the abstract block (adults: M=1.12 and M=.73 for verbalisable and abstract blocks respectively, p=.001; 11-year-olds: M=1.20 and M=.58 for verbalisable and abstract blocks respectively, p<.001), whereas 7-year-olds did not show statistically significant differences across the two blocks (M=.34 and M=.15 for verbalisable and abstract blocks respectively, p=.09). Furthermore, adults and 11-year-olds performed significantly better than 7-year-olds, both in verbalisable (p<.001 for both adults and 11-year-olds) and abstract blocks (p<.001 for adults; p=.001 for 11-year-olds), whereas adults and 11-year-olds performed equally well with each other in both blocks (p>.05 for both blocks). Finally, simple main effects for the trial-type x age-group interaction showed that all participants performed better in cued than in neutral trials (adults: M= 1.38 and M=.47 respectively, p<.001; 11-year-olds: M=1.22 and M=.56 respectively, p<.001; 7-year-olds: M=.43 and M=.07 respectively, p=.001). Adults and 11-year-olds performed significantly better than 7-year-olds, both in cued (p<.001 for both adults and 11-year-olds) and neutral trials (p<.001 for adults; p=.001 for 11-year-olds), whereas adults and 11-year-olds performed equally well to each other in both trial-types (p>.05 for both cued and neutral trials). The interaction was driven by greater benefits in adults than 7-year-olds (see also Difference Score analyses below). As in Experiments 1 and 2, given that the absolute level of performance by the youngest

children was low, I tested whether it differed significantly from chance. In neutral trials, average accuracy on target present trials was M=.51 for verbalisable blocks and M=.48 for abstract blocks, values that did not differ significantly from chance ($p>.05$ in both instances). However, average accuracy on retro-cue trials was M=.61 for verbalisable blocks and M=.58 for abstract blocks, values that did differ significantly from chance ($p=.001$ and $p=.02$ respectively).

In order to investigate differences in cueing benefits associated with the memoranda independently of baseline differences in memory in neutral trials across age-groups, difference scores were also calculated (Figure 21). The analysis on difference scores yielded a main effect of block-benefit [$F(1,57)=10.09$, $p=.002$, $\eta^2=.15$] with greater cueing benefits in the verbalisable blocks (M=.82) than in the abstract blocks (M=.48), and of age-group [$F(2,57)=7.46$, $p=.001$, $\eta^2=.21$] with adults benefiting from cues (M=.91) to a greater degree than 7-year-olds (M=.36, $p=.001$). There were no differences in cue benefits between adults and 11-year-olds (M=.67, $p>.05$) or between 11-year-olds and 7-year-olds ($p>.05$). The block-benefit x age-group interaction did not reach significance [$F(2,57)=.17$, $p=.85$, $\eta^2=.006$].

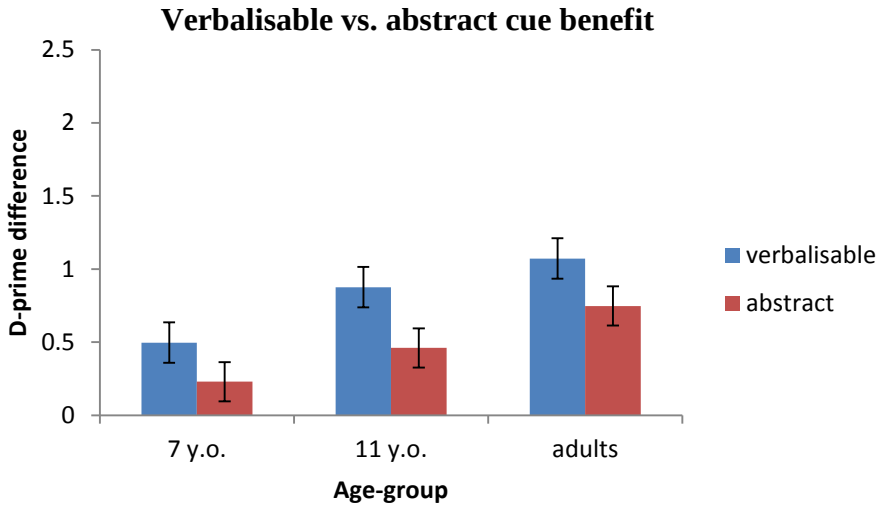


Figure 21. D-prime difference scores from neutral baseline, comparing verbalisable and abstract blocks for all age-groups. Error bars represent standard errors of the mean.

K capacity measure

The analysis on *K* scores yielded significant main effects of block [$F(1,57)=38.70$, $p<.001$, $\eta^2=.40$], trial-type [$F(1,57)=130.59$, $p<.001$, $\eta^2=.70$], and age-group [$F(2,57)=33.48$, $p<.001$, $\eta^2=.54$]. Also, it revealed significant interactions for block x trial-type [$F(1,57)=6.53$, $p=.01$, $\eta^2=.10$], block x age-group [$F(2,57)=3.20$, $p=.05$, $\eta^2=.10$], and trial-type x age-group [$F(2,57)=6.31$, $p=.003$, $\eta^2=.18$]. The 3-way interaction of block x trial-type x age-group did not reach significance [$F(2,57)=.26$, $p=.77$, $\eta^2=.01$]. Mean *K* scores are reported in Table 19.

Analyses of simple main effects for the block x trial-type interaction showed significantly higher *K* scores in the verbalisable block than in the abstract block, both in cued (M=1.74 for verbalisable block and M=1.05 for abstract block, $p<.001$) and neutral trials (M=.70 for verbalisable block and M=.36 for abstract block, $p=.004$), and significantly higher *K* scores in cued than in neutral trials, both in verbalisable

($p<.001$) and abstract blocks ($p<.001$). As in the d-prime analysis, the interaction arose due to the greater difference between verbalisable and abstract items in cued trials than neutral trials (see Difference Scores analyses). Simple main effects for the block x age-group interaction showed that all age-groups had significantly higher *K* scores in the verbalisable than in the abstract block (adults: M=1.51 and M=1.07 for verbalisable and abstract blocks respectively, p=.003; 11-year-olds: M=1.63 and M=.83 for verbalisable and abstract blocks respectively, $p<.001$; 7-year-olds: M=.52 and M=.23 for verbalisable and abstract blocks respectively, p=.04). Adults and 11-year-olds had significantly higher *K* scores than 7-year-olds, both in verbalisable ($p<.001$ for both adults and 11-year-olds) and abstract blocks ($p<.001$ for adults; p=.001 for 11-year-olds), whereas adults and 11-year-olds had equal *K* scores to each other in both blocks ($p>.05$ for both blocks). The interaction was driven by a smaller difference between the two blocks in 7-year-olds compared to 11-year-olds ($p<.02$). Finally, simple main effects for the trial-type x age-group interaction showed that all participants had higher *K* scores in cued than in neutral trials (adults: M= 1.88 and M=.70 respectively, $p<.001$; 11-year-olds: M=1.68 and M=.78 respectively, $p<.001$; 7-year-olds: M=.63 and M=.11 respectively, $p<.001$). Adults and 11-year-olds had significantly higher *K* scores than 7-year-olds, both in cued ($p<.001$ for both adults and 11-year-olds) and neutral trials ($p<.001$ for both and 11-year-olds), whereas adults and 11-year-olds had equal *K* scores with each in both trial-types ($p>.05$ for both cued and neutral trials).The interaction was driven by greater cueing benefits for adults than 7-year-olds (see Difference Score analysis below).

Similar to d-prime, these results were corroborated by greater cueing benefits in the verbalisable blocks (M=1.04) than in the abstract blocks (M=.69), that led to a

significant main effect of block-benefit [F(1,57)=6.53, p=.01, η^2=.10], and by greater cueing benefits from adults (M=1.18) than 7-year-olds (M=.52, p=.002), that led to a main effect of age-group [F(2,57)=6.31, p=.003, η^2=.18]. Again, there were no differences in cue benefits between adults and 11-year-olds (M=.89, p>.05) or between 11-year-olds and 7-year-olds (p>.05). The block-benefit x age-group interaction did not reach significance [F(2,57)=.26, p=.77, η^2=.01]. Figure 22 illustrates the benefit scores across blocks.

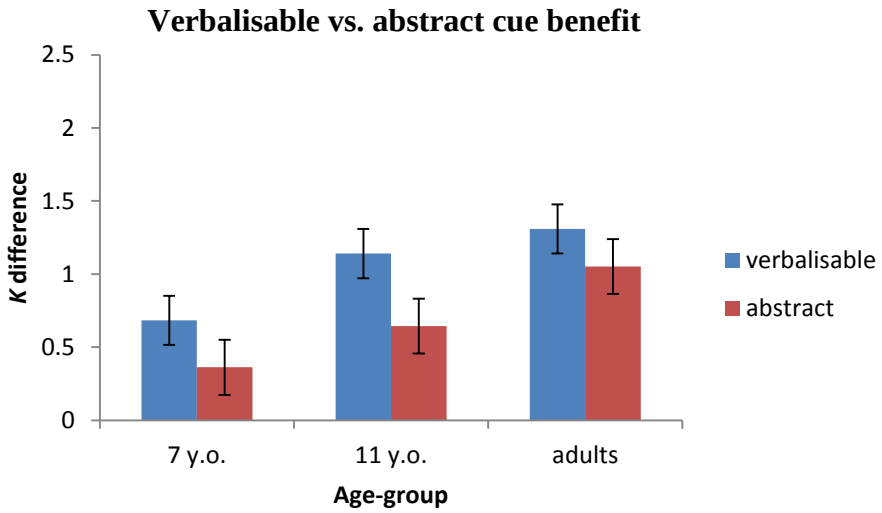


Figure 22. *K* difference scores from neutral baseline, comparing verbalisable and abstract blocks for all age-groups. Error bars represent standard errors of the mean.

Median RTs

There were significant main effects of block [F(1,57)=11.34, p=.001, η^2=.17] driven by faster responses in the verbalisable block (M=987.50) than in the abstract block (M=1085.36), of trial-type [F(1,57)=73.59, p<.001, η^2=.56] caused by faster responses in cued trials (M=908.95) than in neutral trials (M=1163.91), and of age-group [F(2,57)=33.58, p<.001, η^2=.54] due to adults (M=775.44) and 11-year-olds

(M=914.18) performing significantly faster than 7-year-olds (M=1419.67, p<.001 for both adults and 11-year-olds). Adults and 11-year-olds performed equally fast to each other (p>.05). None of the other effects reached statistical significance [F<1 for all interaction effects]. A separate analysis of difference scores (Figure 23) did not reveal any statistically significant main or interaction effects on cueing benefits (F<1 for all effects).

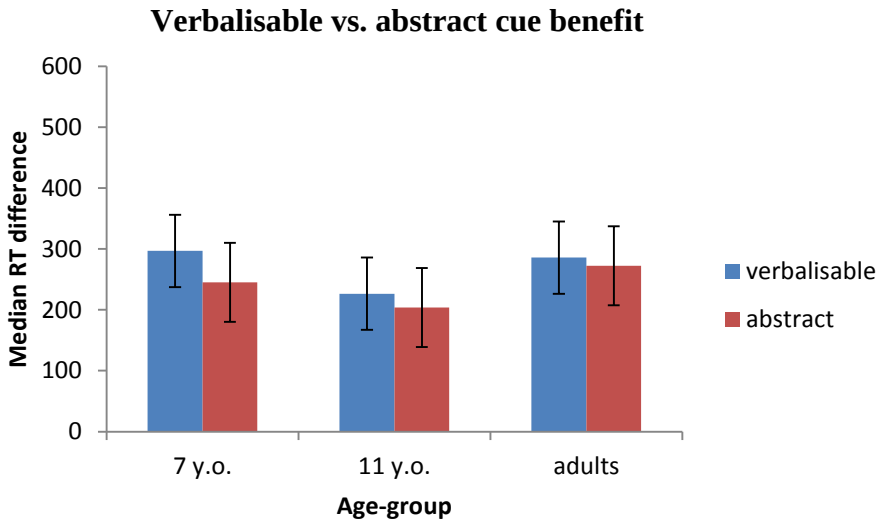


Figure 23. Median RT difference scores from neutral baseline, comparing verbalisable and abstract blocks for all age-groups. Error bars represent standard errors of the mean.

Relations between attentional cueing benefits and VSTM / VWM capacity

Next, I assessed whether individual differences in attentional orienting in each block related to performance on validated VSTM / VWM and verbal STM / verbal WM span tasks. As in Experiment 1 (Chapter 2), age was considered as a continuous variable (age in months), rather than a categorical one, to evaluate fully the relative contribution of age and individual differences in predicting memory

capacity. Partial correlations controlling for chronological age across measures of attentional orienting and memory span performance (raw scores from the two AWMA subscales) are presented in Table 20 and Table 21 for d-prime and *K* respectively.

In summary, performance following retro-cues in *d-prime* and *K* in the *verbalisable* block related significantly to VSTM span (as indexed by the Dot Matrix subscale) and VWM span (as indexed by the Spatial Recall subscale) but not to verbal STM span (as indexed by the Digit Recall subscale) and verbal WM span (as indexed by the Backward Digit Recall subscale). Performance following retro-cues in *d-prime* in the *abstract* block related significantly to VSTM span (as indexed by the Dot Matrix subscale) and verbal STM span (as indexed by the Digit Recall subscale) whereas performance in *K* related significantly only to verbal STM span (as indexed by the Digit Recall subscale). However, when the variability associated with neutral trials (effectively measuring baseline performance of how accurately participants could remember whether the probe item was part of the memory array) was taken into account, only the relations between d-prime and *K* on retro-cue trials in the *verbalisable* block and VSTM and VWM span held.

Tables 20 - 21. *Relations between chronological age (age in months), attentional control measures (d-prime scores, denoted by "d'" in Table 19; K scores in Table 20) and raw scores for VSTM span (Dot Matrix, AWMA, demoted by "DM"), VWM span (Spatial Recall, AWMA, demoted by "SR"), verbal STM span (Digit Recall, AWMA, demoted by "DR"), and verbal WM span (Backward Digit Recall, AWMA, demoted by "BDR"). Values above the diagonal indicate partial correlations across measures controlling for chronological age in months, whereas values below the diagonal indicate partial correlations between d-prime and K on cued trials and AWMA subscales, controlling for both chronological age and d-prime or K on neutral trials. "Verbal-neutral" and "verbal-cued" refer to the "verbalisable" block.*

Table 20. *Correlation table for d-prime.*

	d' verbal-cued	*d*' abstract-neutral	*d*' abstract-cued	DM	SR	DR	BDR
d' verbal-neutral	.509***	.124	.407***	.260*	.285*	.325**	.282*
d' verbal-cued		.062	.411***	.458***	.359**	.195	.126
d' abstract-neutral			.173	.280*	.047	.290*	.142
d' abstract-cued				.253*	.138	.264*	.124
DM	.393**		.216				
SR	.259*		.132				
DR	.036		.227				
BDR	-.021		.102				

**p≤.05, **p≤.01, ***p≤.001.*

Table 21. *Correlation table for K.*

	K verbal-cued	*K* abstract-neutral	*K* abstract-cued	DM	SR	DR	BDR
K verbal-neutral	.518***	.122	.363**	.257*	.230[b]	.277*	.238[c]
K verbal-cued		.084	.398**	.478***	.405***	.186	.174
K abstract-neutral			.177	.302*	.068	.308*	.166
K abstract-cued				.245[a]	.153	.275*	.164
DM	.417***		.204				
SR	.343**		.144				
DR	.051		.236[d]				
BDR	.061		.139				

*[a] p=.06, [b] p=.08, [c] p=.07, [d] p=.07, *p<.05, **p<.01, ***p<.001.*

Discussion

Experiment 5 demonstrated clear effects of the characteristics of the memoranda on VSTM across development with more accurate and faster recognition for familiar and nameable objects than unfamiliar and difficult to label shapes. Importantly, this was the case for all age groups. This finding suggests that all participants had encoded the pictorial nameable objects in both visual and verbal code, whereas they relied on unitary visual codes to represent the unfamiliar abstract shapes. In contrast to the hypothesis that developmental changes in VSTM may also be driven by differences in coding (i.e., that young children are perceptually bound to the modality of the presented material whereas older participants use dual coding upon pictorial presentation leading to an additive benefit in recognition), results demonstrated that from 7 years of age participants represented pictorial nameable items across two cognitive systems, an imagery- and a language-based as argued by Paivio (1971). Dual coding presumably allowed participants to maintain, in addition to the visual representation, a verbal representation for the nameable objects compared to the abstract shapes leading to overall better recognition for this type of items. Although previous studies have reported that 6-year-olds rely on unitary codes, the difference in findings may be due to the fact that these studies included a younger pool of 4- to 6-year-olds (Halliday et al., 1990; Hitch et al., 1991, 1988, 1989; Hitch et al., 1989) compared to the older age range of 6- to 7- year-olds tested here. It may well be that it is around the age of 6- to 7- years that the ability for dual coding emerges (Palmer, 2000a) and it is improved over development. Present results support this possibility. For example, the difference between verbalisable and

abstract items was smaller for younger children than for the other two age groups and reached statistical significance only for one of the accuracy-based dependent measures (*K*). This result demonstrates a quantitative difference in the ability for dual coding among the age groups and more specifically a less efficient process in 7-year-olds. Yet, there were developmental differences in memory recognition despite dual coding being functional from early childhood. Older participants performed better than 7-year-olds whereas 11-year-olds aligned themselves with adults in terms of overall performance across the item types, extending previous results of highly developed memory for serially encoded visuo-spatial material in older children (Hitch et al., 1988, 1989; Hitch et al., 1989) to conditions involving simultaneously presented visual material.

In addition, there were robust cueing benefits for the accuracy and the speed with which information was retrieved from VSTM, both when cues were presented during maintenance of familiar nameable objects and unfamiliar abstract shapes, validating thus earlier conclusions from adult and child studies that re-activating a representation long after array presentation via spatial attention cues facilitates probe recognition (Astle et al., 2012; Griffin & Nobre, 2003; Kuo, Stokes, et al., 2011; Lepsien & Nobre, 2006; Makovski & Jiang, 2008; Makovski et al., 2008; Matsukura et al., 2007). Detection cueing benefits showed a different pattern of modulation for the two item types across measures: for accuracy-based measures, detection cueing benefits were larger when attention was deployed when maintaining familiar nameable objects rather than when maintaining unfamiliar and difficult to label shapes for all age groups, indicating that top-down attentional control biased maintenance differentially across item types in favour of the familiar nameable

objects for all participants. Developmental differences emerged in the extent to which cues during maintenance helped participants; that is, maintenance benefits were smaller for younger children than for adults. For speed-based measures, detection cueing benefits were of equal size across item types and across age groups indicating that the characteristics of the memoranda, i.e., familiarity and nameability, had an additive benefit to that of age on how fast the internal representations were accessed. As in previous experiments, the two measures, accuracy and RT, seem to index distinct effects on how well stimuli are represented in memory and information is accessed respectively (Prinzmetal et al., 2005). While retro-cues allowed older individuals to represent the item to-be-probed more accurately than young children, once the item-to-be probed was selected and enhanced, participants of all age groups benefited equally from the cue in accessing and comparing the selected item with the probe.

In summary, findings here corroborate the results of Chapters 2 and 3 (see also Astle et al., 2012) showing that the ability to voluntarily apply spatial biases during maintenance is refined over development. The novel finding here is that the coding of the memoranda interacts with attentional control in such a way that allows or constrains participants to maintain accurate and durable representations in VSTM. For example, it seems that dual coding allowed participants to form multiple internal representations for the familiar items so that when the retro-cue appeared, it re-activated or refreshed more reliably a veridical representation for this item type than for the novel abstract shapes. Ricker and Cowan (2010) proposed that some visual features cannot be attentionally refreshed as successfully as others and therefore are inevitably lost over item. Features of unconventional characters, similar to the

abstract shapes used in this experiment, have been shown to be more prone to this failure compared to familiar items (Ricker & Cowan, 2010). Present results extend the findings for Ricker and Cowan with adults by showing that the less optimal refreshing of abstract stimuli is present from early childhood.

The performance differences observed between the familiar and unfamiliar items in the present experiment are more readily explained by the differences in the semantic codes that participants formed during encoding rather than differences in phonological codes or subvocal rehearsal. Both item types were perceptually similar ensuring that they were processed only based on their visual features (i.e., shape) across conditions and subvocal rehearsal was prevented[17]; therefore, any differences observed can be attributed to items being familiar or unfamiliar. Indeed, inhibiting phonological coding in VSTM does not disrupt semantic coding (Baddeley, 1986) and results here clearly show that highly familiar items that are present in LTM are easier to maintain and recognise than novel items. It seems thus that object familiarity triggered access to representations stored in LTM and their semantic codes, subsequently generating dual coding that led to better recognition for familiar than novel abstract shapes. This is in line with the top-down theories of object perception positing that stimuli are recognized by comparing encoded information to stored knowledge (e.g., Riddoch & Humphreys, 2001). When the present stimulus matches semantic information in LTM, individuals can rely on their existing knowledge to name the stimulus and maintain it in STM. Results here indicate that spatial attentional biases are more effective in objects with both visual and semantic

[17] Although subvocal rehearsal cannot be ruled out with 100% certainty in this experiment, debriefing indicated that participants did not rehearse the array. Furthermore, even if a small number of older participants tried to rehearse, the difficulty in rehearsing 4 long-name objects in a brief ISI would not allow participants to rehearse all items across all trials in such a way that it would add a systematic error in the experiment.

codes than for objects with visual codes only. Importantly, the processes that underlie these effects seem to take place from early childhood, yet are less mature, indicating that developmental changes in VSTM may be better understood within a wider cognitive network that takes into account the influences of LTM on WM / VSTM (Baddeley, 2000, 2002; Cowan, 1999; Logie, 2003; Logie & van der Meulen, 2009; but see van der Meulen et al., 2009 for a discussion on the three theoretical models of WM and their relation to LTM[18]) and how these systems interact with attentional biases during maintenance, rather than in the early narrow context of WM (Baddeley & Hitch, 1974). In adults, for example, it has already been demonstrated that long-term memories for the locations of objects drive attentional orienting in order to optimise perception and action (Summerfield, Lepsien, Gitelman, Mesulam, & Nobre, 2006) and findings here suggest that utilizing a developmental approach along this line would be fruitful in advancing our understanding about the nature of VSTM. Indeed, Dixon, Zelazo, and De Rosa (2010) demonstrated memory-guided attention in children 5 to 9 years of age using a contextual-cueing paradigm during which children searched faster for a target stimulus among distractors in old, repetitive displays compared to new displays, suggesting that experience leads to efficient deployment of attention.

A point that emerges from this experiment refers to the role of surface features in object encoding and maintenance in VSTM. Participants' performance in all age groups in Experiment 5 was poorer relative to performance in the corresponding age groups in Experiment 1 (Chapter 2) across cued and baseline

[18] Results here seem to be more in agreement with the workspace and the unitary models that allow perceptual information to activate directly LTM representations rather than the gateway model that requires perceptual input to pass through WM first. However, a systematic examination of the three models is beyond the scope of this chapter.

neutral trials. In particular, performance in baseline neutral trials by the youngest children in Experiment 5 was at chance, although cues during maintenance improved their performance. One possible reason for the discrepancy in performance across the two experiments is that Experiment 1 contained similarly shaped yet dissimilar colourful items, rendering the array items perceptually highly discriminable from each other. Existing evidence pinpoints visual perceptual similarity as a factor that deteriorates memory performance both in children and in adults (Hitch et al., 1988; Hitch, Woodin, et al., 1989; Logie et al., 2000; Walker et al., 1993; Walker et al., 1994) and this "colour" difference between Experiment 1 and Experiment 5 in terms of surface information is important for object recognition, a point that I return to in the General Discussion.

Finally, analyses on the relations between the ability to use visuo-spatial orienting cues during the maintenance of different types of items and visual / verbal STM / WM span on validated measures used to assess these constructs in childhood were at odds with what was expected. Performance in cued trials of the verbalisable block related only to traditional measures of VSTM / VWM span but not to measures of verbal STM / WM span and performance in cued trials of the abstract block related only to traditional measures of visual and verbal STM but to none of the visual / verbal WM measures. Importantly though, only the relations between the ability to use visuo-spatial orienting cues during the maintenance of familiar and nameable items and VSTM / VWM span remained significant once baseline performance was controlled for. Performance in the verbalisable blocks may have not correlated with the two verbal subscales of the AWMA because execution of the two tasks (i.e., the verbalisable blocks in the Attentional Orienting Task and the

verbal subscales of the AWMA) may have tapped different cognitive systems (visual vs. language). While Forward and Backward Digit Span subscales are considered to measure verbal STM and WM respectively, they entail the encoding of auditory digits and their spoken recall. Furthermore, the sequential auditory presentation of the digits allows participants to subvocally rehearse them while they listen to the examiner. Therefore, the retention of the digits until recall may have relied on articulatory rehearsal process. In contrast, the verbalisable blocks in the Attentional Orienting Task entailed the encoding of visual items and their visual recognition. Furthermore, the simultaneous presentation of items with long-names deemed subvocal rehearsal highly unlikely. As already suggested, the retention of the familiar items has possibly relied on visual and semantic codes. According to the multicomponent model of WM (Baddeley, 2003; Baddeley, 2000), information received auditorily gains automatic access to the phonological store whereas information received visually gains automatic access to the visual cache (Logie, 2011). If the information can be verbalised, it requires subsequent phonological recoding before being stored in the phonological store. Given that nameable items in the Attentional Orienting Task have not undergone phonological processing, it seems unlikely that they have been stored in the phonological store. Thus, it may well be that the completion of the two verbal subscales of the AWMA relied heavily on the phonological loop and the language system whereas the encoding and maintenance of familiar and nameable items in the Attentional Orienting Task depended more on the processing of visual and semantic codes in the visuospatial sketchpad and LTM systems. Such an explanation is in line with the finding of strong relations between performance in the verbalisable blocks and VSTM / VWM span of the AWMA. Both

visual AWMA subscales are derivatives of the Corsi Block task which, as shown in past studies, does not recruit verbal strategies in remembering spatial locations (Farmer et al., 1986; Kemps et al., 2000). Therefore, the strong relations between the verbalisable blocks of the Attentional Orienting Task and the VSTM / VWM subscales of the AWMA may indicate that the visual and semantic codes generated by the familiar items and their spatial location in the memory array are more important for the maintenance of these items in memory than their phonological codes. Although it has been suggested that phonological codes dominate and mask the use of visual representations in tasks requiring encoding and maintenance of pictorial nameable objects, phonological codes do not replace the visual codes (Hitch et al., 1989; Hitch, 2006; Palmer, 2000a). Using familiar items with long names that prevented the generation of phonological codes in the current experiment unveiled the significance of visual and semantic codes during the maintenance of the pictorial nameable items in memory. Overall, these results suggest that phonological encoding and/or verbal rehearsal do not account for all developmental differences in VSTM. Rather they demonstrate that the ability to actively bias locations and objects in space on one hand and form semantic codes for visual familiar items on the other hand contribute significantly to the maintenance of these items.

With respect to performance in the abstract blocks in the Attentional Orienting Task and its relation to VSTM / VWM span, it is unclear why performance with novel and difficult to label shapes did not relate to any of the traditional visual memory span measures. If anything, it was expected that performance in these blocks would correlate more strongly with the VWM span (indexed by Spatial Recall) presumably because the greater ability to use orienting cues to bias and maintain

meaningless objects, the greater the ability would be to protect their internal representations from interference. A possible account for why performance in the abstract blocks did not relate to any of the visual span measures of the AWMA is that these items were so meaningless to participants that they were very difficult to attentionally refresh and maintain in memory. If this is the case, then participants may have recruited broad attentional resources that relate to the storage of information and may have used different processing strategies for maintenance compared to those used in the verbalisable blocks and in the AWMA subscales. It may be, for example, that participants relied mainly on the perceptual features of the shapes (e.g., their contour) to retain them in VSTM whereas in the AWMA subscales, participants relied mainly on biasing the location of the dots in space (as also demonstrated in Experiment 1, Chapter 2). The puzzling absence of links between the three tasks renders ambiguous what attentional processes participants have used to maintain the unfamiliar shapes and the extent to which these tasks rely on visual and spatial components.

In summary, results from Experiment 5 indicate that top-down attentional processes support differentially the maintenance of different types of visual material and pinpoint the involvement of different mnemonic strategies for maintaining these different types of material. Critically, this experiment demonstrated that both attentional processes and mnemonic strategies are refined over development.

As a whole, results from all experimental chapters in the current thesis so far allowed us to examine how well selective attention serves memory performance across development. More specifically, results from Experiments 1 to 5 (Chapters 2 to 6 respectively) established that attention cues can bias encoding and maintenance

in VSTM, however the ability to use selective attention to facilitate VSTM follows different developmental trajectories from early childhood to young adulthood. While children as young as 7 years of age can draw benefits from cues to bias encoding in VSTM equally well to 11-year-olds and adults, their ability to use cues after encoding the memory array to bias the maintenance of one selected item is less developed and it is constrained both by the memory load and the temporal demands. Importantly, experiments in this thesis showed that by middle childhood children show an adult-like behavioural profile in their attentional abilities to bias VSTM. However, it is unclear whether older children and adults use attention cues in the same way to modulate a memory representation. While attentional orienting began with the presentation of the attention cues, behavioural responses to the memory question about the probe may have been achieved through distinct processing routes. The cascade of events leading to a response is complex and although behavioural findings here imply similar attention mechanisms for encoding and maintaining information in VSTM in older children and adults, such a conclusion cannot be inferred on the behavioural effects solely. It may be, for example, that older children recruit different neural pathways to support selective encoding and maintenance in VSTM that nevertheless change over development. There are multiple methodological approaches to study cognitive development and electroencephalography (EEG) with the analysis of event-related brain potentials (ERP) is an ideal medium in this context because it tracks brain responses with a millisecond by millisecond resolution, allowing us to disentangle the processing stages preceding a behavioural response. In the memory paradigm I used in the current thesis so far, I asked how people use a cue (prior to encoding or during

maintenance) to modulate a memory representation and how this ability changes with development. If attention indeed selects stimuli from the memory array in a way that reflects their spatial layout, then I would expect to see differences in brain activity over the contralateral compared to the ipsilateral sites relative to the direction of the cue. Chapter 7 examines whether there are similarities and/or differences in how attention operates at the neural level in older children and adults when preparing to perceive visual input compared to when attention operates on visual representations maintained in VSTM.

Chapter 7: Orienting of attention in later childhood and adulthood: Temporal dynamics

Numerous electrophysiological studies that employed the spatial cueing paradigm (Posner, 1980) have shown early sensory modulations in the hemifield that processes the attended compared to the unattended stimuli (Eason, 1981; Eimer, 1993, 1994a, 1994b, 1995; Heinze & Mangun, 1995; Heinze, Luck, Mangun, & Hillyard, 1990; Hillyard & Münte, 1984; Hillyard, Luck, & Mangun, 1994; Hillyard & Mangun, 1987; Hillyard, Mangun, Luck, & Heinze, 1990; Luck, Fan, & Hillyard, 1993; Luck, Heinze, Mangun, & Hillyard, 1990; Mangun, 1995; Mangun, Buonocore, Girelli, & Jha, 1998; Mangun & Hillyard, 1991; Mangun, Hansen, & Hillyard, 1987; Mangun & Hillyard, 1987). These sensory biases are believed to index the spatial selection of a stimulus.

A parallel and equally vast literature concentrates on examining the preparatory neural mechanisms underlying attentional shifts prior to selection (Eimer & Van Velzen, 2002; Eimer, Van Velzen, & Driver, 2002; Harter, Miller, Price, LaLonde, & Keyes, 1989; Hopf & Mangun, 2000; Kennett, Van Velzen, Eimer, & Driver, 2007; Nobre, Sebestyen, & Miniussi, 2000; Praamstra & Kourtis, 2010; Seiss, Gherri, Eardley, & Eimer, 2007; Simpson et al., 2006; Talsma, Sikkens, & Theeuwes, 2011; Talsma, Slagter, Nieuwenhuis, Hage, & Kok, 2005; Van Velzen & Eimer, 2003; Van der Lubbe, Neggers, Verleger, & Kenemans, 2006; Van der Stigchel, Heslenfeld, & Theeuwes, 2006; Yamaguchi, Tsuchiya, & Kobayashi, 1994, 1995). These electrophysiological studies focus primarily on the neural mechanisms of attentional orienting per se and are therefore time-locked to the presentation of

attentional cues such as arrows. They examine the electrical changes taking place after the cue onset and before the target presentation by comparing the ERP waveforms that are ipsilateral and contralateral to the direction of the cue. The advantage of this methodological approach is that it provides direct evidence for attentional biases driven by visuo-spatial orienting, instead of inferring that the sensory modulation of the attended stimulus is due to a change in attentional biases. This is because an ERP is a neural index of the electrical activity underlying a cognitive process with a temporal resolution of a millisecond. Tracing the cascade of covert processes, even in the absence of a behavioural response, gives insight into the dynamics of brain activity elicited by a stimulus (Brandeis & Lehmann, 1986; Bressler, 2002; Friedman & Johnson, 2000), for example a cue, and permits investigating whether equivalent behavioural performance is underpinned by similar neural processes.

In their seminal study, Harter and colleagues (1989) instructed 6- to 9-year old children to orient their attention to a location cued by an arrow and to respond if a target was present at the cued location. Harter et al. found an early negative deflection at posterior electrode sites contralateral to the side of the attentional shift ("Early Directing Attention Negativity", EDAN), followed by a contralateral positivity at posterior electrode sites ("Late Directing Attention Positivity", LDAP). Later ERP studies with adults (Eimer et al., 2002; Harter & Anllo-Vento, 1991; Hopf & Mangun, 2000; Jongen, Smulders, & Van der Heiden, 2007; McDonald & Green, 2008; Nobre et al., 2000; Seiss, Driver, & Eimer, 2009) replicated these two lateralized components and additionally found an enhanced negativity at frontal electrodes contralateral to the attentional shift ("Anterior Directing Attention

Negativity", ADAN), thus suggesting that these three components possibly reflect successive neural processes involved in the spatial orienting of attention. More specifically, EDAN appears at approximately 200ms after the cue onset at occipito-parietal areas and is believed to reflect the processing of the directional cue and the subsequent initiation of the attentional orienting. It should be noted that a few studies argue that EDAN is possibly a disguised N2pc that relates to the processing of the asymmetric arrow rather than a genuine process of voluntary spatial attention (Van Velzen & Eimer, 2003; Woodman, Arita, & Luck, 2009), but results from other studies provide evidence against this proposition (Murray, Nobre, & Stokes, 2011; Nobre et al., 2000; Praamstra & Kourtis, 2010). ADAN appears at approximately 300ms after the cue onset over frontal and/or premotor cortex and is believed to reflect top-down attentional control. Finally, LDAP appears at approximately 500ms after the cue onset over the lateral occipital cortex and is believed to reflect the bias of cortical excitability when anticipating the upcoming target at the selected location.

The studies mentioned above have focused on lateralized components that relate to preparatory attentional mechanisms prior to perceiving an upcoming target: participants had to make a detection or discrimination judgment on an imperative stimulus that always followed the cue. However, as I reviewed throughout the preceding chapters, a growing literature reveals that top-down attentional processes also bias representations of stimuli in VSTM. Indeed, multiple studies using both behavioural measures and functional neuroimaging have shown that selective attention modulates the encoding and maintenance of information in VSTM (Astle et al., 2011; Kuo, Yeh, et al., 2011; Landman et al., 2003; Lepsien et al., 2005; Lepsien & Nobre, 2006, 2007; Lepsien et al., 2011; Makovski & Jiang, 2007; Makovski et

al., 2008; Matsukura et al., 2007; Nobre et al., 2004; Schmidt et al., 2002; Sligte et al., 2008; Vandenbroucke et al., 2011). Notably, Nobre and colleagues have shown that in adults, attentional biases applied to items held in VSTM elicit just as much behavioural benefit as attentional biases applied to the encoding of perceptual items in VSTM (Griffin & Nobre, 2003; Nobre et al., 2004). Complementing these behavioural data, numerous electrophysiological studies have attempted to unravel the processing cascade and neural mechanisms by which attention operates on VSTM representations using paradigms in which participants search their memory for a specified target and/or features (Astle et al., 2010; Carlisle & Woodman, 2011; Dell'Acqua, Sessa, Toffanin, Luria, & Jolicoeur, 2010; Eimer & Kiss, 2010; Kuo, Rao, Lepsien, & Nobre, 2009) while maintaining information on-line (Arend & Zimmer, 2011; Sander, Werkle-Bergner, & Lindenberger, 2011), and under increasing memory load sizes (Kuo, Stokes, et al., 2011; Machizawa, Goh, & Driver, 2012; McCollough, Machizawa, & Vogel, 2007; Nobre et al., 2008; Vogel & Machizawa, 2004). However, the precise attentional mechanisms gating VSTM have received little attention so far (see Gazzaley & Nobre, 2011 for a discussion). Investigating these mechanisms further is particularly relevant in the context of the current thesis, because equivalent behavioural benefits of attentional cues for VSTM in children and adults may be attained through distinct processing routes and neural circuits. Electrophysiological data allow mapping temporal dynamics and are therefore ideally suited to investigate both similarities and differences leading from stimulus processing to behavioural responses in children and adults.

Griffin and Nobre (2003) investigated the extent to which attentional shifts to perceptually-available representations engage similar neural processes as shifts to

internal representations held in VSTM. Although benefits accrued behaviourally through cues presented prior to encoding and during maintenance were similar, electrophysiological results showed both similarities and differences across these two types of attentional orienting events, suggesting partially but not wholly overlapping neural processes for prospective and retrospective orienting in VSTM. On one hand, an early posterior negative modulation and a later frontal and central negative modulation were found in both conditions, but on the other hand a non-lateralized increased positivity over posterior sites and a negativity over anterior sites were found for retro-cues compared to pre-cues. More importantly, in terms of distinguishing the two conditions, an early lateralized positivity over the anterior sites was found only for retro-cues. Griffin and Nobre suggested that this early frontal modulation is specific to the retrospective orienting of attention during VSTM maintenance. Recently, Murray, Nobre, and Stokes (2011) found that the three well-established lateralized components of visuo-spatial orienting (EDAN, ADAN, and LDAP) underlie the efficient *encoding of information into VSTM*. However, none of these studies examined whether these lateralized neural markers mediate attentional shifts *during VSTM maintenance*. For example, Griffin and Nobre investigated the attentional shifts elicited by the two cue types by comparing orienting attention to the left and right of fixation but did not contrast these findings with other established lateralized components of attentional orienting obtained by considering ERPs contralateral and ipsilateral to the direction of cues (e.g., Harter et al., 1989; Jongen et al., 2007; Nobre, Sebestyen, et al., 2000). Murray et al. did not examine whether these components are present in preparatory shifts during the maintenance of information in VSTM. Whether lateralized neural modulations underlie attentional

shifts triggered retrospectively during the maintenance period that are analogous to those supporting the prospective attentional shifts, remains to be explored. Critically, no study so far has examined whether these neural markers are involved in spatial biases on encoding and maintenance of information in VSTM from childhood and if so, how these processes change across development.

A number of open questions are ideally suited for electrophysiological investigations. Behavioural data suggest that, in children, attentional orienting operates differently when in service of encoding as opposed to maintenance in VSTM (Astle et al., 2012; see also Experiment 1, Chapter 2). Yet, whether these processes are dissociated at the neural level in childhood is largely unknown. Furthermore, multiple studies reported in this thesis indicate that, while 7-year-olds are less efficient than adults in orienting attention during maintenance (Experiments 1 and 5, Chapters 2 and 6 respectively), both 7-year-olds and 11-year-olds orient attention as efficiently as adults in preparation for encoding (Experiment 1), and 11-year-olds benefit as much as adults from attentional cues during maintenance under a variety of conditions (Experiments 1 and 5). Especially in comparing 11-year-olds and adults, it remains unclear whether equivalent efficiency of orienting in preparation to encoding and during maintenance is underpinned by similar temporal dynamics.

Finally, there is substantial literature with adults (Anderson, Vogel, & Awh, 2011; Awh & Vogel, 2008; Fukuda & Vogel, 2009, 2011; Gazzaley et al., 2005; Jost et al., 2011; Linke et al., 2011; Machizawa & Driver, 2011; Murray et al., 2011; Palva et al., 2010; Rutman et al., 2010; Todd & Marois, 2005; Vogel & Machizawa, 2004; Vogel et al., 2005; Zanto & Gazzaley, 2009) demonstrating a strong link

between individual differences in selective attention and VSTM, but none has examined how individual differences can elucidate the distinctions between selection for encoding and maintenance and their neural correlates in children. Employing an individual differences approach in cognitive neuroscience has theoretical assets for human cognition: it validates that the underlying neural activity observed while executing a cognitive task is a genuine reflection of the cognitive process being measured rather than an epiphenomenon that emerges from mediating neural processes, it reveals the functional association between two cognitive processes beyond the observed overlapping neural networks, and it can reveal neural dissociations between two otherwise theoretically associated cognitive processes (see Vogel & Awh, 2008 for further discussion).

Experiment 6: Developmental and individual differences in attentional orienting dissociate neural mechanisms of encoding and maintenance in VSTM

Understanding the neurocognitive mechanisms that underlie the relation between attentional control and memory has important implications not only for developmentalists (Casey, Giedd, & Thomas, 2000; Casey, Tottenham, Liston, & Durston, 2005; Craik & Bialystok, 2006; Crone & Ridderinkhof, 2011; Johnson & Munakata, 2005; Jolles et al., 2011; Samuelson & Smith, 2000; Tsujimoto, 2008) but also for cognitive neuroscientists investigating adult attention and VSTM. This is because such knowledge can shed light on the neural mechanisms characterizing the adult-end state. For example, seemingly similar neural processes prior to encoding and during maintenance in adulthood (Griffin & Nobre, 2003; Nobre et al., 2004)

might be achieved via different neural pathways and at different time-points in development, suggesting their spatio-temporal dissociation, a hypothesis that is also predicted by their behavioural dissociation in childhood. As briefly outlined earlier, ERPs provide a well-suited methodology for studying neural processes underlying attentional shifts in childhood because of their non-invasive nature and of high temporal resolution; that is, they provide a continuous measure of the neural activity on a millisecond-by-millisecond basis, permitting the researcher to determine the multiple cognitive processing stages preceding a response along with their time-course (Scerif, Kotsoni, & Casey, 2006; see also Hillyard & Anllo-Vento, 1998; Luck, Woodman, & Vogel, 2000 for further discussions on the benefits of using ERPs in general for studying visual attention).

Experiment 6 aimed at investigating three critical questions: First, by exploiting EDAN, ADAN, and LDAP, it examined whether adults employ similar neural processes when allocating attention retrospectively to internal representations by means of retro-cues (i.e., visuo-spatial cues presented during the maintenance period) compared to when allocating attention prospectively in anticipation of perceptual input via pre-cues (i.e., visuo-spatial cues presented prior to encoding). This is a question that has not been addressed so far in terms of conventional lateralised neural markers. I hypothesized that retro-cues would elicit an enhanced contralateral negativity over the posterior (EDAN) and frontal (ADAN) sites as these two components reflect the processing of the directional cue and the orienting of attention respectively. I examined the presence of LDAP only in pre-cues as there was no lateralised upcoming target for selection following retro-cues in this experiment.

Second, by examining whether neural markers in adults are also found in children, I assessed whether children apply similar neural biases when encoding spatial information in VSTM (via pre-cues) and if so, whether they show similar neural biases when they orient their attention retrospectively to VSTM (via retro-cues). I hypothesized that if children apply these neural biases then EDAN would be observed with both pre-cues and retro-cues and LDAP with pre-cues. Also, I hypothesized that both cue types would elicit the ADAN component. However, previous studies have associated attentional orienting with frontal activity (Corbetta, 1998; Corbetta et al., 2000; Corbetta & Shulman, 2002; Fan, McCandliss, Fossella, Flombaum, & Posner, 2005; Nobre, Gitelman, Dias, & Mesulam, 2000) and evidence from developmental brain imaging indicates protracted maturation of the frontal cortex in childhood (Bunge et al., 2002; Durston et al., 2002; Giedd et al., 1999; Sowell et al., 2004; Sowell, Trauner, Gamst, & Jernigan, 2002). Therefore, children's neural markers of attentional orienting may demonstrate a significant but nonetheless smaller ADAN than adults. Alternatively, it is possible that children may deploy distinct neural pathways to support orienting compared to adults, even in the face of robust behavioural benefits from both cue types (as evidenced for 11-year-olds across preceding chapters of this thesis), although these behavioural benefits are sometimes smaller than those measured in adults (cf. Astle et al., 2012). For these reasons, I explored spatial biases at the neural level in children separately from adults.

Third, I explored whether individual differences in attentional control relate to individual differences in VSTM capacity in children. To do so, I computed correlations between neural activity while children selectively allocated their

attention prior to encoding in VSTM and during maintenance with behavioural measures of VSTM capacity. I hypothesized that more efficient allocation of attention for selective encoding in VSTM and for selective maintenance of a mental representation would be associated with higher VSTM capacity in children.

Methods

Participants

Seventeen children (5 males and 12 females) aged 10-11 years old (M=10.2 years old, SD=.39; "10-year-olds" henceforth) and 15 adults (8 males and 7 females) aged 21 to 34 years old (M=26.4 years old, SD=3.76) participated in this experiment[19]. One adult participant was excluded from the analyses due to significantly below-chance performance in one experimental condition. Children were recruited from primary schools in Oxfordshire and adults were recruited from the University of Oxford.

Measures

Attentional Orienting Task: The task used was identical to that of Experiment 1 in the central-cue group except for the total number of test trials included in the task. The task is presented schematically in Figure 24. As a brief reminder of details presented in Chapter 2, participants viewed arrays of four colored items, followed by a single colored probe item after a variable delay and were instructed to indicate

[19] Seven additional children aged 6-7 years old were tested with EEG in this experiment as the initial goal was to acquire data from all three age groups similar to the behavioural experiments. However, due to very low accuracy and a few technical problems that prevented from obtaining EEG codes for all experimental trials during recording, data pre-processing for those seven children resulted in an insufficient number of trials. Therefore, there were not enough trials per young child to compute waveform averages in each condition.

whether the probe matched in color one of the initial four items and thus was present in the array by pressing the mouse buttons (left for presence and right for absence). Arrays were preceded or followed by central cues (white arrows) that were informative (100%) or uninformative in nature depending on the type of trial: pre-cue, retro-cue, or neutral trials. Figure 25 illustrates a sample trial with the temporal parameters.

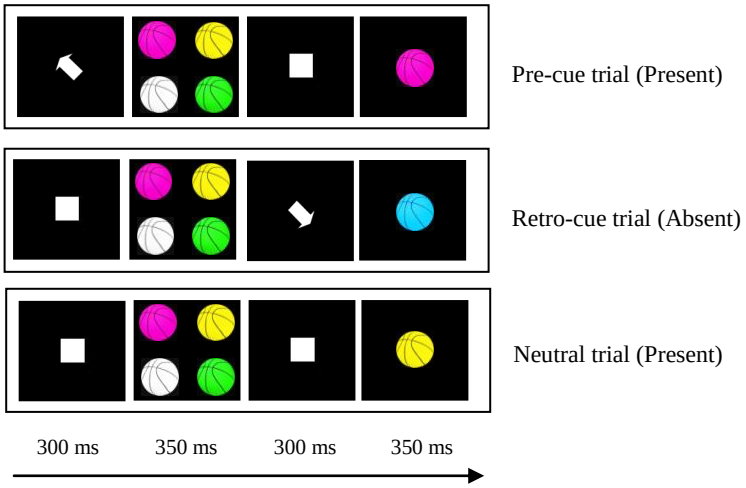


Figure 24. Schematic illustration of the task and the 3 trial-types. Items are magnified relative to the background for display purposes.

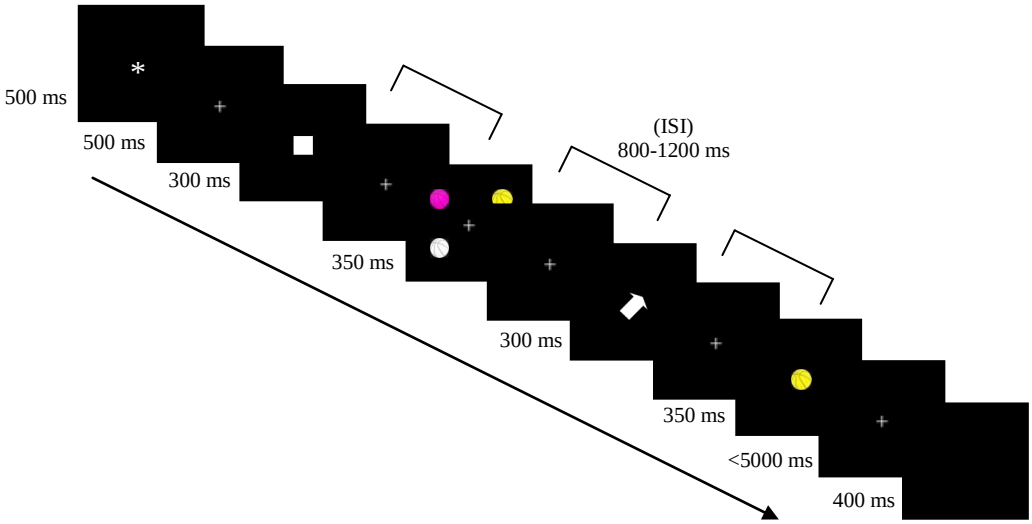


Figure 25. Schematic illustration of the sequence of events and their temporal parameters on each test trial.

Participants completed 2 practice blocks of 6 trials each to familiarize themselves with the task, followed by 8 test blocks of 48 trials in each, totaling 384 experimental trials; 256 probe-present (66.6%) and 128 (33.3%) probe-absent trials. Half of all trials were cued (equally likely to point to one of the four possible locations) and half were neutral. Of the probe-present trials, 64 were pre-cue, 64 were retro-cue, and 128 were neutral trials. Of the probe-absent trials, 32 were pre-cue and 32 were retro-cue trials to ensure that cues did not indicate a "present" response, and 64 were neutral trials. The task was split into 4 "pre-cue" blocks, containing pre-cue and neutral trials, and 4 "retro-cue" blocks, containing retro-cue and neutral trials to prevent children from being confused by continually changing cue-types across trials. Test blocks alternated throughout the task to ensure that participants would complete an equal number of "pre-cue" and "retro-cue" blocks if they decided to terminate the task before they completed all 8 test blocks. Their order

of presentation was also counterbalanced across participants. Cued and neutral trials occurred randomly within each block.

Procedure

All participants were tested at the B&C Lab, University of Oxford. Upon arrival, adult participants, children, and their parents were given a brief tour of the laboratory that was followed by a general description of the EEG procedure and how it depicts brain activity. During electrode cap placement children watched cartoons of their choice on a portable DVD player to avoid discomfort and anxiety. Finally, participants were given a short training session on how to reduce artifacts such as eye blinks and movements. After electrode placement, participants were comfortably seated in an electrically shielded and dimly illuminated room where they were given written and verbal instructions along with examples on cards. The instructions, the example cards (see Appendix B, Figure B1), and the practice sessions were identical to those for the central-cue group in Experiment 1. Participants held the mouse with their right hand and were advised to respond as quickly and accurately as possible while focusing their gaze on the fixation point throughout the trial. They were also asked to blink as little as possible, preferably after they responded, and to try to remain still during the task. All participants were monitored throughout the task via a camera and an intercom system to ensure that they were engaged in the task and that they were not moving or blinking during the test blocks. Breaks between the test blocks were self-paced. Overall, each participant was tested in one session lasting approximately 2 – 2.5 hours. All participants completed all 8 test blocks except from a child who only completed 6 blocks, 3 pre-cue and 3 retro-cue blocks, due to fatigue

and loss of interest in the task. All children received stickers as rewards for the completion of the test blocks and a certificate of participation at the end of the testing. Adults were reimbursed with £15 for their time.

EEG recording and Data processing

Electroencephalographic (EEG) activity was recorded continuously from 19 sites according to the International 10-20 system (AEEGS, 1991), using a NuAmp (Neuroscan, Inc.) amplifier and silver/silver chloride (Ag/AgCl) sintered ring electrodes mounted on an elastic cap (Easy cap). EEG data were stored and processed using the NeuroScan 4.3 software. The montage (Figure 26) included 4 midline scalp sites (Fz, FCz, Cz, Pz) and 5 scalp sites over each hemisphere (F3/F4, C3/C4, P3/P4, PO7/PO8, O1/O2). The horizontal EOG (HEOG) was recorded bipolarly with two electrodes placed on the outer canthi of both eyes to monitor for eye-movements. The vertical EOG (VEOG) was measured with one electrode placed below the right eye to monitor eye blinks. Additional electrodes were used as ground and reference sites. The electrode placed at AFz on the midline served as the ground whereas two electrodes were placed on the left and right mastoids (A1, A2) and served as reference sites. Electrode impedances were kept below 5 kΩ. The ongoing brain activity at all scalp sites was sampled every 1ms (1000 Hz analogue-to-digital sampling rate) and filtered with a band-pass of 0.50 – 70 Hz. The EEG was referenced on-line to the FCz electrode and then re-referenced off-line to the algebraic average of the left and the right mastoids.

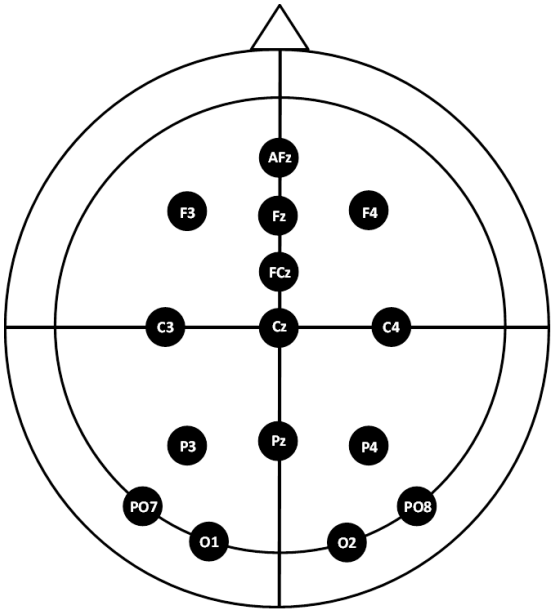


Figure 26. Illustration of the EEG montage with the recording electrode sides shown in filled black circles. The 5 sites recording from HEOG, VEOG, and left/right mastoids are not depicted on the montage.

The EEG data were then filtered off-line with a low-pass filter of 40 Hz to exclude high frequency noise. Bipolar electro-oculogram (EOG) signals were derived by computing the difference between the voltages at electrodes placed to the side of the left and right eyes (HEOG) and between F4 and below the right eye (VEOG). The continuous EEG was further processed to segment ERPs for each stimulus type (i.e., pre-cue, retro-cue). Epochs started 100ms prior to- and ended 600ms after stimulus (cue) onset. ERP amplitude values were baseline corrected relative to a -100 to 50 ms stimulus interval to ensure that any lasting effects from brain activation in previously presented stimuli or response artifact contamination (i.e., responses tended to be accompanied by blinks) were removed. EOG deflections exceeding ± 50 μV for adults and ± 100 μV for children as well as any other artifacts

in all other scalp sites exceeding ± 100 μV for adults and ± 150 μV for children were automatically rejected. In addition, all ERP trials were visually inspected for any residual artifacts (e.g., eye-movements, blinks, muscle activity) and were manually eliminated. This 2-step artifact rejection procedure resulted in approximately 82% of overall trials (range between 67 – 95%) for adults and 85% of overall trials (range between 48 – 97%) for children. Only ERPs from artifact-free, probe present trials, and trials with correct behavioural responses were included in the analyses. The accepted minimum number of trials in each trial-type condition (pre-cue, retro-cue) per participant was set to 20 trials.

ERP analyses

The aim of this experiment was to investigate whether the orienting of attention internally to mental representations held in VSTM (retro-cue trials) elicits well established lateralized components that have been observed in previous perceptual detection tasks and the extent to which these neural processes, if any, resemble those observed in VSTM encoding (pre-cue trials) across development. For this reason, the ERP analyses focused only on cue-locked epochs prior to VSTM encoding (pre-cues) and during maintenance (retro-cues).

Pre-cue and retro-cue ERP conditions were derived by averaging the cue-locked epochs for pre-cue and retro-cue trials respectively. In addition, because this experiment targeted known preparatory components such as EDAN, ADAN, and LDAP, I investigated lateralized neural activity relative to the direction of the cue. Epochs from leftward and rightward cue trials were combined with an averaging procedure that preserved the spatial location of the electrode relative to the direction

of the cue (i.e., contralateral or ipsilateral). EDAN, ADAN, and LDAP were then quantified as the mean voltage difference between contralateral and ipsilateral sites. Subsequently, I carried out statistical analyses on the mean voltage difference over consecutive time bins of 40ms each between 180 and 600ms post-stimulus (i.e., pre-cue, retro-cue), across all recorded anterior and posterior sites, to determine the presence of each component at the electrode sites and time-windows suggested by the literature. Analyses on consecutive time bins for both adults and children could pinpoint potential differences in topography and latency for the three components across the age groups. Based on previous findings, EDAN was expected to occur, and therefore measured, between 180 and 400ms at posterior electrodes, P3/4, PO7/8, and O1/2 (e.g., Harter et al., 1989; Hopf & Mangun, 2000; Jongen et al., 2007; McDonald & Green, 2008; Praamstra & Kourtis, 2010; Van der Stigchel et al., 2006). Given the results of Harter et al. (1989) with children, EDAN was also measured at central electrodes, C3/4, during this time interval; ADAN was measured between 300 and 500ms at frontal and central electrodes, F3/4 and C3/4 (e.g., Eimer et al., 2002; Hopf & Mangun, 2000; Jongen et al., 2007; Nobre et al., 2000; Van der Stigchel et al., 2006); and LDAP was measured between 400 and 600ms at posterior electrodes, P3/4, PO7/8, and O1/2 (e.g., Harter et al., 1989; Jongen et al., 2007). Even though LDAP has been traditionally reported in longer and/or later time-windows (e.g., Hopf & Mangun, 2000; Murray et al., 2011; Seiss et al., 2009), I segmented smaller ERP time-windows of 600ms to limit trial loss due to blinks, especially for children (note that the time-window employed is the same as the time-window used by Harter et al. (1989) and Jongen et al. (2007). Repeated measures ANOVA (with electrodes and laterality, i.e., contralateral/ipsilateral, as the within-

subject factors) and 2-tailed paired samples t-tests (on each electrode pair) were conducted on the mean voltage difference of each component separately for pre-cues and retro-cues. The ERP components were then quantified as present in the time-window and electrode sites where they were largest within the measured time-windows reported above. Finally, I explored functional links between electrophysiological activity and behavioural performance in children, via Spearman's correlations and split-half paired-sample t-tests on high- and low-memory capacity groups separately.

Statistical design and behavioural analyses

Separate 2 (block: pre-cue vs. retro-cue) x 2 (trial-type: cued vs. neutral) ANOVAs were performed on d-prime, *K*, and median RT scores, for each age group, to mirror the ERP analyses to follow. An omnibus ANOVA, with the same within-subject factors and age-group as a between-subject factor, was also carried out on these behavioural measures (as for Experiment 1) and is reported in full in Appendix D. However, because of the difficulties inherent to comparing directly electrophysiological data across age groups (e.g., differences depending on scalp thickness and other anatomical, rather than functional differences, see Scerif et al., 2006, for a discussion), an equivalent omnibus ANOVA was not appropriate in that context. Difference scores were also calculated to assess the size of cueing effects in accuracy and latency.

Results

Adults

Behavioural results

D-prime, K, and median RTs

Table 22. *D-prime, K, and RT scores for pre-cue, retro-cue, and neutral trials for adults. Standard deviations are reported in parentheses.*

	Pre-cue block		Retro-cue block	
	Cued	Neutral	Cued	Neutral
D-prime	4.22 (0.48)	2.10 (0.74)	3.50 (0.47)	2.26 (0.78)
K	3.83 (0.13)	2.66 (0.62)	3.62 (0.19)	2.80 (0.66)
RT (ms)	557.36 (135.01)	727.00 (146.26)	539.46 (144.84)	723.50 (147.02)

Mean d-prime, *K*, and median RT scores are reported in Table 22. The analysis on d-prime scores revealed main effects of block [$F(1,13)=4.57$, $p=.05$, $\eta^2=.26$] and trial-type [$F(1,13)=115.05$, $p<.001$, $\eta^2=.90$], and a significant interaction of block x trial-type [$F(1,13)=19.20$, $p=.001$, $\eta^2=.60$]. Analyses of simple main effects for the interaction showed that adults performed significantly better in cued than in neutral trials both in pre-cue ($p<.001$) and retro-cue blocks ($p<.001$). The interaction was driven by adults performing significantly better in the pre-cue block than in the retro-cue block in cued trials ($p=.003$) but equally so between the two blocks for neutral trials ($p>.05$). *K* analysis revealed a main effect for trial-type [$F(1,13)=49.64$, $p<.001$, $\eta^2=.79$], and a significant interaction of block x trial-type [$F(1,13)=9.99$, $p=.008$, $\eta^2=.44$]. Similar to d-prime, adults performed significantly

better in cued than in neutral trials both in pre-cue ($p<.001$) and retro-cue blocks ($p<.001$), but again the interaction was driven by adults performing significantly better following cues in the pre-cue compared to the retro-cue block ($p=.009$). There were no differences in neutral trials across the blocks ($p>.05$). The analysis on the median RT scores revealed a main effect of trial-type [$F(1,13)=70.60$, $p<.001$, $\eta^2=.84$], with adults performing significantly faster in cued ($M=548.41$) than in neutral ($M=725.25$) trials. Separate analyses of difference scores (Figure 27) in d-prime and *K* corroborated that the interactions were driven by greater benefits from pre-cues than retro-cues compared to the neutral baseline ($M=2.12$ and $M=1.24$, $p=.001$ and $M=1.17$ and $M=.83$, $p=.008$ respectively). The analysis of difference scores for RT showed no differences in benefits between pre-cues and retro-cues ($p>.05$), thus corroborating the absence of an interaction.

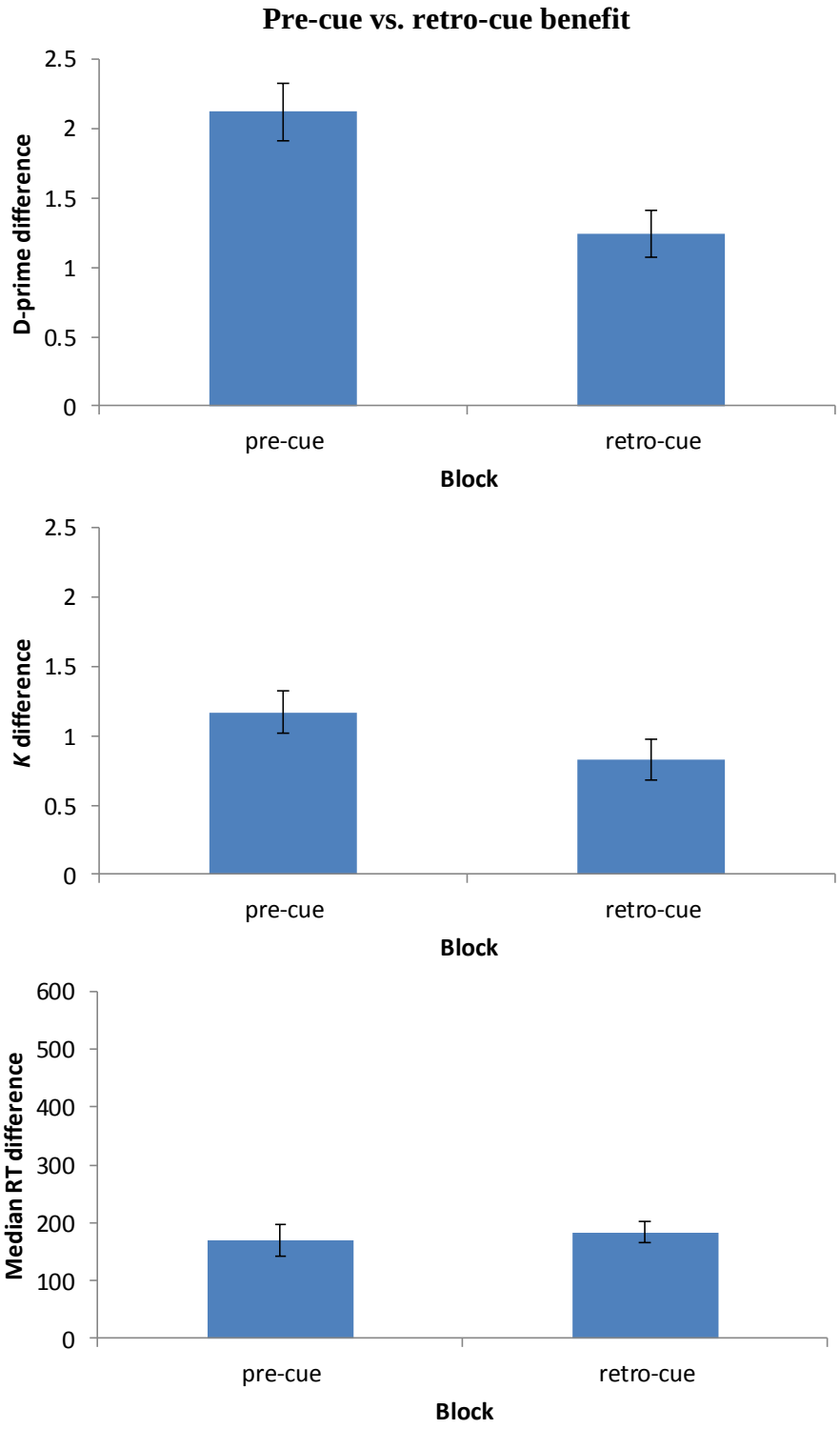


Figure 27. D-prime, *K*, median RT difference scores from neutral baseline, comparing pre-cue and retro-cue blocks for adults. Error bars represent standard errors of the mean.

ERP results

As predicted, for pre-cues, EDAN, ADAN, and an LDAP-like component were observed (Figure 28). There was a significant enhanced negativity contralateral to the direction of the cue between 180 and 200ms at O1/2 sites [t(13)= -2.64, p=.02] signifying EDAN (M= -1.73μV and M= -1.44μV for contralateral and ipsilateral sites respectively), followed by a significant enhanced negativity contralateral to the direction of the cue between 300 and 370ms at F3/4 sites [t(13)= -2.34, p=.036] signifying ADAN (M=3.61μV and M=3.95μV for contralateral and ipsilateral sites respectively). Finally, a significant enhanced positivity contralateral to the direction of the cue between 480 and 560ms at PO7/8 and O1/2 [F(1,13)=9.29, p=.009] was observed, signifying an LDAP-like component (M= -2.38μV and M= -2.78μV for contralateral and ipsilateral sites respectively).

For retro-cues, the EDAN and the ADAN were observed indicating similar neural activity across pre-cue and retro-cue blocks (Figure 28). As with pre-cues, there was a significant enhanced negativity contralateral to the direction of the cue between 180 and 200ms at O1/2 sites [t(13)= -2.76, p=.016] signifying EDAN (M= -.74μV and M= -.37μV for contralateral and ipsilateral sites respectively), followed by a significant enhanced negativity contralateral to the direction of the cue between 300 and 370ms at F3/4 sites [t(13)= -2.12, p=.05] signifying ADAN (M= -3.14μV and M= -2.82μV for contralateral and ipsilateral sites respectively). Unexpectedly, with retro-cues a second later negativity contralateral to the direction of the cue reached significance at posterior sites (PO7/8) at 310-330ms [t(16)= -2.32, p=.038; M= -.08μV and M=.24μV for contralateral and ipsilateral sites respectively]. This second posterior contralateral negativity resembled the N2pc component that has

been linked to visual search activity both in service of perception and VSTM (e.g., Eimer, 1996; Kuo et al., 2009) and suggested recruitment of additional parietal-occipital sites when orienting attention to representations held in VSTM.

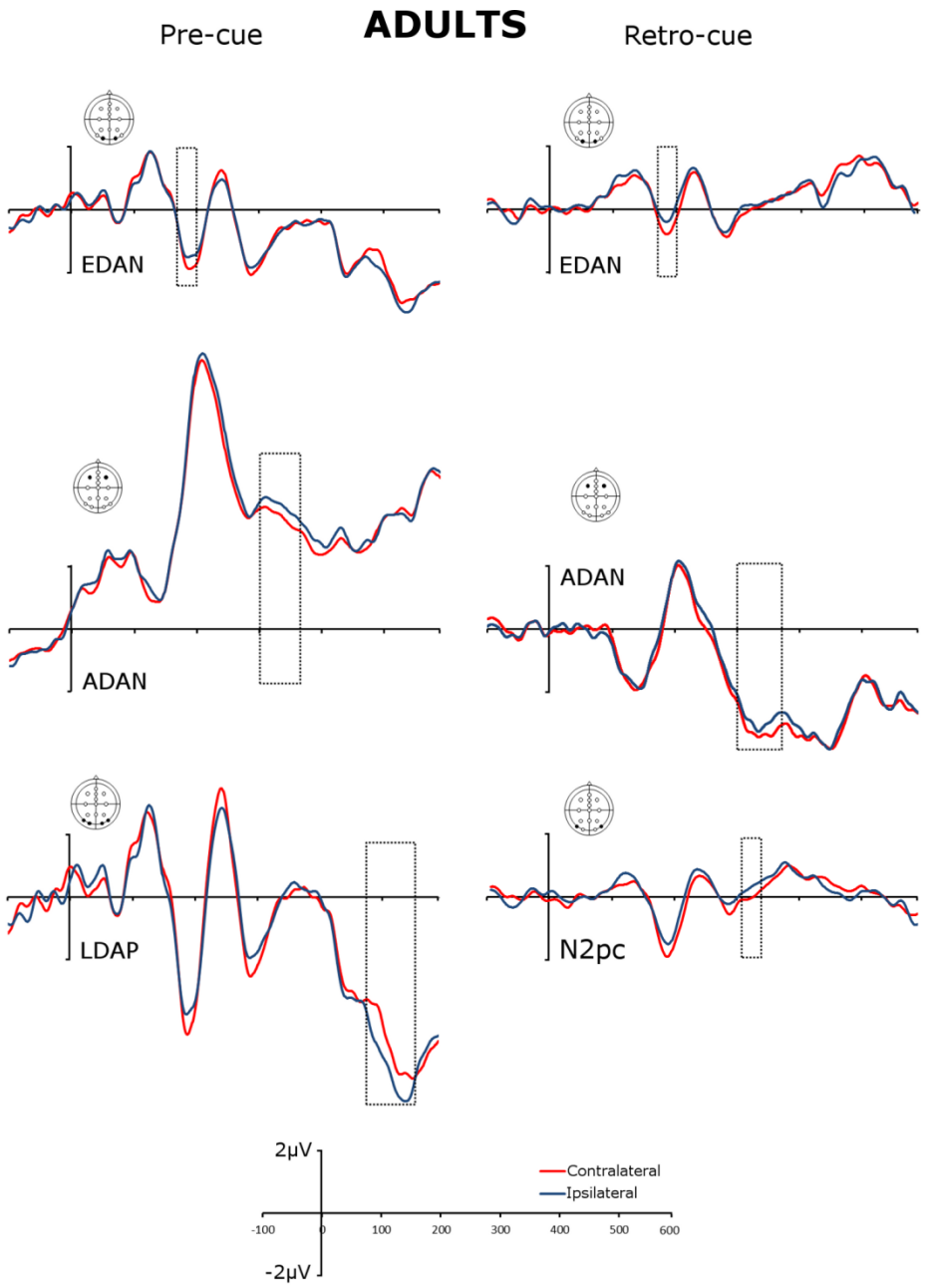


Figure 28. Grand-averaged waveforms elicited by pre-cues and retro-cues in adults. Red lines indicate neural activity contralateral to the side directed by the cue and blue lines indicate neural activity ipsilateral to the side directed by the cue. Positive voltage is plotted upwards. The montage used for the experiment and the electrode sides that were found significant for each component are shown next to each ERP waveform panel. Boxes highlight the time-windows during which the mean voltage difference of each component was found significant.

Children

Behavioural results

D-prime, K, and median RTs

Table 23. *D-prime, K, and RT scores for pre-cue, retro-cue, and neutral trials for children. Standard deviations are reported in parentheses.*

	Pre-cue block		Retro-cue block	
	Cued	Neutral	Cued	Neutral
D-prime				
	3.11 (1.34)	1.14 (0.60)	1.79 (1.09)	1.19 (0.73)
K				
	3.10 (1.09)	1.56 (0.77)	2.25 (1.11)	1.63 (0.90)
RT (ms)				
	838.71 (223.30)	1216.35 (274.62)	919.68 (288.51)	1303.18 (318.06)

Children showed a similar pattern of behavioural results to adults. Mean d-prime, *K*, and median RT scores are reported in Table 23. The analysis on d-prime scores revealed main effects of block [$F(1,16)=19.71$, $p<.001$, $\eta^2=.55$], and trial-type [$F(1,16)=41.44$, $p<.001$, $\eta^2=.72$], and a significant interaction of block x trial-type [$F(1,16)=38.35$, $p=<001$, $\eta^2=.71$]. Analyses of simple main effects for the interaction showed that children performed significantly better in cued than in neutral trials both in pre-cue ($p<.001$) and retro-cue blocks ($p=.006$). The interaction was driven by children performing significantly better in the pre-cue block than in the retro-cue block in cued trials ($p<.001$) but equally so between the two blocks for neutral trials ($p>.05$). *K* analysis complemented d-prime results by revealing main effects for block [$F(1,16)=9.48$, $p=.007$, $\eta^2=.37$] and trial-type [$F(1,16)=34.54$, $p<.001$, $\eta^2=.68$], and a significant interaction of block x trial-type [$F(1,16)=31.34$, $p<.001$, $\eta^2=.66$].

Similar to d-prime, children performed significantly better in cued than in neutral trials both in pre-cue ($p<.001$) and retro-cue blocks ($p=.005$), but again the interaction was driven by children performing significantly better following cues in the pre-cue compared to the retro-cue block ($p<.001$). There were no differences in neutral trials across the blocks ($p>.05$). The analysis on median RT scores revealed main effects of block [$F(1,16)=10.32$, $p=.005$, $\eta^2=.39$], and trial-type [$F(1,16)=32.27$, $p<.001$, $\eta^2=.67$], with children performing significantly faster in pre-cue ($M=1027.53$) than in retro-cue ($M=1111.43$) blocks, and in cued ($M=879.19$) than in neutral ($M=1259.77$) trials. Separate analyses of difference scores (Figure 29) corroborated d-prime and *K* ANOVAs by revealing greater benefits from pre-cues than retro-cues compared to the neutral baseline ($M=1.98$ and $M=.59$, $p<.001$ and $M=1.54$ and $M=.61$, $p<.001$ respectively). The analysis of difference scores for RT showed no differences in benefits between pre-cues and retro-cues ($p>.05$), thus supporting the absence of an interaction in the RT ANOVA.

In addition, an omnibus ANOVA with age-group as a between-subject factor confirmed that, as in Experiment 1 (Chapter 2), 10-year-old children and adults drew equivalent benefits from pre-cues and retro-cues after controlling for baseline differences in memory on neutral trials (see Appendix D).

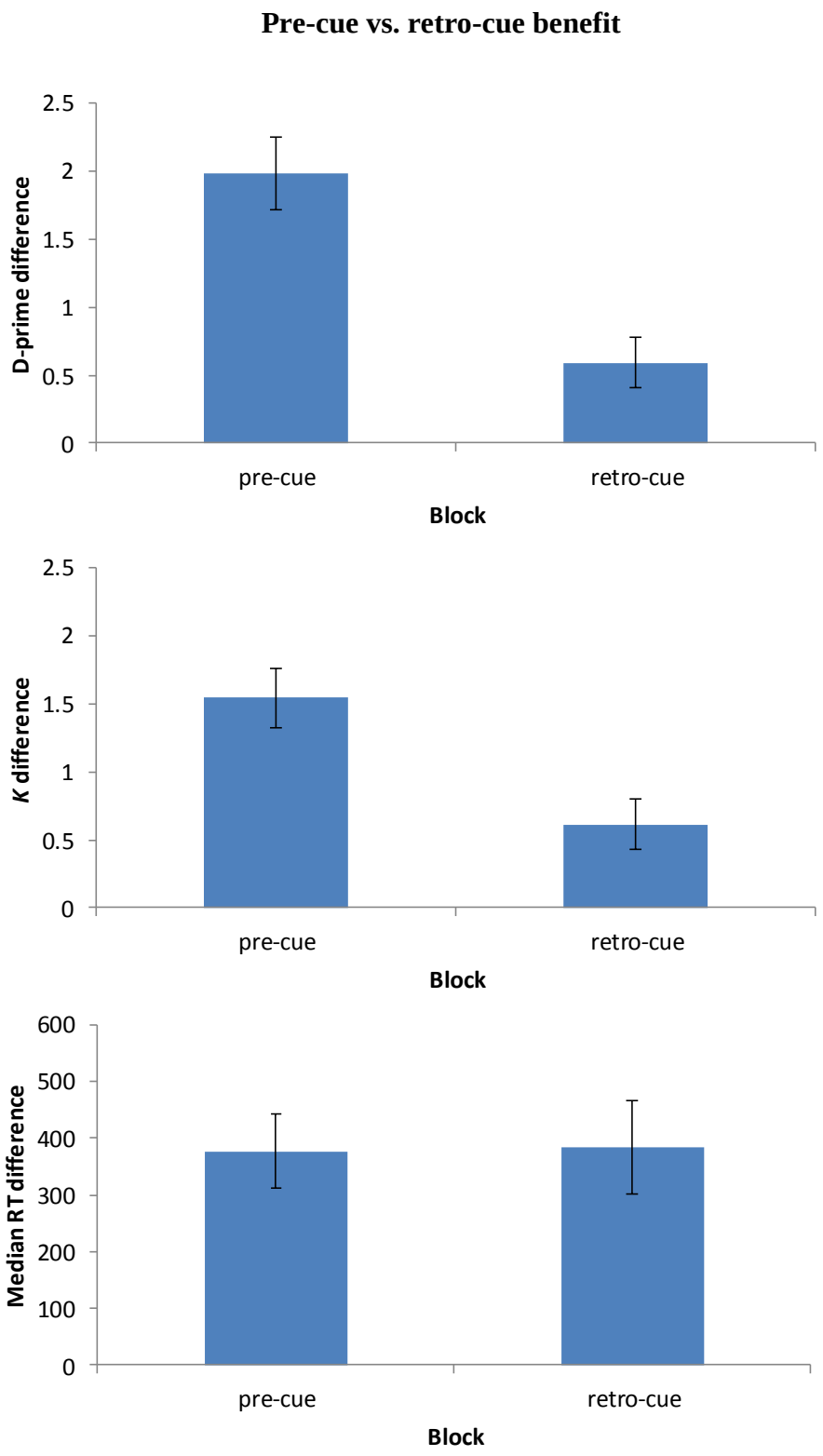


Figure 29. D-prime, *K*, median RT difference scores from neutral baseline, comparing pre-cue and retro-cue blocks for children. Error bars represent standard errors of the mean.

ERP results

The statistical analyses on the children's amplitudes showed a different pattern of results compared to adults, both in terms of topography and timing of components (Figure 30). For pre-cues, there was a significant enhanced negativity contralateral to the direction of the cue between 180 and 200ms at C3/4 sites [t(13)= -2.32, p=.034] signifying EDAN at central sites (M=1.30μV and M=2.21μV for contralateral and ipsilateral sites respectively) and a trend for significance for an enhanced negativity contralateral to the direction of the cue between 180 and 200ms at PO7/8 sites [t(16)= -1.90, p=.075], indexing a weak EDAN at posterior sites (M= -4.86μV and M= -3.67μV for contralateral and ipsilateral sites respectively). Also, a significant enhanced positivity contralateral to the direction of the cue between 540 and 600ms at PO7/8 and O1/2 [F(1,16)=5.38, p=.034] signifying an LDAP-like component was observed (M= -7.04μV and M= -7.79μV for contralateral and ipsilateral sites respectively).

Retro-cues yielded both similarities and differences with pre-cues (Figure 30). There was only a trend for an enhanced negativity contralateral to the direction of the cue between 180 and 200ms at PO7/8 sites [t(16)= -1.89, p=.077] reflecting a weak EDAN at posterior sites similar to pre-cues (M= -3.54μV and M= -2.45μV for contralateral and ipsilateral sites respectively). Like adults, with retro-cues a second later negativity was observed contralateral to the direction of the cue between 280 and 320ms at posterior sites (PO7/8) that reached significance [t(16)= -2.24, p=.04; M= 1.52μV and M=2.55μV for contralateral and ipsilateral sites respectively]. Similarly to adults, this contralateral negativity resembled the N2pc component and suggested the recruitment of additional parietal-occipital areas when orienting

attention to mental representations held in VSTM in children as well. However, the ADAN did not emerge for the children in either condition.

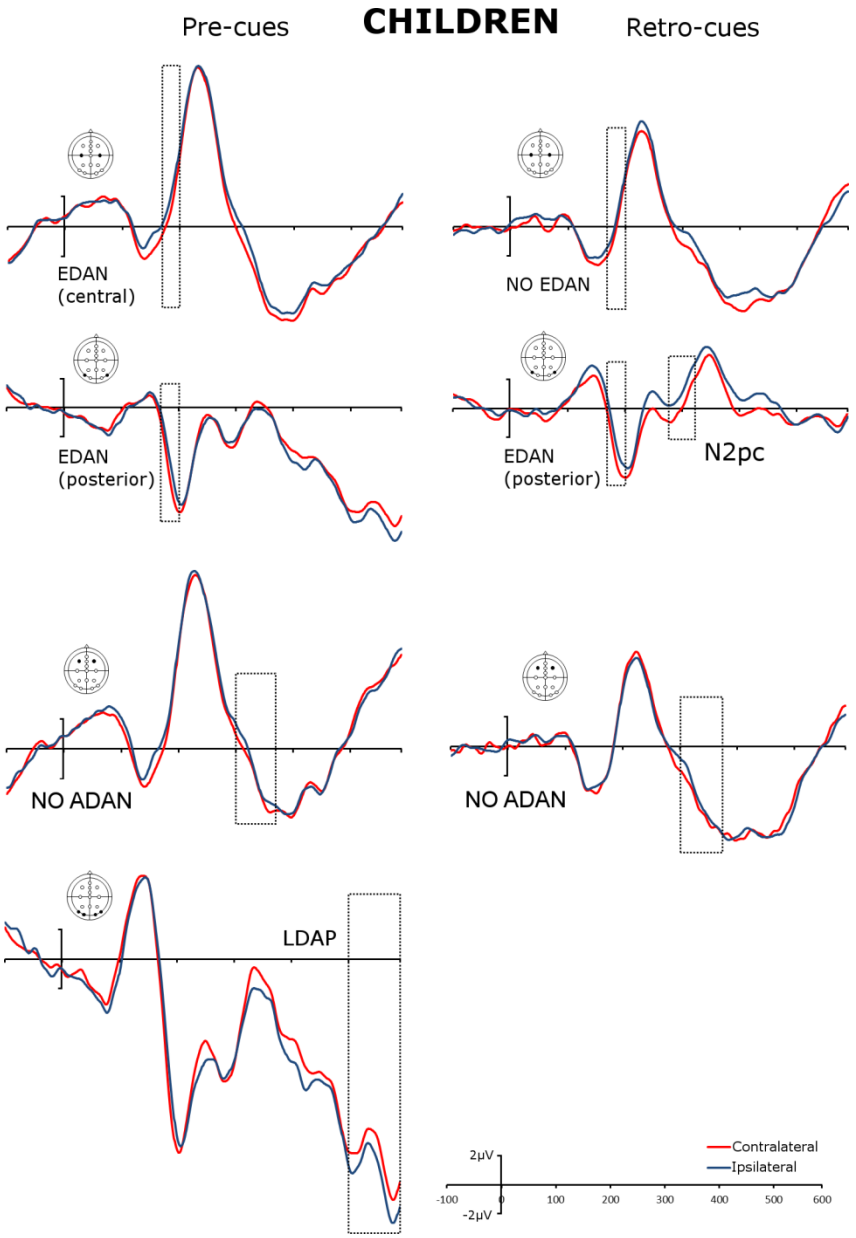


Figure 30. Grand-averaged waveforms elicited by pre-cues and retro-cues in children. Red lines indicate neural activity contralateral to the side directed by the cue and blue lines indicate neural activity ipsilateral to the side directed by the cue. Positive voltage is plotted upwards. The montage used for the experiment and the electrode sides that were found significant for each component are shown next to each ERP waveform panel. Boxes highlight the time-windows during which the mean voltage difference of each component was found significant.

Relations between electrophysiological markers and VSTM capacity in children

I carried out Spearman's correlation analyses on the time-windows and scalp sites where EDAN and ADAN were observed in adults but not in children and on the difference scores (cued – neutral) in *K* to explore whether the magnitude of adult-like neural activity of attentional control related to variation in VSTM capacity in children. This was done to examine whether a child's potential ability to orient attention as efficiently as an adult does, measured via the spatio-temporal characteristics of the component that was observed in adults, would relate to the child's VSTM capacity. Figure 31 plots these individual scores as a function of children's memory capacity. The analyses showed that individual differences in the magnitude of the neural activity correlated with individual differences in behaviour. Specifically, EDAN in the pre-cue block, measured at O1/2 at 180-200ms, and ADAN in the pre-cue block, measured at F3/4 at 300-370ms, correlated with *K* pre-cue benefit [r(15)=.50, p=.02 and r(15)=.47, p=.028 respectively]. I then complemented these analyses by performing median-split analyses and dividing children into high- and low-capacity groups (on the basis of *K*) and carrying out paired-sample t-tests between contralateral and ipsilateral amplitudes to explore the presence of EDAN and ADAN in each capacity group separately. Splitting the children into those who showed a large vs. small cue benefit following pre-cues in terms of *K* revealed a significant enhanced negativity contralateral to the direction of the cue between 180 and 200ms at O1/2 sites [t(8)= -2.43, p=.04], signifying EDAN for the large cue benefit group (M= -5.46μV and M= -4.21μV for contralateral and ipsilateral sites respectively). In contrast, there was no EDAN in the small cue benefit group [t(7)=.63, p=.55; M= -1.54μV and M= -1.90μV for contralateral and

ipsilateral sites respectively]. Splitting the children into high vs. low pre-cue *K* capacity groups revealed a significant enhanced negativity contralateral to the direction of the cue between 300 and 370ms at F3/4 sites [t(7)= -2.36, p=.05], signifying ADAN for the high-capacity group (M= -1.68μV and M= -.72μV for contralateral and ipsilateral sites respectively). In contrast, there was no ADAN in the low-capacity group [t(8)= -.09, p=.93; M= -1.58μV and M= -1.50μV for contralateral and ipsilateral sites respectively]. Finally, there were no reliable correlations and capacity group differences for retro-cues suggesting differences between pre-cue and retro-cue attentional shifts in childhood.

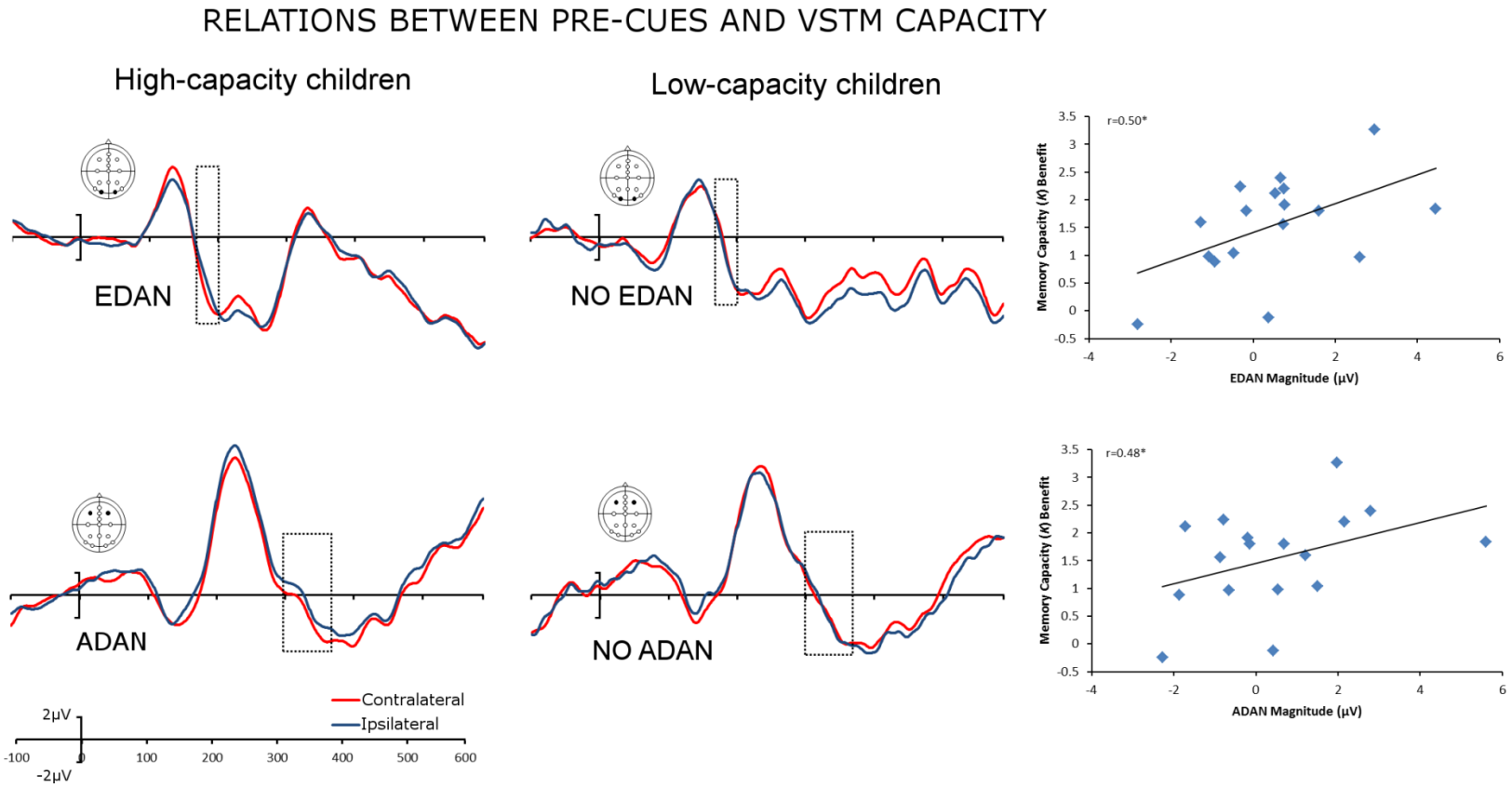


Figure 31. Grand-averaged waveforms for EDAN (on top) and ADAN (on bottom) elicited by pre-cues and divided between high- and low- memory capacity children. Red lines indicate neural activity contralateral to the side directed by the cue and blue lines indicate neural activity ipsilateral to the side directed by the cue. Positive voltage is plotted upwards. Correlations between the ERP magnitudes (EDAN on top row and ADAN on the bottom row) and benefit in VSTM capacity measured with *K* are shown next to the relevant ERP waveforms.

Discussion

Experiment 6 aimed at investigating i) whether the neural processes that adults employ when allocating attention retrospectively to internal representations are similar to those employed in prospective orienting in anticipation of perceptual input, ii) whether children exhibit neural activity with the same temporal dynamics as adults across the two orienting conditions or whether their neural profile differs even in the face of robust behavioural benefits from both cue types, and iii) whether the efficient allocation of attention for selective encoding and maintenance in VSTM relates to higher VSTM capacity in children.

Behavioural results were similar to those of Experiment 1, which is the closer analogue to this experiment from all experiments reported in the thesis. All participants benefited from cues both prior to encoding and during maintenance and no developmental differences emerged to the extent to which adults and 10-year-olds benefited from the two cue types beyond differences in overall accuracy, storage capacity, and speed. These results replicate previous behavioural findings indicating that attentional shifts prior to encoding and during maintenance modulate VSTM recognition (e.g., Astle et al., 2012; Griffin & Nobre, 2003; Kuo, Stokes, et al., 2011; Murray et al., 2011) and confirm that all participants used the cue. Therefore, the ERP results from both age groups can be reliably interpreted as indexes of the events leading to equivalent behavioural benefits in children and adults.

Yet, the pattern of neural activity differed across the age groups, indicating that children in middle childhood deployed neural pathways supporting attentional orienting less efficiently than adults, despite the absence of age-related differences in cueing effects (see Appendix D). As predicted, adults elicited EDAN, ADAN, and

LDAP during prospective orienting in preparation to encoding stimuli into VSTM and EDAN and ADAN during retrospective orienting in preparation to maintaining an internal representation in VSTM. Children, on the other hand, elicited reliably only EDAN and LDAP during prospective orienting prior to encoding information in VSTM, and EDAN only reached a trend following retro-cues. Furthermore, EDAN differed in terms of its spatial location compared to the adult component and LDAP differed in latency compared to adults. At the group level, no significant ADAN was found in conjunction with children's prospective or retrospective orienting. Surprisingly, an N2pc was observed during both children's and adults' retrospective orienting. This component shared the same spatial location across the age groups but differed in latency. Finally, individual differences in the extent to which ERP markers of attentional control were "adult-like" correlated with VSTM capacity at the behavioural level in children.

The finding of similar neural modulations for adults across prospective and retrospective orienting suggests that attentional biases to perceptual input and to internal representations in adulthood share a sequence of lateralised neural markers, each reflecting a different processing stage. First, in both orienting conditions, there was an early posterior (O1/2) negativity contralateral to the directional cue, starting from 180 to 200ms after cue onset, indicating EDAN and the decoding of the meaning of the cue along with the subsequent initiation of attentional orienting. EDAN was followed by frontal (F3/4) negativity contralateral to the directional cue, starting from 300 to 370ms after cue onset in both orienting conditions, indicating ADAN and the directing of attention. Nevertheless, the two conditions were differentiated after ADAN was elicited. That is, during prospective orienting, ADAN

was followed by a posterior (PO7/8 and O1/2) positivity contralateral to the directional cue, starting from 480 to 560ms after cue onset, indicating an LDAP-like component and the cortical excitability of the visual areas anticipating the upcoming stimulus in the memory array at the selected spatial location. In contrast, during retrospective orienting and immediately after ADAN was elicited, there was a posterior (PO7/8) negativity contralateral to the directional cue starting from 310 to 330ms after cue onset, indicating an N2pc and the visual search of the target-stimulus (in this case the item to-be-maintained until probe response).

The adult ERP results during prospective orienting, i.e., the *preparation of encoding in VSTM*, extend the findings of studies that have related the three preparatory markers (EDAN, ADAN, and LDAP) with *perceptual biases in detection and discrimination tasks* (Harter et al., 1989; Hopf & Mangun, 2000; Jongen et al., 2007; Nobre et al., 2000; Seiss et al., 2009; Talsma et al., 2005; Van der Stigchel et al., 2006; Yamaguchi et al., 1994). They are also in line with those from a recent study that identified these markers during the *selective encoding into VSTM* (Murray et al., 2011). Focusing on *attentional orienting within VSTM*, Experiment 6 revealed for the first time the involvement of EDAN, ADAN, and N2pc in the *selective maintenance of information in VSTM* in adults.

Many recent studies have been carried out to provide mechanistic accounts of how cues during maintenance enhance internal representations and facilitate memory performance (Astle et al., 2011; Lepsien et al., 2005; Makovski & Jiang, 2007; Makovski et al., 2008; Matsukura et al., 2007; Sligte et al., 2008, 2010). However, none of them has examined whether retrospective attentional shifts are characterized by conventional lateralised neural markers that index specific cognitive processes

such as the decoding of the cue and the subsequent initiation of the attentional orienting (EDAN), top-down attentional control (ADAN), and visual search (N2pc).

The N2pc has been traditionally associated with perceptual visual search and spatial selection of targets among distractors (Brisson & Jolicoeur, 2007; Eimer, 1996; Hickey, Di Lollo, & McDonald, 2009; Hickey, McDonald, & Theeuwes, 2006; Jolicoeur, Brisson, & Robitaille, 2008; Kiss, Van Velzen, & Eimer, 2008; Luck, Girelli, McDermott, & Ford, 1997; Luck & Hillyard, 1994; Robitaille & Jolicoeur, 2006; Woodman et al., 2009; Woodman & Luck, 2003; Woodman & Luck, 1999) and only recently has been identified in the search and detection of targets held in VSTM (Dell'Acqua et al., 2010; Eimer & Kiss, 2010; Kuo et al., 2009). Obtaining an N2pc here suggests that retrospective orienting employs additional processes besides cue processing and directing of attention, such as actively searching the memory array in order to selectively maintain the critical information for later recognition. Overall, adult findings here corroborate previous suggestions from studies using electrophysiology (Griffin & Nobre, 2003) and functional neuroimaging (Nobre et al., 2004) which compared directly cues presented before or after the memory array. These studies showed that although there is substantial spatio-temporal overlap of neural activity underlying the processing of pre-cues and retro-cues, there is also activity that is unique to retrospective orienting. While Griffin and Nobre (2003) showed that the electrophysiological correlates of these two orienting processes share both similarities and differences, the novelty here is that the conventional lateralised markers of attentional orienting and the N2pc provide a good way for understanding and conceptualising how these two processes may differ by identifying the specific cognitive steps that participants follow to maintain information internally.

In contrast to adult findings, children's ERP results across prospective and retrospective orienting suggest both similarities and differences in how attentional biases to perceptual input and to internal representations operate in childhood at the neural level: prospective orienting in children elicited an early central (C3/4) negativity contralateral to the directional cue starting from 180 to 200ms after cue onset, indicating an EDAN-like component and the decoding of the meaning of the cue, whereas at the group level no such neural activation was found significant in retrospective orienting. However, there was also a trend towards an early posterior (PO7/8) negativity contralateral to the directional cue starting from 180 to 200ms after cue onset which was observed in both orienting conditions, possibly implying the presence of a developing adult-like EDAN in prospective and retrospective orienting in VSTM, as it shared the typical spatio-temporal characteristics previously reported for this component in adult studies in service of perception (e.g., McDonald & Green, 2008; Nobre, Sebestyen, et al., 2000; Van der Stigchel et al., 2006). Nevertheless, in children, these two more adult-like early posterior components did not reach significance. EDAN in prospective orienting was followed by a posterior (PO7/8 and O1/2) positivity contralateral to the directional cue starting from 540 to 600ms after cue onset indicating an LDAP-like component and the cortical excitability of the visual areas anticipating the upcoming stimulus at the selected spatial location. In contrast, during retrospective orienting, there was a posterior (PO7/8) negativity contralateral to the directional cue starting from 280 to 320ms after cue onset indicating an N2pc and the visual search of the item to-be-maintained until probe response.

The differences in the early effects across the orienting conditions in 10-year-olds point to differential processing of the cue during prospective and retrospective attentional orienting in childhood, despite the fact that in adults the two types of orienting yielded rather similar neural profiles. For example, the fact that EDAN was reliably present with pre-cues but not with retro-cues suggests that processing of the directional cue prior to encoding and during maintenance follows a different developmental trajectory before it reaches the adult end-state: findings here demonstrate that the neural substrates underlying cue processing across the orienting conditions in childhood can be activated as early after cue onset as in adulthood, however in children this activation was reliably significant during prospective but not retrospective orienting and for central but not posterior brain areas. It has been proposed that central cues are overlearned symbols in adulthood with the processing of the cue becoming automatic to some extent (Eimer, 1997; Ristic et al., 2002; Tipples, 2002) and it is possible that with development this decoding process and the initiation of orienting shifts from central to more posterior brain areas. Similar developmental changes in anterior to posterior neural circuits underlying other cognitive processes that require attention and WM have been reported between middle childhood to young adulthood. For example, frontal to posterior parietal regions shifts over development have been reported for symbolic number processing and number comparison. These shifts have been interpreted as children progressing from a controlled and effortful processing of numerical magnitude to a more automatic one and with the parietal areas becoming functionally specialised to process numerical magnitude (Ansari & Dhital, 2006; Ansari, Garcia, Lucas, Hamon, & Dhital, 2005). The differences in terms of latency in the current context of cue

processing are compatible with earlier findings: Nobre et al. (2004) suggested that the latency of EDAN may vary across the adult studies depending on the time needed to convert the meaning of the cue to a spatial expectation with regards to the predicted location of the relevant stimulus. Based on this reasoning and from a developmental perspective, since the cue was identical for the two age groups in the present experiment, it is possible that while the neural mechanisms supporting cue processing start at the same time following cue onset from middle childhood and onwards, children may still require more time to decipher the meaning of the cue and initiate orienting compared to adults in order to sufficiently activate posterior sites. This account is compatible with the presence of a reliable significant posterior EDAN in the study of Harter et al. (1989; they reported EDAN at P3/4 and O1/2 electrode sites between 180 and 220ms), in contrast with the present experiment, a discrepancy that is possibly due to key task differences. In Harter et al.'s task, the arrow was presented for 1000ms and pointed to the left or to the right side of the screen rendering cue decoding and thus anticipation for detection in the selected side fairly easy, whereas in the task used here, the arrow was presented for only 300ms and pointed to one out of the four corners of the screen requiring children to translate the cue and initiate orienting in more than two alternative orienting locations. It should still be noted that the presence of a central EDAN is not completely surprising as in the study by Harter et al. the posterior EDAN in children was also shifted at central sites (C3/4). These effects deserve further investigation using parametric manipulations of the duration of the cue presentation and the alternatives of orienting directions across development.

Furthermore, the difference in neural substrates underlying prospective and retrospective orienting in children may well be related to how children perceive action requirements following cue presentation and which may have affected the strategy children used to support encoding into VSTM on one hand and VSTM maintenance on the other hand. Indeed, the evidence of a reliable N2pc across age groups but not of the other lateralised components with retro-cues strongly suggests that children oriented their attention within VSTM in a different manner compared to adults. Yet, children seem to have understood that they needed to search their memory in order to select an item from those encoded in VSTM and maintain it for later comparison, but they did so differently, possibly because their ability to initiate and recruit top-down attentional control to direct their attention to a spatial location is yet to be fully developed. Indeed, there was no group-level reliable evidence of ADAN in 10-year-olds when examined irrespective of their VSTM capacity either prior to encoding or during maintenance. As hypothesized, this is possibly due to the frontal cortex not being adequately developed in childhood (Casey et al., 2000; Craik & Bialystok, 2006; Diamond, 2002; Giedd et al., 1999; Klingberg, 2006) to allow for sophisticated voluntary allocation of attention. This finding here is also consistent with Harter et al.'s result (1989) in which no ADAN was observed in service of perception and extends it by demonstrating the absence of directing attention (ADAN) for the selective encoding in VSTM and for the selective maintenance of an already encoded item. The absence of ADAN might also justify the latency and duration difference of the N2pc across the age groups; that is, children elicited the N2pc earlier and for longer than adults possibly because adults first directed their attention voluntarily to a spatial location by recruiting frontal brain areas (Corbetta et

al., 2000; Corbetta & Shulman, 2002; Hopfinger et al., 2000; Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999) and then briefly selected the item-to-be remembered from the remaining array items by recruiting posterior brain areas, in agreement with the proposal for the involvement of a fronto-parietal network in both selective attention and VWM (Bledowski, Rahm, & Rowe, 2009; Corbetta, 1998; Postle & D'Esposito, 1999).

Nonetheless, despite the limited presence of clear neural markers of attentional orienting in VSTM in children, the most prominent finding in this experiment is the demonstration of an "adult-like" neural modulation prior to the encoding of perceptual input in VSTM by high-capacity children. While children failed to demonstrate neural modulations as a group, individual differences seemed to be a better indicator of their true potential. High-capacity children elicited both EDAN and ADAN sharing the same spatio-temporal characteristics of the components observed in adults, while low-capacity children did not. For high-capacity children this was the case during prospective orienting only, corroborating the proposal that developmental and individual differences in attentional orienting dissociate neural mechanisms of encoding and maintenance in VSTM. To my knowledge, this is the first study to show neural links between attentional orienting and VSTM capacity in childhood, extending thus the findings from a plethora of adult studies (Anderson et al., 2011; Awh & Vogel, 2008; Fukuda & Vogel, 2009, 2011; Gazzaley et al., 2005; Jost et al., 2011; Linke et al., 2011; Machizawa & Driver, 2011; Murray et al., 2011; Palva et al., 2010; Rutman et al., 2010; Todd & Marois, 2005; Vogel & Machizawa, 2004; Vogel et al., 2005; Zanto & Gazzaley, 2009) to the developmental domain.

Chapter 8: General Discussion

The current thesis aimed to examine the precise cognitive mechanisms through which visuo-spatial attentional biases operate within VSTM across development. Many attention theories suggest that visuo-spatial biases act as a gateway to learning and memory (e.g., Desimone, 1996), as they enable individuals to select only the relevant amongst all information from both the external environment and the internal world. These biases have the potential to be particularly relevant to young learners, who have to face complex environments (e.g., a classroom) and its interface with their prior knowledge (e.g., educational material that has already been learned). Yet, there is surprisingly limited direct evidence on how these visuo-spatial biases might change over development.

A systematic investigation of the developmental changes underpinning the mechanisms of spatial orienting within VSTM was expected to offer new insights on the attentional contributions to encoding and maintenance in VSTM. To do so, a number of experiments manipulating different parameters were carried out and presented here. These parameters included the physical properties and the predictive nature of the cue that is used to orient attention prospectively and retrospectively, the load of the memory array to be encoded and maintained in VSTM, the temporal constraints on maintaining information, and the characteristics of the memoranda. The experiments allowed to investigate the cognitive and neural correlates of attentional effects on VSTM performance in younger and older school-aged children and adults and to examine whether variation in attentional control goes hand in hand with individual differences in VSTM and VWM capacity.

I conclude this thesis by first highlighting the key findings of the experimental chapters and subsequently discussing how these findings contribute to models of attention, of VSTM, and of cognitive development and WM. Finally, limitations and future directions are briefly discussed, followed by concluding remarks.

Overview of main findings

Experiment 1 (Chapter 2) highlighted four key findings. First, results demonstrated attentional cueing benefits for both the accuracy and speed with which information was retrieved from VSTM, both when cues were presented prior to encoding and, most importantly, during maintenance of visual information (Griffin & Nobre, 2003; Lepsien et al., 2005; Makovski & Jiang, 2007; Schmidt et al., 2002; Sligte et al., 2008), for both children and adults. Therefore, these findings extend the bulk of cued perceptual detection studies with children and adults (e.g., Akhtar & Enns, 1989; Brodeur & Enns, 1997; Iarocci et al., 2009; Luck et al., 1996) in service of memory. However, a second key result is that, while the benefits from cues presented before encoding were of equal magnitude across the age groups, the benefits from cues presented during the maintenance interval were smaller for younger children compared to older children and adults, consistent with differential developmental trajectories by which attention cues facilitate encoding and maintenance in VSTM (Astle et al., 2012). Thirdly, as demonstrated here for the first time, these findings were consistent across central and peripheral cues, indicating that the differential developmental time-course of the ability to retroactively enhance maintenance and/or retrieval, unlike basic detection or discrimination (Akhtar &

Enns, 1989; Brodeur & Enns, 1997; Goldberg et al., 2001; Iarocci et al., 2009) does not depend on the physical or symbolic characteristics of the attentional orienting cues. Fourthly, cueing benefits during maintenance related to individual differences in traditional measures of VSTM and VWM span, over and above basic memory performance. The strongest relations were obtained between retrospective attentional orienting and complex WM span, rather than simple VSTM span, suggesting that top-down attention mechanisms shared more variance with tasks requiring participants to ignore interference and thus protect visual representations during maintenance.

Although Chapter 2 established novel findings and replicated previously demonstrated results, a number of questions remained open. Could age group differences (e.g., young children's poorer orienting to memory) and similarities (e.g., older children's adult-like performance) both be underpinned by differences in reflexive orienting for children compared to adults? The main focus of Experiment 2 (Chapter 3) was to establish whether this was the case. In this experiment, I changed the predictive value of cues by introducing trials with invalid cues and informed participants of this. In contrast to the marked differences in cueing effects between young children and the other two age groups found in Experiment 1 (Chapter 2), benefits from cues during maintenance were greatly decreased and the previously obtained age-related differences in retro-cueing effects were eliminated. These findings demonstrated that participants were able to ignore the cues in order to avoid selecting the invalid item (as shown by the absence of costs). They also suggested that in Experiment 1 participants in all age groups understood the value of the cue and followed the instructions to optimise VSTM performance; i.e., to make use of

the cues in order to facilitate encoding and maintenance of the to-be-probed item (as shown by the presence of benefits). Taken together, these findings strongly suggest that attentional benefits during maintenance depend on controlled voluntary orienting rather than on automatic processes and that developmental differences observed in Experiment 1 reflect the less developed ability of 7-year-olds to retrospectively orient attention to selectively refresh and enhance the representation of a memory item.

Given that the physical characteristics of the cues did not account for developmental differences in benefits from cues during maintenance and that children as young as 7 years old could voluntarily guide attention to selectively maintain and/or ignore competing information in VSTM, but did so less efficiently, I examined in turn a number of non-attentional factors potentially underpinning these developmental differences. First, having to encode and maintain a set of 4 items may have exceeded 7-year-olds storage capacity, compromising thus their ability to recruit top-down attentional control to retrospectively refresh and enhance an internal representation. In Experiment 3 (Chapter 4), I reduced memory load to 2 items. Results demonstrated no reliable benefits from cues presented either prior to encoding or during maintenance with a memory load size of 2 items, indicating that, when set size is well within capacity limits (Cowan et al., 2005; Riggs et al., 2006, 2011), children rely simply on their storage capacity and broad attentional resources to maintain items in VSTM, rather than using cues to guide encoding. In contrast, with 4 items in the memory array, 7-year-olds demonstrated reliable benefits when cues were presented in advance of encoding, attenuating thus the deleterious effects of increasing load. Cues during maintenance, on the other hand, resulted in smaller

and less reliable benefits indicating that while young children can voluntarily orient their attention to facilitate VSTM performance and while they understand that doing so facilitates their performance, their ability for retrospective orienting is modulated by memory load. Furthermore, despite being less reliable at the group level, cueing benefits during maintenance related to individual differences in VSTM span over and above basic memory performance, but only with a memory load of 4 items. Taken together, findings from Experiment 3 suggest that children can recruit top-down attentional control during maintenance strategically in the face of increased visual competition and the refined ability to do so relates to better VSTM capacity.

In view of the fact that higher memory load calls for top-down attention mechanisms, it was then important to investigate whether additional non-attentional factors, such as the temporal demands of the task, constrain the recruitment of voluntary attention during the maintenance of information in VSTM in 7-year-olds. In Experiment 4 (Chapter 5), I examined whether, beyond the limits imposed by high memory load, information encoded in VSTM decays at a faster rate so that when the retro-cue eventually appears in the case of high memory load as in Experiments 1 and 3, the quality of the representations on which it can operate is degraded to a greater extent. I manipulated the duration of the interval between encoding and retro-cue presentation to be short or long, so that 7-year-olds had to maintain a set size of 4 items either in iconic memory ("IM") or in VSTM. In cognitive terms, this translates to a cue enabling the selection of an internal representation from a high capacity system containing fragile and short-lived representations or from a limited-capacity system containing more durable and longer-lived representations. Results showed better performance and increase in storage capacity when retro-cues operated on

transient iconic traces rather than on VSTM representations and a passive decay of memory traces as a function of time (e.g., Cowan et al., 2000; Towse & Hitch, 1995; Towse et al., 1998) even in the absence of interference from a concurrent task (Ricker & Cowan, 2010). Together, the findings of Experiments 3 and 4 document that cueing benefits in early childhood depend heavily on both memory load and the temporal demands of the maintenance period. When memory load exceeds capacity, attentional biases are more effective when they operate on iconic traces (Astle et al., 2011; Sligte et al., 2008, 2010). This may be because 7-year-olds are less efficient in transferring information from IM to VSTM, resulting in smaller VSTM capacity compared to older individuals. This possibility sets the ground for future research to examine the cognitive mechanisms responsible for this transfer over development.

Another critical question on what factors influence the efficiency of attentional orienting within VSTM pertains to the nature of the information to be maintained in memory itself. In Experiment 5 (Chapter 6), I examined whether top-down attentional biases during VSTM maintenance operate differentially depending on the type of items in memory, i.e., familiar and nameable objects vs. novel and difficult to label shapes, and if so, whether the pattern of attentional biases changes across development, reflecting at the same time a change in mnemonic strategies. Here, benefits were larger for familiar than novel items for all participants indicating that coding of the memoranda in VSTM interacted with attentional control differentially for item types, allowing or constraining participants' ability to maintain enhanced and durable representations in VSTM. Findings were consistent across age groups, documenting the employment of dual coding for familiar items from early childhood (Palmer, 2000a). Yet, this process was less efficient in 7-year-olds

compared to the older individuals, suggesting a quantitative difference in this mnemonic strategy among the age groups rather than its absence and modality-dependence for 7-year-olds. Furthermore, dual coding for familiar objects was more readily explained by the semantic codes that participants formed during encoding than by phonological (i.e., speech) codes or subvocal rehearsal, suggesting that highly familiar items that are stored in LTM are easier to enhance, maintain, and recognise than novel items (Baddeley, 2000, 2002a; Cowan, 1999; Logie, 2003).

It should be noted that the cueing benefits in some of the experiments were observed in the context of generally low task performance by the youngest children. This was particularly evident when baseline memory performance was measured, although valid cues significantly improved this, especially under some conditions. For example, in Experiment 5 (Chapter 6) 7-year-olds' performance in baseline neutral trials was at chance. Critically, retro-cues improved their accuracy in both conditions of the experiment, demonstrating that attentional orienting facilitates performance from early childhood, albeit to a lesser degree compared to older participants.

As in Experiment 1 (Chapter 2), in Experiment 5 (Chapter 6), 11-year-olds aligned themselves with adults (Hitch et al., 1988, 1989; Hitch et al., 1989) indicating an adult-like behavioural profile by middle childhood. Therefore, in Experiment 6 (Chapter 7), I examined whether this adult-like behavioural profile is also mirrored in their neural correlates. I investigated the temporal dynamics of neural activity when 10-year-olds and adults oriented attention prospectively in anticipation of perceptual input for encoding in VSTM as well as the temporal dynamics when participants oriented attention retrospectively to internal

representations held in VSTM. I presented participants with the task used in Experiment 1 while recording EEG activity and I measured well-established preparatory ERP components that were previously examined mainly in service of perception, i.e., EDAN, ADAN, and LDAP (e.g., Harter et al., 1989; Nobre et al., 2000). Behavioural results were similar to those of Experiment 1, with both age groups benefiting from attention cues prior to encoding and during maintenance to the same degree. Adults elicited the expected preparatory components across the two orienting conditions demonstrating that attentional biases to perceptual input for encoding in VSTM and to internal representations held in VSTM in adulthood share a sequence of conventional lateralised neural markers (Harter et al., 1989; Hopf & Mangun, 2000; Jongen et al., 2007; Murray et al., 2011; Nobre et al., 2000) and suggesting that these orienting mechanisms in service of VSTM in adulthood are broadly subserved by an analogous cognitive and neural architecture of top-down biases to the one subserving top-down biases in service of perception (Gazzaley & Nobre, 2011). In contrast to the absence of developmental differences in cueing benefits, 10-year-olds deployed neural pathways supporting attentional orienting less efficiently than adults and differentially across the two orienting conditions, suggesting their neural dissociation. These findings are consistent with the development of fronto-parietal circuits in service of attentional control and VWM from childhood to adulthood (Astle & Scerif, 2009, 2011; Klingberg, 2006; Olesen et al., 2007; Scerif, 2010). Furthermore, both age groups elicited an N2pc component during retrospective orienting indicating recruitment of additional neurocognitive processes to those recruited during prospective orienting, such as searching for the item-to-be-probed amongst the array items for selection and retention. The pattern of

findings in Experiment 6 suggests that the spatio-temporal overlap of neural activity underlying the two orienting mechanisms obtained previously (Griffin & Nobre, 2003; Lepsien & Nobre, 2006; Nobre et al., 2004) fractionates developmentally and that these seemingly similar orienting mechanisms are functionally dissociated. Critically, individual differences in the extent to which ERP markers of attentional control were "adult-like" related to individual differences in VSTM capacity in children for prospective but not retrospective orienting, bolstering that developmental and individual differences in attentional orienting dissociate neural mechanisms of encoding and maintenance in VSTM and cast light on the adult-end state.

Broader theoretical and practical implications for selective attention and VSTM / VWM

The importance of the central findings in the current thesis lies first in uncovering the functional significance of top-down attentional biases in VSTM encoding and maintenance across development, second in documenting the developmental differences in attentional benefits during the maintenance period, their constraining parameters and, third, in revealing the contribution of attentional benefits to VSTM / VWM capacity. In each case, I draw implications from these findings for, in turn, theories of attentional selection, conceptualisations of VSTM, and their integration in adults and over development.

1. Benefits of visuo-spatial biases for VSTM encoding and maintenance

1.1. Implications for and from models of adult selective attention

Overall, the current findings demonstrate robust and voluntary attentional cueing benefits in function of VSTM both prior to encoding and during maintenance of visual information, for children as young as 7 years of age as well as for older children and adults. These benefits in turn suggest that deploying attentional control can facilitate the accurate and fast retrieval of information from VSTM, suggesting a close coupling between attentional control and memory from childhood (Astle et al., 2012; Ross-Sheehy et al., 2011; Tam et al., 2010). Active and voluntary visuo-spatial attentional biases that have long been known to influence the processing of competing incoming perceptual input (e.g., Desimone & Duncan, 1995) seem to also play a critical role in constraining competing representations held in VSTM and are influenced by them, certainly in adults (Chun et al., 2011; Gazzaley & Nobre, 2011; Stokes, 2011; Stokes & Nobre, 2011), but also from early childhood. Moreover, cueing benefits show that the locus of item selection in service of VSTM is flexible and may occur at multiple stages within the stream of information processing based on current goals and expectations, similar to the flexible, early or post-perceptual, locus of attentional filtering in service of perception (Chun & Wolfe, 2000; Luck & Vecera, 2002; Luck & Hillyard, 2000). The way in which active selection operates flexibly within the stream of information processing in VSTM seems to be functional from early childhood. Intriguingly, orienting benefits in service of memory, in addition to perception, were part of a very influential formulation of orienting mechanisms (e.g., Posner, 1980), but their developmental fractionation adds a level of complexity to which I return shortly (see section 2.1.).

1.2. Implications for and from models of adult VSTM / VWM

Beyond models of attention, the benefits of visuo-spatial attention cues are consistent with findings and theoretical models of WM that include attentional constraints on the encoding and maintenance of stimulus features in memory (e.g., Baddeley et al., 2011; Salway & Logie, 1995; Ueno, Allen, et al., 2011; Vandierendonck et al., 2004). Indeed, influential models of WM ascribe to "attentional control" a fundamental role in their architecture either as a "central executive" responsible for controlling and manipulating representations stored in slave modality-specific systems and for ensuring the communication of these systems with LTM via the episodic buffer (Baddeley, 2002a, 2002b, 2003; Baddeley & Hitch, 1974; Baddeley, 1998) or as a "focus of attention" responsible for maintaining a subset of the contents of WM in a state of high activation (Cowan, 1988, 1999, 2005; McElree, 2001, 2006; Oberauer, 2002, 2003). Given the limited capacity of WM (Cowan, 2001; Luck & Vogel, 1997), not all representations can be kept in an accessible state and therefore a common requirement among these models is the need to select and actively maintain those WM representations that are most relevant to the on-going task. Selection of the most relevant visuo-spatial information seems to be achieved via top-down attentional biases while their active maintenance takes place via attentional refreshment (e.g., Raye et al., 2007), in agreement with WM accounts proposing that the active and short-term maintenance of spatial information engages focal shifts of spatial attention at memorised locations (Smyth & Scholey, 1994) that act as an attention-based rehearsal mechanism (Awh et al., 1998). Similarly, top-down modulations and their differential interaction with the

memoranda seem to be compatible with the role of episodic buffer in communicating with visual semantics and LTM (Baddeley, 2000).

2. Developmental differences in visuo-spatial biases for VSTM encoding and maintenance

2.1. Implications for theories of attentional development and for adult theories of attention

In addition to commonalities in attentional benefits across age groups, the current experiments reported clear developmental differences; this is the second central finding of the current thesis. Cues prior to encoding resulted in the strongest benefits and these were similar across age groups, most likely because they provided the opportunity to select a single item amongst the four in the memory array for encoding and retention until test. Even 10-month-old infants are capable of using pre-cues to prioritise and maintain such a limited amount of information (Ross-Sheehy et al., 2011) accounting for the stability of benefits from cues prior to encoding across the target age groups here. However, 7-year-old children benefited less than older individuals from attention cues during maintenance demonstrating changes in voluntary deployment of attention internally. This is consistent with the vast literature documenting developmental improvements in children's ability to orient attention in service of detection and discrimination (Akhtar & Enns, 1989; Brodeur & Boden, 2000; Brodeur & Enns, 1997; Brodeur et al., 1997; Enns & Brodeur, 1989; Goldberg et al., 2001; Iarocci et al., 2009; Ristic & Kingstone, 2009; Wainwright & Bryson, 2002), but adds to the more limited investigation of these visuo-spatial attentional processes in service of VSTM in childhood (Astle et al., 2012). Developmental differences during maintenance persisted even when 7-year-

olds' overall poorer ability to store information in neutral trials was taken into account in various ways, suggesting that the amount of information children are capable of storing is not the sole limiting factor to the efficiency of orienting within VSTM. Cueing benefits were modulated by memory load size, but also by the temporal delays during maintenance and the characteristics of the memoranda. Orienting to both external and internal space are part of Posner's (1980) influential formulation of orienting mechanisms and the two conditions were hypothesized to have a common basis at least in adults, but their developmental trajectories did not receive empirical research until recently (Astle et al., 2012). By tracing the developmental origin of the close coupling between attention and memory, the current data show that while goal-driven perceptual selection is available from early childhood, the ability to select a memory item from competing encoded memory items and importantly the ability to modulate its processing for later retrieval, is what distinguishes the age groups, revealing distinct bases across the two orienting conditions.

2.2. Implications for and from adult models integrating attention and VSTM / VWM

As recently suggested, an organizing taxonomy of attentional processes operating on externally- vs. internally-focused representations can inform us how attention facilitates adults' VSTM and vice versa (Chun et al., 2011). However, this taxonomy has not been applied as a theoretical framework for understanding developmental findings so far. Indeed, models of attentional development have focused on examining attentional biases in service of perception and have proposed taxonomies that aim to explain the *mechanisms* by which attention operates on these representations, e.g., top-down/endogenous vs. bottom-up/exogenous attention.

These distinctions, typically being predicated on the cues' characteristics, are useful for understanding the mechanisms involved in processing the bulk of information experienced at any given moment; yet, they do not take into account the *type of representations* that these mechanisms operate on, e.g., perceptual representations, representations actively held in VSTM, or representations recalled from LTM. An external vs. internal taxonomy of attention aims to provide a comprehensive account that considers these mechanisms along with the type of representations that they operate on. For example, while bottom-up attention is a property of external attention only, top-down attention operates on representations of both external and internal attention (Chun et al., 2011). A developmental application of such taxonomy here, clearly explains how controlled attentional processes operating on representations in different states in VSTM may become fractionated at different developmental time-points: externally-focused representations in early childhood vs. internally-focused processes in late childhood. This potentially explains to some extent why age-group memory differences in Cowan et al.'s studies persisted even when slow encoding was taken into account (Cowan et al., 2011, 2010). Findings in the current thesis suggest that young children in those studies might have been less able to attentionally refresh and maintain selected items until test. This suggestion is further supported by the fact that in Cowan et al.'s study (2010), developmental differences across attentional conditions were observed in large but not in small size arrays. Indeed, current data show that in large memory arrays, in which there is presumably a greater need for selection and maintenance, individuals with fewer attentional resources, such as 7-year-olds, may perform poorly because of more limited resources available to refresh and protect selected representations (e.g., Cowan et al., 2010). In contrast,

in small memory arrays in which all items are encoded and sufficient attentional resources are available for their active maintenance, top-down selection and modulation is not as critical.

Moreover, the differential abilities of 7-year-olds during prospective and retrospective orienting are informative about the precise mechanisms via which visual attention enhances representations in VSTM even for adults. In the adult literature, it has been proposed that cues during maintenance enhance the active maintenance of relevant items and/or suppress the activation of irrelevant items (Lepsien & Nobre, 2006, 2007), protect the representation of the selected item from decay or interference during the retention interval (Makovski & Jiang, 2007; Makovski et al., 2008; Matsukura et al., 2007), and provide direct retrieval routes to items in memory by prioritizing the comparison process of the selected item with the probe (Astle et al., 2011). Findings here demonstrate that cues during maintenance operate by refreshing and protecting selected representations during maintenance, at least when cues are fully informative and at the limits of VSTM capacity.

2.3. Implications for theories of VSTM and VWM development

The smaller retro-cueing benefits of visuo-spatial attention cues for younger children also speak to the nature of the changing VSTM capacity limits over childhood into adulthood. Current models of VSTM development propose that what changes is simply the capacity to store more items in VSTM / VWM and not encoding efficiency or attentional filtering abilities (Cowan et al., 2011, 2010). Results here indicate that, while children have a more limited storage capacity that follows a monotonic increase with development, as indicated by baseline differences on neutral trials (Cowan et al., 2011, 2010; Riggs et al., 2006; Simmering, 2012),

older participants are better able to use visuo-spatial attention cues to maintain information in VSTM in a way that allows them to later access that information more accurately and readily. Importantly, these benefits were shown to relate to visual memory capacity measures. I do not argue against the claim that increasing storage capacity is an important factor for developmental improvements in VSTM / VWM. However, I suggest that voluntary attentional processes, such as orienting visuo-spatial attention, can also contribute to optimising VSTM maintenance and retrieval by re-activating the to-be-probed representation. Developmental data in the current thesis document that top-down modulatory mechanisms during VSTM maintenance indeed engage visuo-spatial orienting and these mechanisms can dynamically bias mental representations based on the current goals and expectations in agreement with previous adult findings (e.g., Griffin & Nobre, 2003; Kuo, Stokes, et al., 2011; Kuo, Yeh, et al., 2011; Nobre et al., 2008). In short, current findings challenge existing models of VSTM development by showing that they have underspecified how top-down biasing mechanisms operate to subserve the active maintenance of VSTM representations that optimise VSTM performance. Therefore, in addition to the already proposed capacity-growth with age (Cowan et al., 2011, 2010), data here advocate for protracted development of the attention mechanisms mediating these biases during maintenance.

The smaller attentional benefits for younger compared to older children are also consistent with the suggestion by Barrouillet et al. (2009) that attentional refreshment mechanisms may influence WM span differentially from 5 to 14 years of age. But, unlike in adults and the elderly (Johnson et al., 2002; Raye et al., 2002, 2008), in children these mechanisms had thus far only been investigated for the

verbal modality (e.g., Portrat et al., 2009; Tam et al., 2010). Attentional refreshment mechanisms also influence the visual modality, demonstrating thus that domain-general processes interact with domain-specific systems in a top-down fashion in order to maintain information in VWM although differentially from early childhood to adulthood.

The smaller benefits for younger children are also consistent with time-based forgetting models proposing that memory traces in early childhood decay fast with time (Hitch et al., 2001; Towse & Hitch, 1995; Towse et al., 2002; Towse et al., 1998), complementing the evidence that decay occurs even in the absence of a concurrent task. Importantly though, decay, and thus the integrity of representations, seems to be modulated by the number and characteristics of items that need to be encoded and maintained in memory, with decay being faster when the number of items exceeds the limits of VSTM capacity and when the items are difficult to refresh. This indicates that maintenance duration, although important, cannot alone account for the poorer VSTM and that the need for top-down biases and attentional refreshment of a memory item is greater when encoding and maintaining a high rather than a low information load. Furthermore, in contrast to what was previously suggested (e.g., Towse & Hitch, 1995), even for 7-year-olds, maintenance of a low information load is active rather than passive and engages broad attentional processes, as indexed by the relation between 7-year-olds' retro-cue benefits and their performance in the VSTM span task.

A question that arises from the current thesis and is important for theories of cognitive development is why information decays to a greater extent in young children when it exceeds VSTM capacity. This issue seems to relate to the

mechanisms responsible for transferring memory representations from the transient iconic system to the durable VSTM system when the number of items exceeds the limits of VSTM capacity. Perhaps this limitation can be explained by a modified model of visual attentional refreshment, building on the TBRS time-based forgetting model (Barrouillet et al., 2009), potentially explaining why fewer and/or more degraded representations are transferred from IM to VSTM in younger compared to older participants. It may be for example that once individuals are presented with a memory array and while having an afterimage for each item available (e.g., visual / informational persistence), they start re-activating the representation of all items to prevent their loss. Such a re-activation process may occur via a non-articulatory rehearsal mechanism similar to the "memory scanning" process proposed by Cowan (1992) for the verbal STM domain. According to this process, mentally scanning the item to-be-recalled across the items stored in verbal STM prevents memory decay and enhances recall. Developmental differences in storage capacity may possibly reflect immaturity in this early attentional re-activation mechanism to some extent. The more refined and faster this mechanism is, the fewer traces will decay and more robust representations will be transferred to durable VSTM, reflecting thus greater slot availability across age groups. Further to that, the transferred durable VSTM representations need to be maintained in VSTM until probe response. So, older individuals might keep re-activating these (transferred) durable representations via this scanning and refreshing mechanism either until probe response [(e.g., neutral trials) – reflecting thus the general attentional processes needed for active maintenance] or until retro-cue presentation where they recruit top-down biasing mechanisms and then refresh only the selected item until probe response [(e.g., retro-

cue trials) – reflecting thus the voluntary visuo-spatial attentional orienting]. If the item indicated by the retro-cue has successfully been transferred from the IM system to the VSTM system, then the individual can attentionally refresh a veridical and robust representation via retro-cues. If the representation has not been re-activated enough times and thus has degraded to a great extent, then top-down biasing and attentional refreshment is not as successful. In this account, the number of items that will be transferred to VSTM equals the number of items that children have re-activated before these representations have degraded. In other words, fewer items during encoding allow more items to be re-activated and transferred before decay even in young children whose mechanism is less developed, whereas more items during encoding allow fewer items to be re-activated and transferred with remaining traces becoming lost due to decay. In light of the current results, it may be the case that *when the memory load is low* and therefore well within capacity limits, young children are able to re-activate all the representations stored in IM before they decay by mentally scanning and attentionally refreshing rapidly all items; this way the representations are transferred to the durable VSTM system. In contrast, *when the memory load is high* and therefore exceeds capacity limits, a portion of the representations stored in IM will deteriorate and perhaps lost before children have the chance to re-activate all representations via this mental memory scanning and refreshing process. Moreover, the memoranda characteristics will also constrain or enhance maintenance further. The more difficult items (e.g., meaningless items) will slow down attentional re-activation thus allowing fewer items to be transferred to VSTM system from the IM system.

3. Implications of the individual differences findings

These accounts lead to the third central finding that, over and above age-related changes, individual differences in attentional benefits during the maintenance period related to VSTM and VWM capacity, consistent with behavioural data in children (Astle et al., 2012) and extensive cognitive neuroscience research in adults (e.g., Fukuda & Vogel, 2009; Vogel & Machizawa, 2004; Vogel et al., 2005). While these analyses are correlational in nature and directionality should be interpreted with caution, they provide developmental results that are consistent with parallel adult findings on VWM mechanisms that highlight the role of executive processes in maintaining and protecting internally held representations from interference (Awh et al., 1998; Baddeley et al., 2011; Smyth & Scholey, 1994; Ueno, Allen, et al., 2011). In summary, while I acknowledge the importance of increasing storage for VSTM / VWM capacity over development (Cowan et al., 2010), maximizing VSTM / VWM capacity may also require actively biasing locations and objects in space to effectively maintain information. Attentional orienting, thus, seems to be a critical underlying process to VSTM / VWM performance and should be treated as more "than merely a correlated phenomenon" (Awh & Jonides, 2001, p. 120).

4. Practical implications

In addition to the mechanistic questions about the sources of developmental differences explored and reported here, the current results also have important practical implications. The current findings demonstrating that attentional control relates to VSTM / VWM capacity in children and that high capacity children show adult-like neural biases, suggest that the neural circuits that support top-down modulations operating on perceptual input and internal representations are

susceptible to plasticity changes. Therefore, there exists the potential to promote cognitive function and development either in early childhood or even earlier in infancy by training and enhancing selective attention within VWM (Gazzaley & Nobre, 2011). Ultimately, this has tremendous value for clinicians as training attentional control can potentially transfer to poor VSTM / VWM and other higher executive processes (Diamond & Lee, 2011; Holmes et al., 2010; Holmes, Gathercole, & Dunning, 2009; Kelley & Yantis, 2009; Klingberg et al., 2005; Klingberg, 2010; Klingberg, Forssberg, & Westerberg, 2002b; Morrison & Chein, 2011; Wass, Scerif, & Johnson, in press; Wass, Porayska-Pomsta, & Johnson, 2011) which may lead to improvements in learning and interventions for atypical populations exhibiting attention and VSTM / VWM deficits. Indeed, Johnson (2012) recently proposed that higher executive functions allow children, even those at-risk for developmental disorders such as autism and ADHD, to compensate atypical functioning caused by other risk factors in other neural systems early in life and therefore prevent the development of clinical symptomatology later in life. Similarly, by understanding the attentional processes that mediate capacity and VSTM performance and hence the means via which children establish stable internal representations at different age periods, more effective educational practices can be applied in the classroom.

Limitations of the current thesis and future directions

Results here demonstrate a strong link between attentional control biases and VSTM performance and so far I have made a strong argument about the functional significance of attentional mechanisms in VSTM capacity and VSTM performance.

However, by no means do I propose that the relation between attentional orienting and VSTM / VWM is unidirectional. In contrast, a number of adult studies have shown that the content of VWM also drives attentional effects (Astle et al., 2010; Downing, 2000; Kim et al., 2010; Kumar et al., 2009; Olivers et al., 2006; Soto et al., 2005, 2008; Woodman et al., 2007) and results from Experiment 5 (Chapter 6) indicated that the memoranda indeed constrain top-down attentional biases differentially. The current experiments were designed to investigate precisely developmental changes and mechanisms involved in orienting attention to memory, and so the primary focus was the nature of the attention cues, their predictive role for all age groups, and their constraining parameters such as the temporal delay and the memory load for 7-year-olds. The memoranda were therefore limited to highly familiar colours in almost all experiments, except in Experiment 5 (Chapter 6), but it is critical to study further how the nature of the items to be refreshed in visual memory interacts with the changing attentional control skills demonstrated here: for example, semantic characteristics and visual perceptual similarity of the memoranda are well known to influence developmental changes in memory capacity (Hitch et al., 1989). Visual complexity (Alvarez & Cavanagh, 2004), categorical membership (Awh et al., 2007) and item interference (Lewandowsky et al., 2010) are also factors well known to influence adults' memory capacity. However, it is still rather unclear how changing attentional biases operate on these developing representations, aid their development and in turn, how they are influenced by them. Results from an additional non-reported experiment I carried out with 7-year-olds, 11-year-olds, and adults indicated that categorical (semantic) relatedness on one hand and colour competition causing interference amongst the memory items on the other hand

constrain attentional biases for all age groups. Yet, having additional semantic information such as colour in familiar items similar to those presented in Experiment 5 (Chapter 6) resulted in better VSTM performance and higher VSTM capacity rather than maintaining these items only based on their shape and without any surface information. The role of surface information is central in theoretical accounts of how the visual system recognizes objects (Rossion & Pourtois, 2004; Tanaka, Weiskopf, & Williams, 2001) with colour being a significant factor in addition to shape. Hence, it seems beneficial to study how this bi-directional relation (attention mechanisms and WM content) changes with development by also investigating how the mechanisms drawing on LTM, and ultimately the mechanisms of learning, modulate the deployment of attention across development.

Also, attentional cueing benefits and costs may vary as a function of expectation and as a function of the interaction of memory load with temporal delay. With regards to the former, cueing benefits and costs were examined under circumstances in which participants were explicitly informed that attention cues would either be helpful and should be attended or would not be beneficial and should be ignored. The aim for this was to gain understanding of whether age groups differ in their ability to voluntarily allocate attention or resist automatic effects in order to facilitate VSTM when they are explicitly instructed to do so. Nevertheless, it will be interesting to examine cueing benefits and costs under circumstances in which participants will not be informed about the role of the cues because it may be that the pattern of behavioural differences across age groups is task-dependent. For example, when participants are not informed about the role of attention cues, cueing effects in early childhood might be automatic whereas participants in late childhood and

adulthood may be faster than the younger ones to determine whether the cues are beneficial or not and thus to decide whether they should pay attention to them or not. With regards to the interaction of memory load and temporal delay, cueing benefits were examined in isolation for these two factors during maintenance. Although results demonstrated that cueing benefits during maintenance change as a function of these factors and provided insight as to how the memory load or temporal delays constrain orienting effects in isolation, further study is needed to determine the exact parameters under which young children benefit to a greater degree from these cues and how the interaction between memory load and temporal delay changes over development.

Experiments in the current thesis focused on the attentional parameters constraining VSTM performance, hence the number of memory items in the array was kept constant to 4 items across experiments (except Experiment 3, Chapter 4). However, a parallel and equally vast line of research has focused on examining the nature of VSTM / VWM capacity by varying the number of items. This research has yielded a debate as to whether VWM represents a system with a fixed number of slots that can be occupied by memoranda (Fukuda, Vogel, Mayr, & Awh, 2010; Luck & Vogel, 1997) or one that can accommodate an unlimited number of items with the number, however, influencing the precision (resolution) of the items. With regards to the latter view, individuals can maintain either fewer items with high resolution or more items with low resolution but there is no upper limit in the number of stored items (Bays et al., 2009; Bays & Husain, 2008; Bays, Wu, & Husain, 2011). Although the debate is on-going, other behavioural and neuroimaging findings argue in favour of a hybrid, two-factor model in which the quantity (i.e., number of items)

and the quality (i.e., resolution) of stored representations represent distinct aspects of VWM capacity (Alvarez & Cavanagh, 2004; Anderson & Awh, 2012; Anderson et al., 2011; Awh et al., 2007; Barton et al., 2009; Xu & Chun, 2006; Zhang & Luck, 2008). According to this model, the resolution of an item decreases as the number of items maintained in VWM increases; however, resolution will reach an asymptote when the number of items exceeds the individual's limited WM capacity (Anderson & Awh, 2012; Anderson et al., 2011). Experiments in the current thesis do not allow taking a stand on this topic but perhaps a developmental application of such a model in addition to studying the improvement by which attention biases the maintenance of these representations may shed more light on the nature of VWM. It may be, for example, that the precision by which individuals retain memory items develops with age (Burnett Heyes, Zokaei, van der Staaij, Bays, & Husain, 2012) because presumably there is also an increase in the available resources that can be distributed among items, resulting thus in better VSTM performance. Nevertheless, precision in older individuals may be further facilitated by their greater ability to dynamically bias the maintenance of memory representations. As already demonstrated by the findings here, developmental data hold promise for resolving controversies in the adult literature.

As evident from the preceding chapters, all the experiments reported here have employed a cross-sectional design. Longitudinal designs can provide greater insight to the directionality and the steepness of developmental change from one time-point to another and future research should also employ such a design. As longitudinal designs impose significant demands on completion time and number of participants tested over extended periods of time (e.g., to account for subject

attrition), a cross-sectional design was deemed more important and feasible for the present research. Similarly, age range was restricted between early childhood (beginning of primary school) until young adulthood. It would be interesting thus to examine a broader age range, e.g., starting from kindergarten until old adulthood, in order to understand whether the same processes that seem to develop early in the lifespan are the same as those who seem to deteriorate later in the life (Gazzaley et al., 2008; Johnson et al., 2002).

In the current thesis, I have regarded the enhancement of the item to-be-probed as the underlying mechanism of attentional selection. Top-down attentional biases may be achieved by enhancement of neural activity for relevant stimuli, by suppression of neural activity of irrelevant stimuli and hence inhibition of irrelevant items, or by both mechanisms (Gazzaley, 2010; Kastner & Ungerleider, 2000; Knight, Staines, Swick, & Chao, 1999). As already discussed, voluntary attentional selection and hence enhancement of relevant information is functional from early childhood. It may be that attentional refreshment via retro-cues, although functional, is restrained by children's less developed ability to inhibit irrelevant items in comparison with older individuals (e.g., Tipper, Bourque, Anderson, & Brehaut, 1989). That is, adults may be able to both enhance the neural activity corresponding to selected items and suppress that for non-selected items whereas children may only be able to enhance neural activity for selected items but fail to supress that for non-selected items. Indeed, inhibition follows a protracted development (Diamond, 2002; van der Molen, 2000) and suppression of distracters has been found to relate to VWM maintenance (Vogel et al., 2005). Olesen et al. (2007) already provided neural evidence for children's difficulty in suppressing distractors compared to adults.

Similarly, findings from late adulthood corroborate that age group differences are also driven by suppression deficits (Gazzaley et al., 2008, 2005). Understanding the developmental trajectories of these two higher executive functions will shed light on developmental differences in VSTM maintenance and it will provide further validation to the external vs. internal taxonomy of attention which proposes that VWM maintenance also depends on the ability to inhibit perceptual and mnemonic distraction (Chun, 2011). Any theoretical model of cognition should be able to account for developmental changes in the cognitive processes that it claims to be able to explain (Baddeley & Hitch, 2000). The design of clever tasks will allow future studies to disentangle the role of the two mechanisms in maintaining information in VSTM / VWM.

A potential future research direction might be to examine the role of genetic variation in the efficiency to engage top-down attentional control in tasks with a VSTM / VWM component in relation to behavioural and neural measures. A few studies have demonstrated associations between alleles of specific genes (e.g., DAT1 and DRD4) and higher cognitive functions such as executive attention (Holmboe et al., 2010; Posner, Rothbart, & Sheese, 2007; Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005; see also Holmboe & Johnson, 2005; Posner & Rothbart, 2005 on how genotype and training of attentional control can influence cognitive development). It will be a major advancement to link specific genotypes with individual differences in visuo-spatial biases for encoding into VSTM / VWM and more importantly during VSTM / VWM maintenance, similar to specific polymorphisms associated with storage capacity (Anderson, Bell, & Awh, 2012; Papassotiropoulos et al., 2011; Söderqvist et al., 2010). Such knowledge could

potentially inform research on well-defined genetic disorders, e.g., William's syndrome, Fragile X syndrome, and neurodevelopmental disorders with a mixed etiology, e.g., ADHD, as these exhibit both attention and WM deficits (Cornish et al., in press; Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005; Rowe & Mervis, 2006).

Concluding remarks

The current experiments are the first to explore precise parameters through which developing attentional control modulates encoding and especially maintenance in VSTM during childhood. They define how children develop the ability to voluntarily deploy attentional control in order to maximise their limited VSTM capacity and they demonstrate that the development of multiple non-mutually exclusive neurocognitive processes drive these developmental differences. The study of developmental changes in attentional control and of visual memory corroborate that these two cognitive constructs are closely intertwined (Awh et al., 2006; Chun & Turk-Browne, 2007) and that their underlying developmental changes are clearly ripe for further investigation. Hopefully the current findings will motivate cognitive psychologists and developmental neuroscientists alike to converge their research on this exciting topic.

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APPENDIX A: General Methods

Prior to all experiments, 19 primary schools from Nicosia (Cyprus) and 14 primary schools from Oxford (UK) were contacted to participate in the experiments under the broad research theme "Investigating the relation between attention and memory in school-aged children". Ten schools in Nicosia and 5 schools in Oxford agreed to participate. Seven schools in Nicosia and all 5 schools in Oxford were eventually used for recruitment. Children in Nicosia were recruited for examining the behavioural correlates of visual selective attention and VSTM whereas children in Oxford were recruited for investigating the neural correlates between the two processes. Children were recruited from Years 1, 2, 5 and 6 of primary school via an opt-in procedure. In total, 696 and 1012 (1708 in total) consent forms, explaining the purpose of the research, were sent to the parents through the schools in Nicosia and Oxford respectively. Another 11 parents from the BabyLab's database at the University of Oxford were contacted. Three hundred and eighty three signed consent forms in Cyprus were returned to the teacher and handed over to the experimenter and another 64 signed consent forms in Oxford were returned directly to the experimenter. Each child participated in only one experiment. Children with neurological / psychiatric disorders were excluded from the experiments or the analyses. Hence, reported results reflect the abilities of typically-developing children only.

From those children recruited in Cyprus, 36 were excluded from testing. Three of them were not in the required age range, 4 were absent from school during the testing period, 2 were natives of other countries and could not understand either

Greek or English well, 3 were diagnosed with a clinical or genetic syndrome, 4 were receiving special education and/or were repeating the same year, 3 did not verbally consent to participate, and 17 were not allowed to participate by their teacher despite parental consent. In addition, 9 children in Cyprus were tested but excluded from the analyses as one of them had hearing problems (Experiment 1, peripheral-cue group), another was diagnosed with a non-identified genetic syndrome (Experiment 2), 2 had difficulty understanding the task (Experiments 1 and 3), and 5 completed only 1 out of 4 test blocks because of difficulties in performing the task (Experiments 2, 3 and 4). From children recruited in Oxford, 4 were not tested because their parents changed their mind about participating, 8 parents booked an appointment but failed to show up, 2 children arrived to the lab but were not tested because of a technical failure with the EEG equipment, and 25 parents were not reached when contacted. In addition, 7 children aged 6 and 7 years old were tested in an EEG experiment examining the neural correlates between attentional orienting and VSTM but their data were not fully analysed. This is because initial EEG data pre-processing and behavioural analyses showed that their accuracy was very low and this resulted in an inadequate number of ERP trials for further analyses. For this reason, the experiment was terminated and is not reported in the thesis. No hearing problems were reported by the parents or teachers of those children included in the analyses.

Adults were recruited from the undergraduate and postgraduate university communities in Oxford and in Cyprus via verbal and written advertisements and did not report any neurological / psychiatric problems. Only one adult was excluded from the analyses of the experiment he participated (Experiment 2) as he was classified as a middle-aged adult. All children and adult participants had normal or

corrected-to-normal vision. In total, four hundred and eighty four participants were tested and data from 467 healthy participants were analysed and are reported.

Prior to carrying out any of the experiments, ethical approvals by the Central University Research Ethics Committee of the University of Oxford and the Cyprus Pedagogical Institute were secured and permission of entry in schools in Nicosia was given by the Ministry of Education in Cyprus. Prior to testing, adult participants signed consent forms and children with parental consent forms assented verbally to participate in the experiment. Participants were informed that they could withdraw from the study at any time without any consequences.

APPENDIX B: Instructions and illustrations of the example cards

Figure B1. Instructions for Experiment 1, central-cue group

Pinky and the Brain game



This is a memory game! It is easy and fun.

What is the game about?

Meet Pinky and the Brain. Pinky is a very forgetful mouse, whereas the Brain is a very clever mouse. You will be helping Pinky remember colours. Every time, you will see four identical pictures of different colours: for example, you might see four differently coloured dogs. After a little while, another coloured dog will appear. Your task will always be to search your memory and decide *whether that last coloured dog was one of the four initial ones*: if it was, press the left mouse button (marked with "***yellow smiley face***"). If instead *the last dog was of a colour that was not one of the four initial dogs*, press the right button of the mouse (marked with *"**red smiley face***"). Spot old and new colours as well as you can: the more correct answers, the more points you'll win!

Sometimes, the Brain will give you a cue to help you do well. *The cue is a white arrow and it will always point to the coloured dog out of the four that might re-appear next, so pay attention to it!* However, be careful! An arrow does not mean that the coloured dog was definitely there: every now and again, an arrow appears but the dog was not one of the initial four. Sometimes, the arrow will appear before the four pictures, sometimes afterwards, but don't be confused by this – the Brain will tell you when the *helpful cues* will appear. When no arrow appears, you will just see a white square in its place.

Remember, with either arrows or squares your task is to remember whether the last coloured picture was one of the initial four or not. Arrows are there to help you, so pay attention to them!

Before we start playing the game we will do some examples so that you understand the game well and win many points!

Figure B1. Illustrations of the example cards for Experiment 1, central-cue group

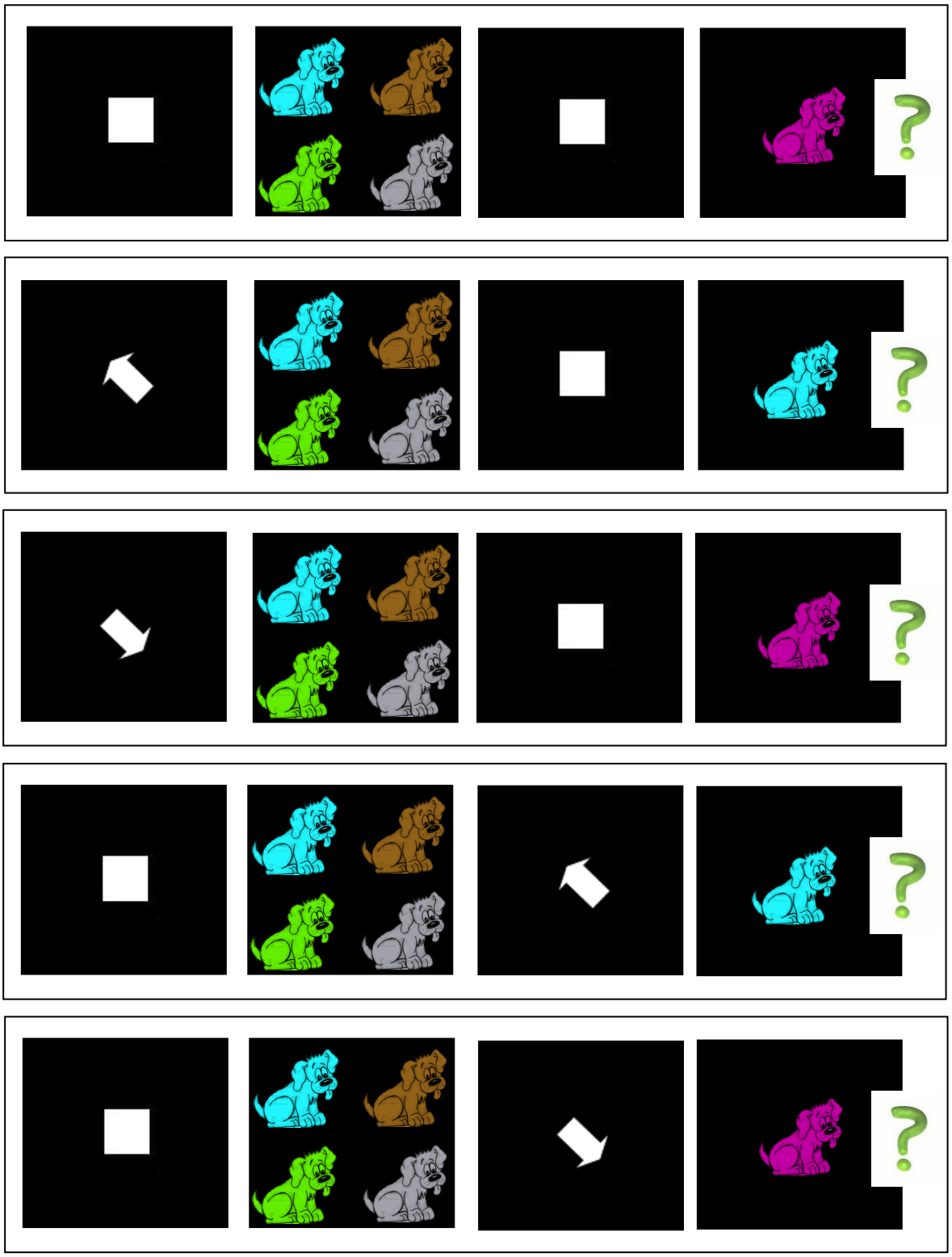


Figure B2. Instructions for Experiment 1, peripheral-cue group

Pinky and the Brain game



This is a memory game! It is easy and fun.

What is the game about?

Meet Pinky and the Brain. Pinky is a very forgetful mouse, whereas the Brain is a very clever mouse. You will be helping Pinky remember colours. Every time, you will see four identical pictures of different colours: for example, you might see four differently coloured dogs. After a little while, another coloured dog will appear. Your task will always be to search your memory and decide *whether that last coloured dog was one of the four initial ones*: if it was, press the left mouse button (marked with "***yellow smiley face***"). If instead *the last dog was of a colour that was not one of the four initial dogs*, press the right button of the mouse (marked with *"**red smiley face***"). Spot old and new colours as well as you can: the more correct answers, the more points you'll win!

Sometimes, the Brain will give you a cue to help you do well. *The cue is a white border and it will always mark the coloured dog out of the four that might re-appear next, so pay attention to it!* However, be careful! A border does not mean that the coloured dog was definitely there: every now and again, a border appears but the dog was not one of the initial four. Sometimes, the border will appear before the four pictures, sometimes afterwards, but don't be confused by this – the Brain will tell you when the *helpful cues* will appear. When no border appears, you will just see a white square in its place.

Remember, with either borders or squares your task is to remember whether the last coloured picture was one of the initial four or not. Borders are there to help you, so pay attention to them!

Before we start playing the game we will do some examples so that you understand the game well and win many points!

Figure B2. Illustrations of the example cards for Experiment 1, peripheral-cue group

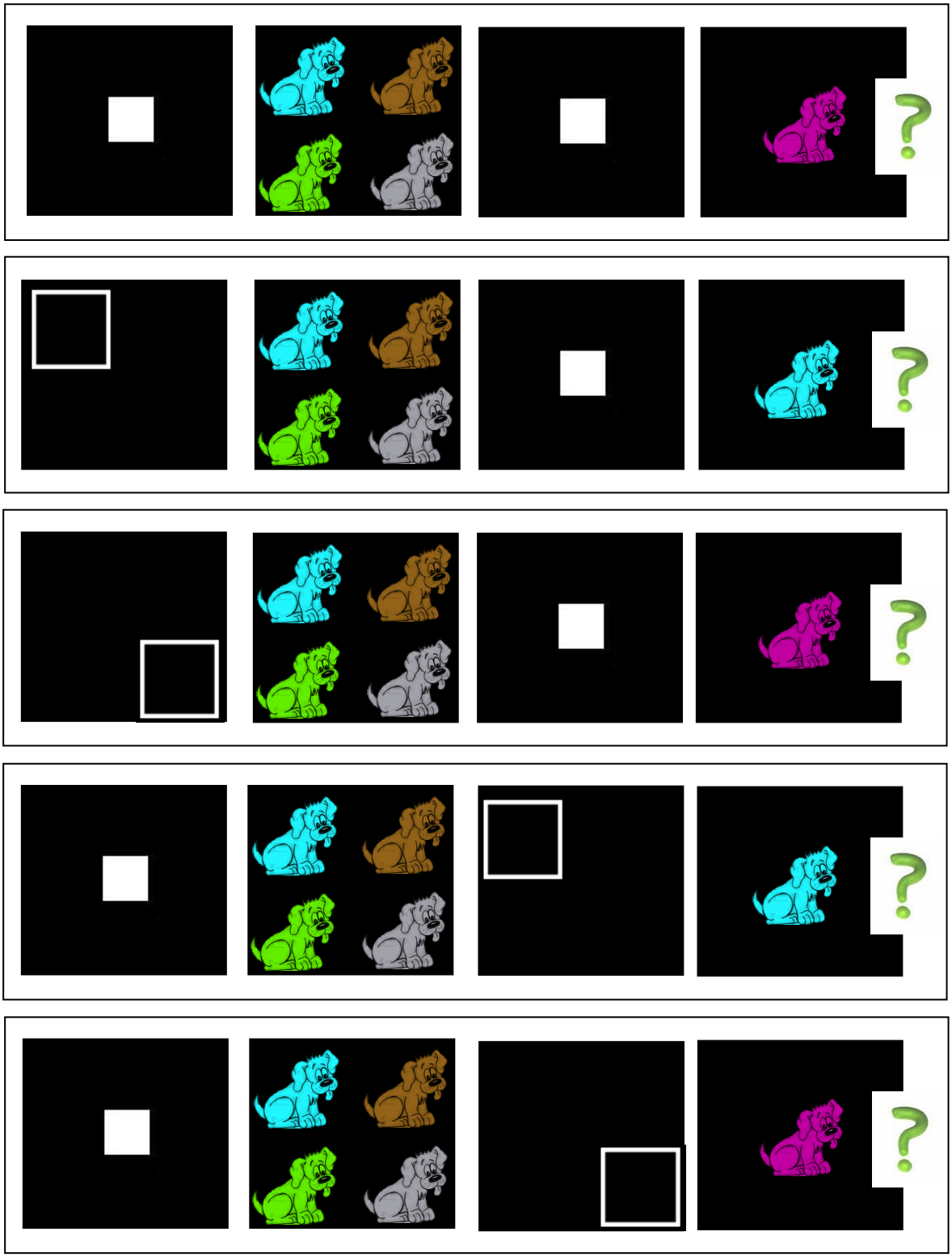


Figure B3. Instructions for Experiment 2

Pinky and the Brain game



This is a memory game! It is easy and fun.

What is the game about?

Meet Pinky and the Brain. Pinky is a very forgetful mouse, whereas the Brain is a very clever mouse, although he is not always very helpful. You will be helping Pinky remember colours. Every time, you will see four identical pictures of different colours: for example, you might see four differently coloured dogs. After a little while, another coloured dog will appear. Your task will always be to search your memory and decide *whether that last coloured dog was one of the four initial ones*: if it was, press the left mouse button. If instead *the last dog was of a colour that was not one of the four initial dogs*, press the right button of the mouse. Spot old and new colours as well as you can: the more correct answers, the more points you'll win!

Sometimes, the Brain will give you a cue. *The cue is either a white arrow or a border.* But don't be confused by this – the Brain will remind you of whether the *cue* will be an arrow or a border. Sometimes the cue will point to or mark the coloured dog out of the four that might re-appear. However, be careful! The Brain is not always helpful: sometimes the cue will point to or mark a spot, but the final coloured dog was somewhere else amongst the four initial dogs (and your answer should be "yes"). Don't let the Brain trick you into saying "no"! Also, an arrow or a border does not mean that the coloured dog was definitely there: every now and again, an arrow or a border appears but the dog was not one of the initial four, so your answer should be "no". Don't let the Brain trick you into saying "yes" then! So, all in all, it is best to ignore arrows and borders if you can. When no arrow or border appears, you will just see a white square in its place.

Remember, with either arrows, borders or squares your task is to remember whether the last coloured picture was one of the initial four or not. Arrows and borders sometimes help, and sometimes they do not. Before we start playing the game we will do some examples so that you understand the game well and win many points!

Figure B3. Illustrations of the example cards for Experiment 2

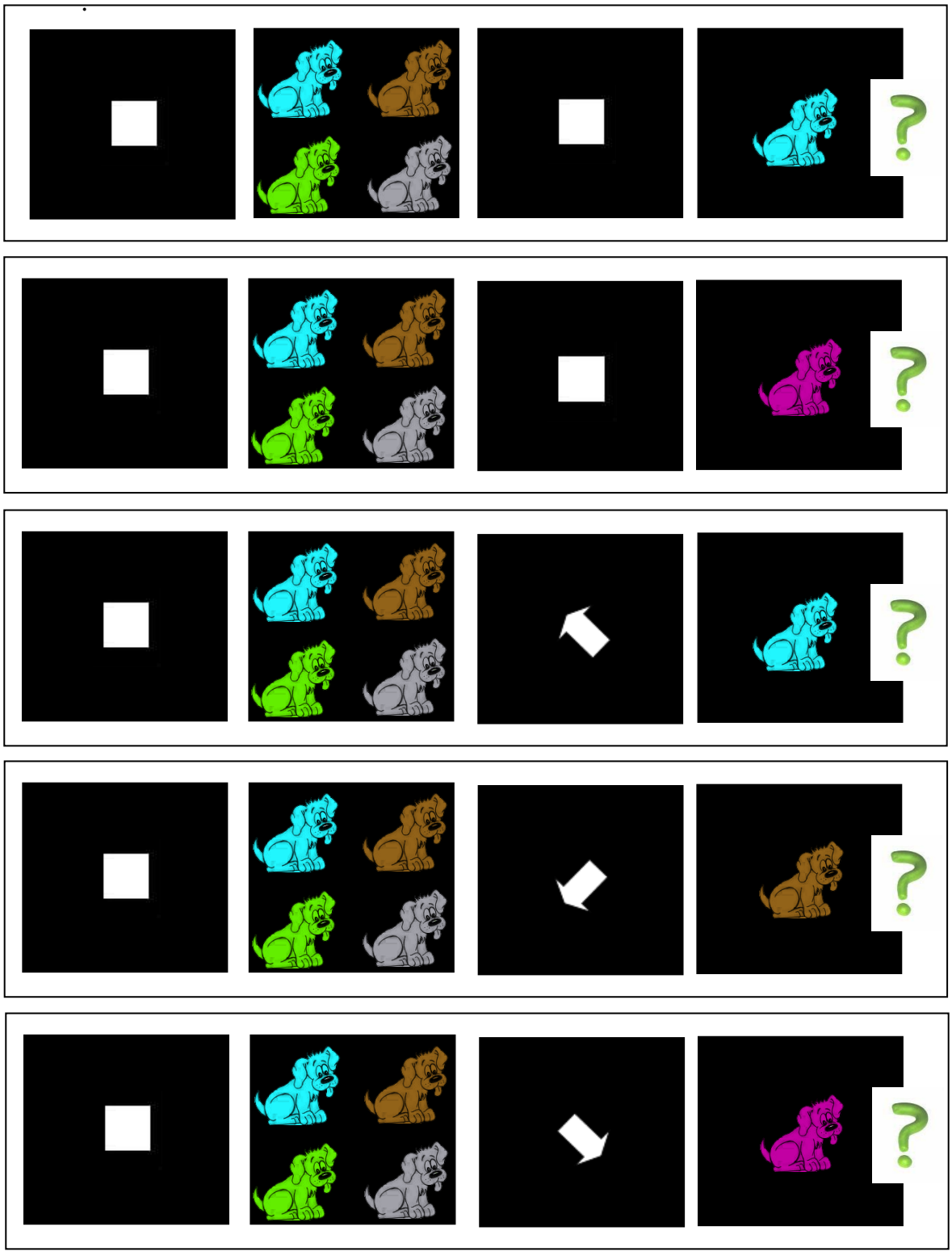


Figure B3. Illustrations of the example cards for Experiment 2

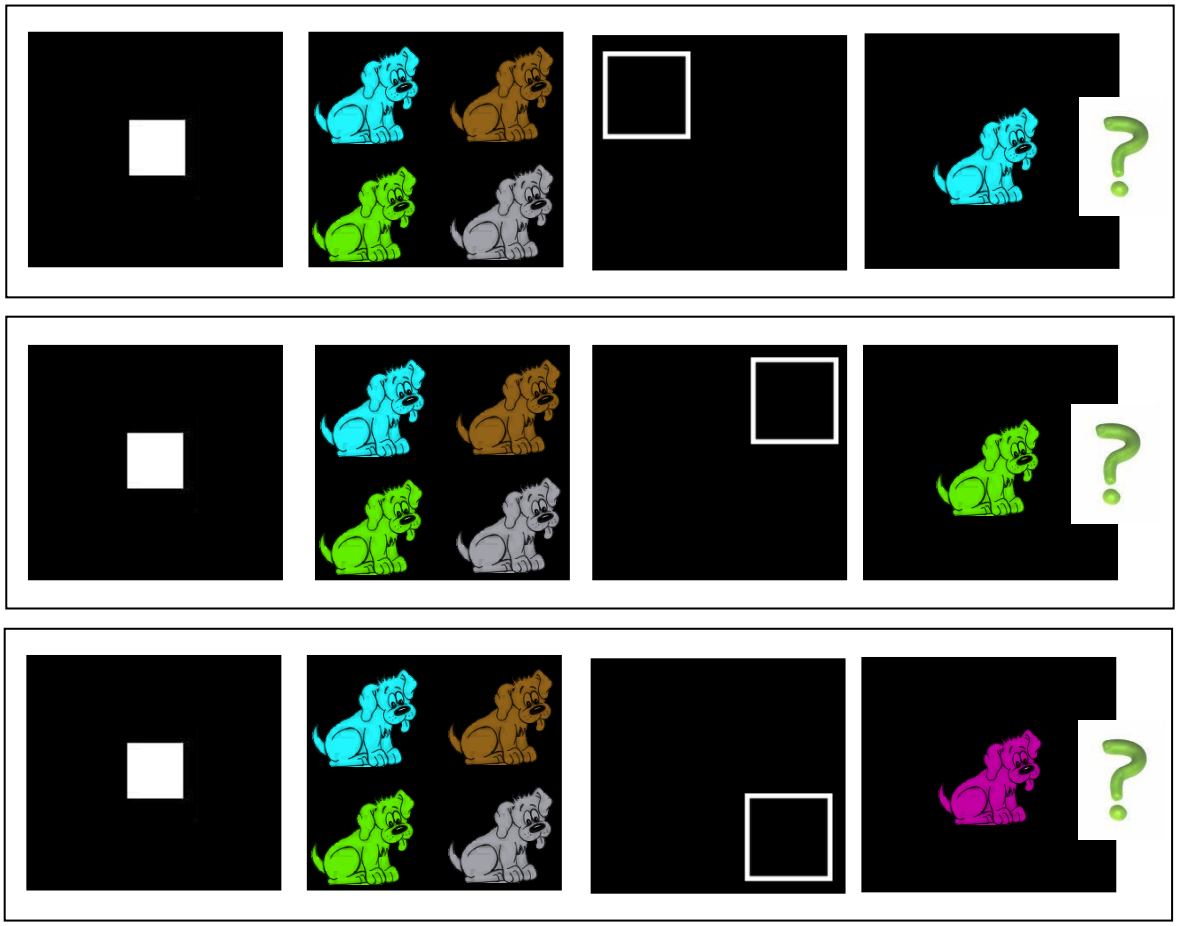


Figure B4. Instructions for Experiment 3

Pinky and the Brain game



This is a memory game! It is easy and fun.

What is the game about?

Meet Pinky and the Brain. Pinky is a very forgetful mouse, whereas the Brain is a very clever mouse. You will be helping Pinky remember colours. Every time, you will see two identical pictures of different colours: for example, you might see two differently coloured dogs. After a little while, another coloured dog will appear. Your task will always be to search your memory and decide *whether that last coloured dog was one of the two initial ones*: if it was, press the left mouse button (marked with "***yellow smiley face***"). If instead *the last dog was of a colour that was not one of the two initial dogs,* press the right button of the mouse (marked with *"**red smiley face***"). Spot old and new colours as well as you can: the more correct answers, the more points you'll win!

Sometimes, the Brain will give you a cue to help you do well. *The cue is a white arrow and it will always point to the coloured dog out of the two that might re-appear next, so pay attention to it!* However, be careful! An arrow does not mean that the coloured dog was definitely there: every now and again, an arrow appears but the dog was not one of the initial two. Sometimes, the arrow will appear before the two pictures, sometimes afterwards, but don't be confused by this – the Brain will tell you when the *helpful cues* will appear. When no arrow appears, you will just see a white square in its place.

Remember, with either arrows or squares your task is to remember whether the last coloured picture was one of the initial two or not. Arrows are there to help you, so pay attention to them!

Before we start playing the game we will do some examples so that you understand the game well and win many points!

Figure B4. Illustrations of the example cards for Experiment 3

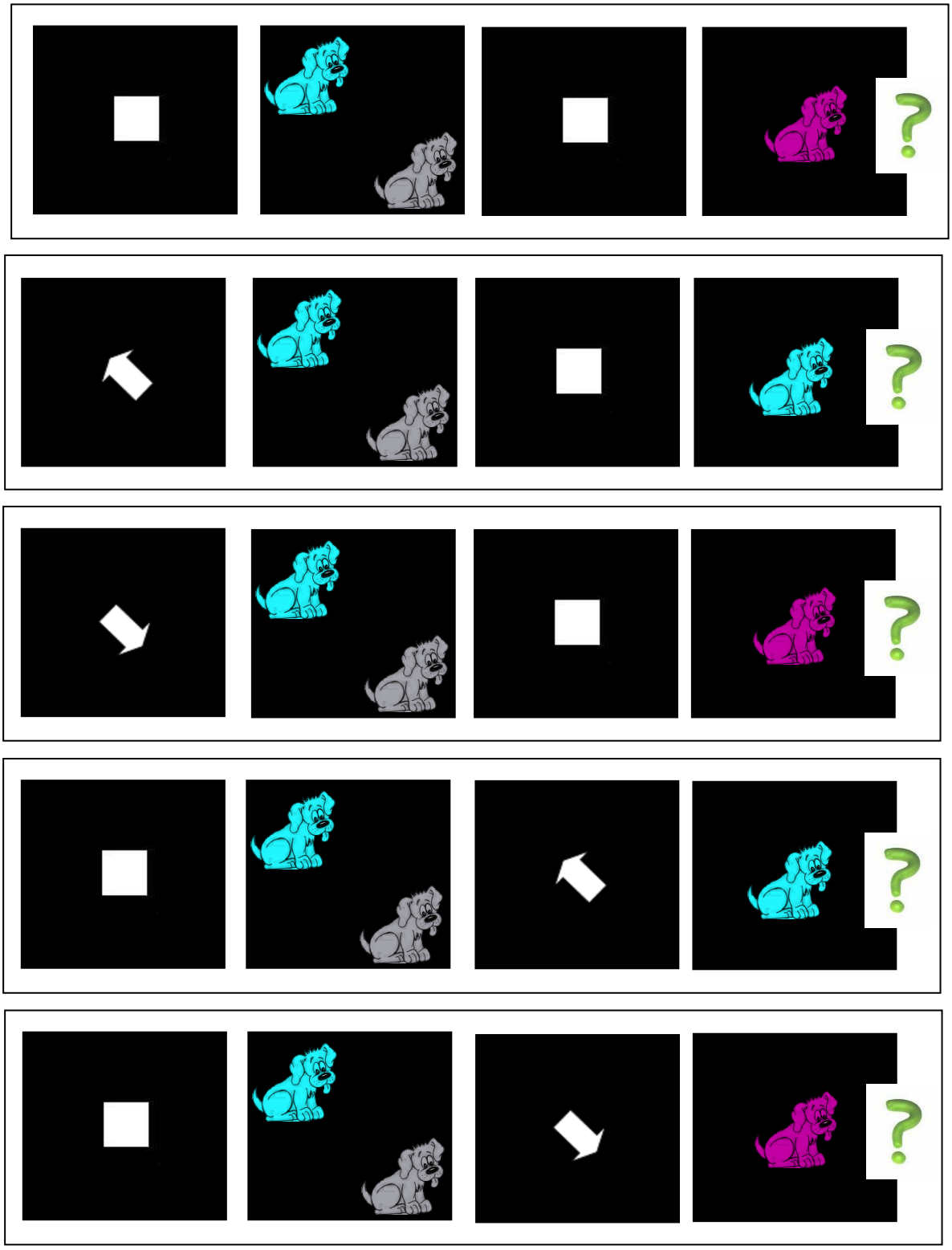


Figure B5. Instructions for Experiment 4

Pinky and the Brain game



This is a memory game! It is easy and fun.

What is the game about?

Meet Pinky and the Brain. Pinky is a very forgetful mouse, whereas the Brain is a very clever mouse. You will be helping Pinky remember colours. Every time, you will see four identical pictures of different colours: for example, you might see four differently coloured dogs. After a little while, another coloured dog will appear. Your task will always be to search your memory and decide *whether that last coloured dog was one of the four initial ones*: if it was, press the left mouse button (marked with "***yellow smiley face***"). If instead *the last dog was of a colour that was not one of the four initial dogs*, press the right button of the mouse (marked with *"**red smiley face***"). Spot old and new colours as well as you can: the more correct answers, the more points you'll win!

Sometimes, the Brain will give you a cue to help you do well. *The cue is a white arrow and it will always point to the coloured dog out of the four that might re-appear next, so pay attention to it!* However, be careful! An arrow does not mean that the coloured dog was definitely there: every now and again, an arrow appears but the dog was not one of the initial four. When no arrow appears, you will just see a white square in its place.

Remember, with either arrows or squares your task is to remember whether the last coloured picture was one of the initial four or not. Arrows are there to help you, so pay attention to them!

Before we start playing the game we will do some examples so that you understand the game well and win many points!

Figure B5. Illustrations of the example cards for Experiment 4

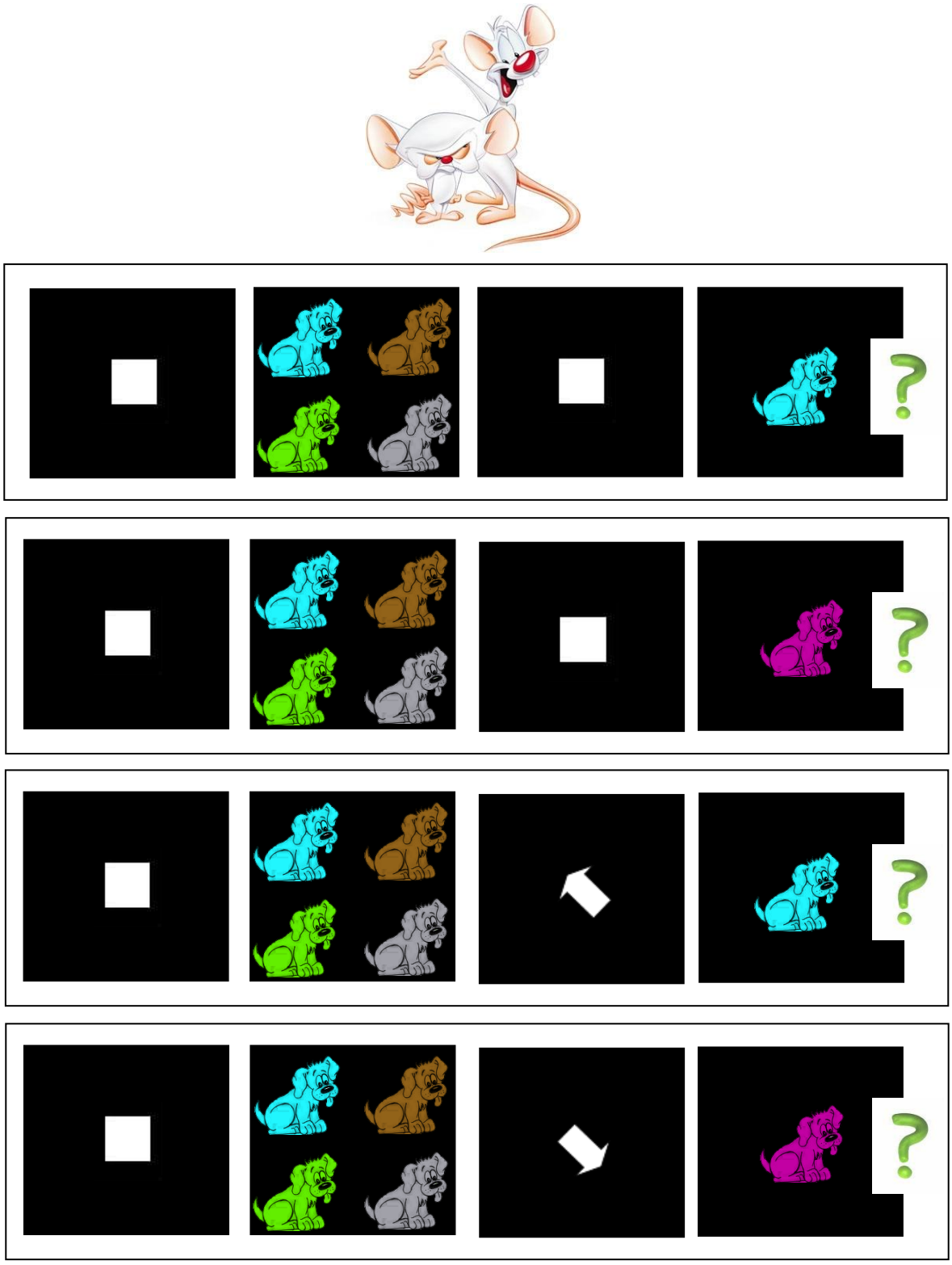


Figure B6. Instructions for Experiment 5, boys

Treasure Island hunt game



This is a memory game! It is easy and fun.

What is the game about?

Meet Captain Jack. Captain Jack is a pirate and he is in search for the lost treasures in 4 islands. You will be helping Captain Jack to find the treasures. In order to collect the treasures you must earn enough points. To earn the points you must remember pictures. Every time, you will see four different pictures of animals or shapes: for example, you might see a cat, a dog, a cow and a zebra. After a little while, another animal will appear. Your task will always be to search your memory and decide *whether that last animal was one of the four initial ones*: if it was, press the left mouse button (marked with "***yellow smiley face***"). If instead *the last animal was not one of the four initial animals (it was a racoon)*, press the right button of the mouse (marked with "***red smiley face***"). Spot old and new animals as well as you can: the more correct answers, the more points you'll win! The same goes for the shapes as well.

Sometimes, Captain Jack will give you a cue to help you do well. *The cue is a black arrow and it will always appear after the 4 pictures and point to the picture out of the four that might re-appear next, so pay attention to it!* However, be careful! An arrow does not mean that the animal or shape that it points to was definitely there: every now and again, an arrow appears but the animal or the shape was not one of the initial four. When no arrow appears after the four pictures, you will just see a black square in its place. In this case it means you have no help and you must try and remember on your own.

Remember, with either arrows or squares your task is to remember whether the last picture was one of the initial four or not. Arrows are there to help you, so pay attention to them!

Before we start playing the game we will do some examples so that you understand the game well and win many points!

Figure B6. Instructions for Experiment 5, girls

Treasure Island hunt game



This is a memory game! It is easy and fun.

What is the game about?

Meet Captain Monica. Captain Monica is a pirate and she is in search for the lost treasures in 4 islands. You will be helping Captain Monica to find the treasures. In order to collect the treasures you must earn enough points. To earn the points you must remember pictures. Every time, you will see four different pictures of animals or shapes: for example, you might see a cat, a dog, a cow and a zebra. After a little while, another animal will appear. Your task will always be to search your memory and decide *whether that last animal was one of the four initial ones*: if it was, press the left mouse button (marked with "***yellow smiley face***"). If instead *the last animal was not one of the four initial animals (it was a racoon)*, press the right button of the mouse (marked with "***red smiley face***"). Spot old and new animals as well as you can: the more correct answers, the more points you'll win! The same goes for the shapes as well.

Sometimes, Captain Monica will give you a cue to help you do well. *The cue is a black arrow and it will always appear after the 4 pictures and point to the picture out of the four that might re-appear next, so pay attention to it!* However, be careful! An arrow does not mean that the animal or shape that it points to was definitely there: every now and again, an arrow appears but the animal or the shape was not one of the initial four. When no arrow appears after the four pictures, you will just see a black square in its place. In this case it means you have no help and you must try and remember on your own.

Remember, with either arrows or squares your task is to remember whether the last picture was one of the initial four or not. Arrows are there to help you, so pay attention to them!

Before we start playing the game we will do some examples so that you understand the game well and win many points!

Figure B6. Illustrations of the example cards for Experiment 5

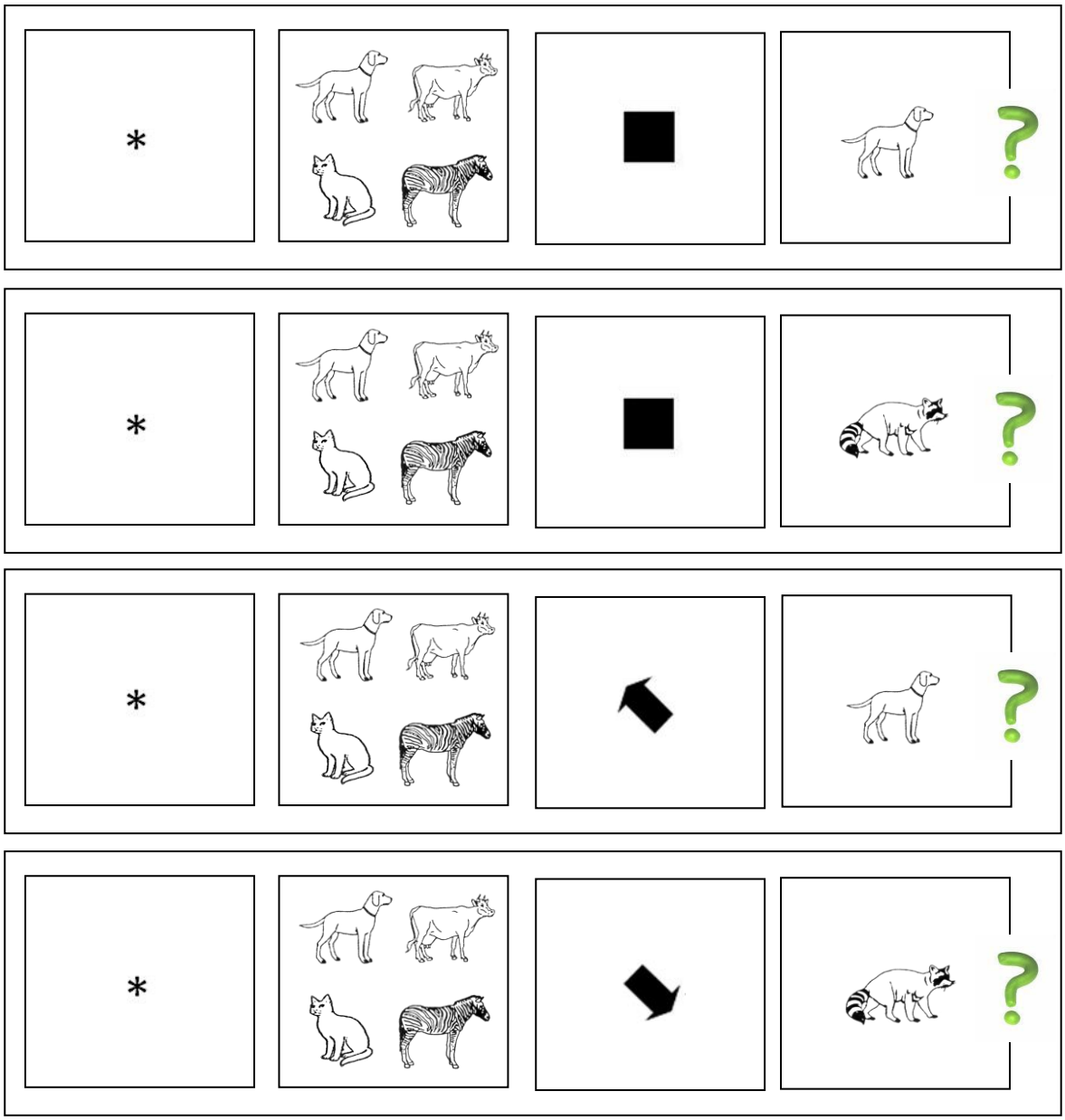
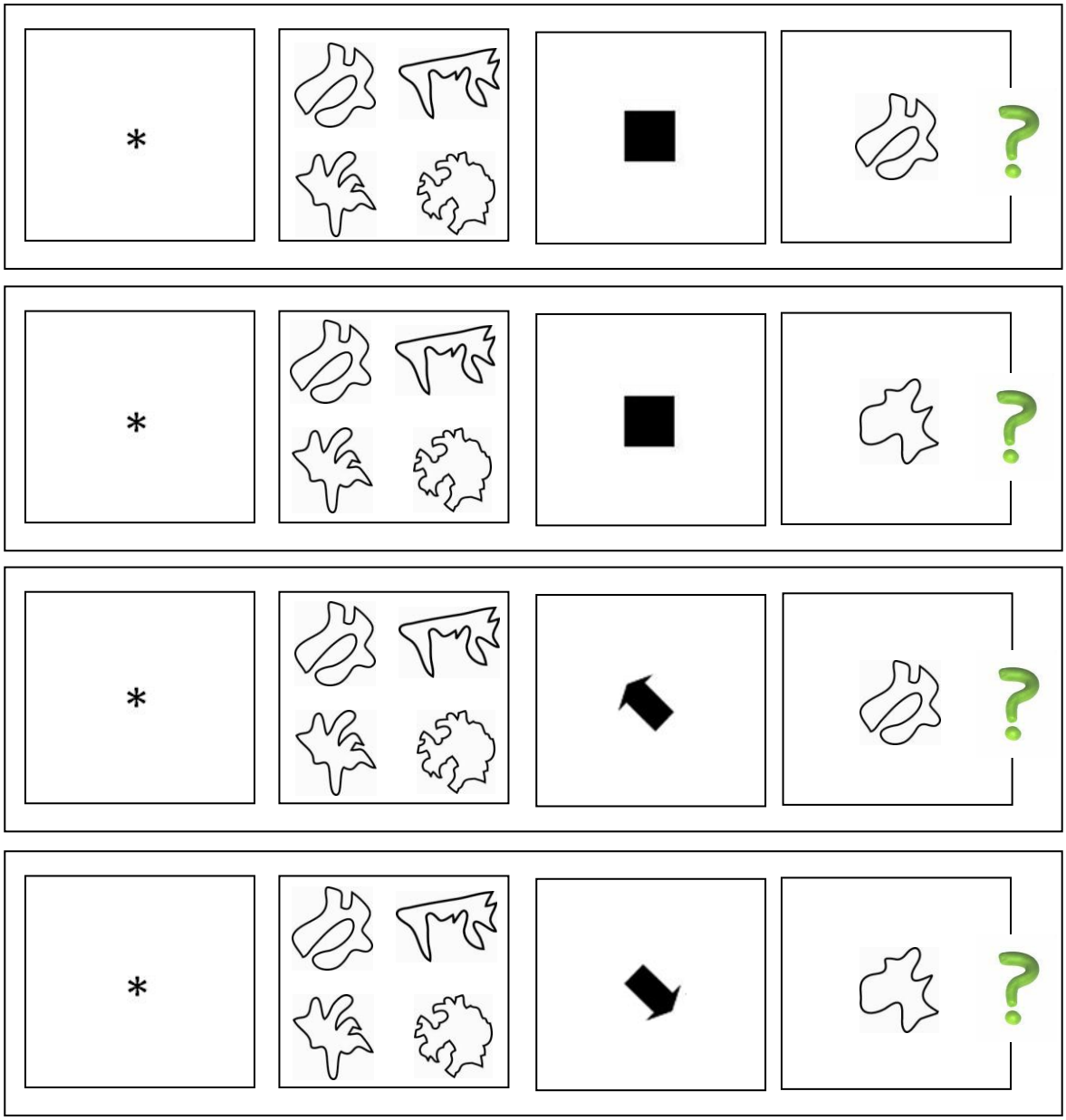


Figure B6. Illustrations of the example cards for Experiment 5



APPENDIX C: Experiments 1B and 1C, Chapter 2

Participants

Nineteen children (10 boys and 9 girls) aged 10 and 11 years old (M=10.58 years old, SD=.61; "11-year-olds" henceforth) and 17 adults (5 males and 12 females) aged 20 to 35 years old (M=24.47, SD=3.47; "adults" henceforth) participated in Experiment 1B. Adults were recruited from the Experimental Psychology Lab (EPL) at the University of Cyprus. Twenty-four children (10 boys and 14 girls) aged 6 and 7 years old (M=6.58 years old, SD=.50; "7-year-olds" henceforth) participated in Experiment 1C.

Measures

Attentional Orienting Task: A general description of the Attentional Orienting Task is provided in the Measures section of Experiment 1 (Chapter 2). Experiments 1B and 1C examined the effects of a peripheral cue on VSTM, as in the peripheral-cue group in Experiment 1 (Chapter 2). The task was identical to the task administered to the peripheral-cue group in Experiment 1 (Chapter 2) except in two respects: First, in contrast to the peripheral-cue group in Experiment 1 in which the peripheral cue was a white border, in Experiments 1B and 1C, the peripheral cue was a white star. As in Experiment 1, the cue was presented at the location that was subsequently or previously occupied by one of the items in the memory array. The neutral cue (i.e., a white square) was presented centrally. Second, participants in Experiment 1B (i.e., 11-year-olds and adults) were presented with four items in the

memory array while participants in Experiment 1C (i.e., 7-year-olds) were presented with two items in the memory array.

Procedure

All parameters were the same with those of Experiment 1 except for the following differences. Adult participants were tested in the EPL at the University of Cyprus. Participants carried out only the Attentional Orienting Task and were given the same instructions as those in the peripheral-cue group in Experiment 1, except that they would be given a white star as a cue, which would sometimes mark the coloured picture out of the two or four (depending on the age group) that could re-appear next. Participants were told that either 2 or 4 (depending on the age group of the participant) identical pictures of different colours would first appear on the screen and after a little while, another coloured picture would appear. Their job was to search their memory and decide whether that last coloured picture was one of the two / four initial ones by pressing the mouse buttons. Illustrations of the example cards are presented at the end of Appendix C, Figures C1 and C2 for Experiments 1B and 1C respectively. The whole task was completed in approximately 35 minutes. All children received stickers as rewards for the completion of the AOT blocks and a certificate of participation at the end of the testing whereas adults participated voluntarily.

Statistical design and analyses

In Experiment 1B, 2 (block: pre-cue, retro-cue) x 2 (trial-type: cued, neutral) x 2 (age-group: 11-year olds, adults) mixed-design ANOVAs were performed on d-

prime and median RT scores. For Experiment 1C the design was fully within-subjects with the block (pre-cue, retro-cue) and the trial-type (cued, neutral) as the independent variables. Significant findings were subsequently followed by pair-wise comparisons using the Bonferroni adjustment. Difference scores were also calculated to assess the size of cueing effects in accuracy and latency.

Results

Experiment 1B

D-prime

The analysis on d-prime scores yielded main effects of block [$F(1,34)=12.35$, $p=.001$, $\eta^2=.27$], trial-type [$F(1,34)=26.47$, $p<.001$, $\eta^2=.44$], and a significant block x trial-type interaction [$F(1,34)=20.98$, $p<.001$, $\eta^2=.38$]. The interaction was driven by better discrimination for cued trials (M=3.31) than neutral trials (M=1.65, $p<.001$) in pre-cue block, but not in the retro-cue block (M=1.95 and M=1.68 respectively, $p=.12$) and better detection following cues in the pre-cue block (M=1.66) than in the retro-cue block (M=.27, $p<.001$). None of the other effects reached significance [highest $F(1,34)=3.17$, $p=.08$, $\eta^2=.09$ for age-group]. Cue benefits are reported in Figure 32.

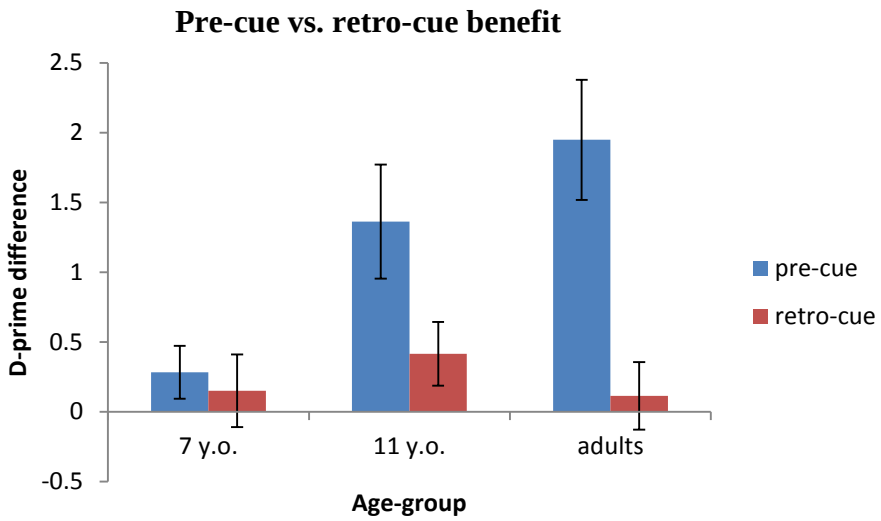


Figure 32. D-prime difference scores from neutral baseline, comparing pre-cue and retro-cue blocks. Error bars represent standard errors of the mean. Adults and 11-year-olds were tested with 4 items in the memory array whereas 7-year-olds were tested with 2 items in the memory array.

Reaction Times

The ANOVA on the RT revealed main effects for block [$F(1,34)=6.84$, $p=.01$, $\eta^2=.70$], driven by faster responses for pre-cue than retro-cue trials, for trial-type [$F(1,34)=41.58$, $p<.001$, $\eta^2=.55$], driven by faster responses for cued ($M=706.04$) than neutral trials ($M= 943.32$, $p<.001$), and for age-group [$F(1,34)=5.75$, $p=.02$, $\eta^2=.15$]. There was also a block x age-group interaction [$F(1,34)= 3.81$, $p=.05$, $\eta^2=.10$]. Simple main effects revealed that adults were faster than 11-year-olds in both the pre-cue ($M = 723.49$ and $M = 860.51$, $p <.001$) and the retro-cue block ($M= 740.09$ and $M=974.65$, $p<.001$). Also, 11-year-olds were faster in the pre-cue block than in the retro-cue block ($p=.002$). None of the other effects were significant ($Fs<1$). Cue benefits are reported in Figure 33.

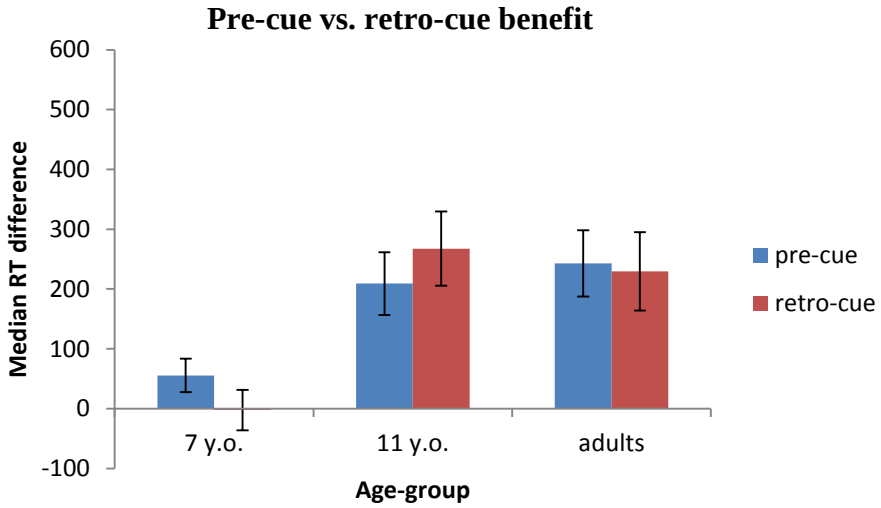


Figure 33. Median RT difference scores from neutral baseline, comparing pre-cue and retro-cue blocks. Error bars represent standard errors of the mean. Adults and 11-year-olds were tested with 4 items in the memory array whereas 7-year-olds were tested with 2 items in the memory array.

Experiment 1C

D-prime and Reaction Times

Results of the ANOVA on the d-prime scores revealed that probe-presence discrimination scores were higher in the retro-cue block (M = 2.56) than in the pre-cue block (M=2.16), as corroborated by the significant main effect of block [$F(1,23)=5.48$, $p<.05$, $\eta^2=.19$]. There were no statistically significant main or interaction effects on RT. Cue benefits for d-prime and median RTs are reported in Figure 32 and Figure 33 respectively.

Figure C1. Instructions for Experiment 1B, 4-item task

Pinky and the Brain game



This is a memory game! It is easy and fun.

What is the game about?

Meet Pinky and the Brain. Pinky is a very forgetful mouse, whereas the Brain is a very clever mouse. You will be helping Pinky remember colours. Every time, you will see four identical pictures of different colours: for example, you might see four differently coloured dogs. After a little while, another coloured dog will appear. Your task will always be to search your memory and decide *whether that last coloured dog was one of the four initial ones*: if it was, press the left mouse button (marked with "***yellow smiley face***"). If instead *the last dog was of a colour that was not one of the four initial dogs*, press the right button of the mouse (marked with *"**red smiley face***"). Spot old and new colours as well as you can: the more correct answers, the more points you'll win!

Sometimes, the Brain will give you a cue to help you do well. *The cue is a white asterisk and it will always mark the coloured dog out of the four that might re-appear next, so pay attention to it!* However, be careful! An asterisk does not mean that the coloured dog was definitely there: every now and again, an asterisk appears but the dog was not one of the initial four. Sometimes, the asterisk will appear before the four pictures, sometimes afterwards, but don't be confused by this – the Brain will tell you when the *helpful cues* will appear. When no asterisk appears, you will just see a white square in its place.

Remember, with either asterisks or squares your task is to remember whether the last coloured picture was one of the initial four or not. Asterisks are there to help you, so pay attention to them!

Before we start playing the game we will do some examples so that you understand the game well and win many points!

Figure C1. Illustrations of the example cards for Experiment 1B, 4-item task

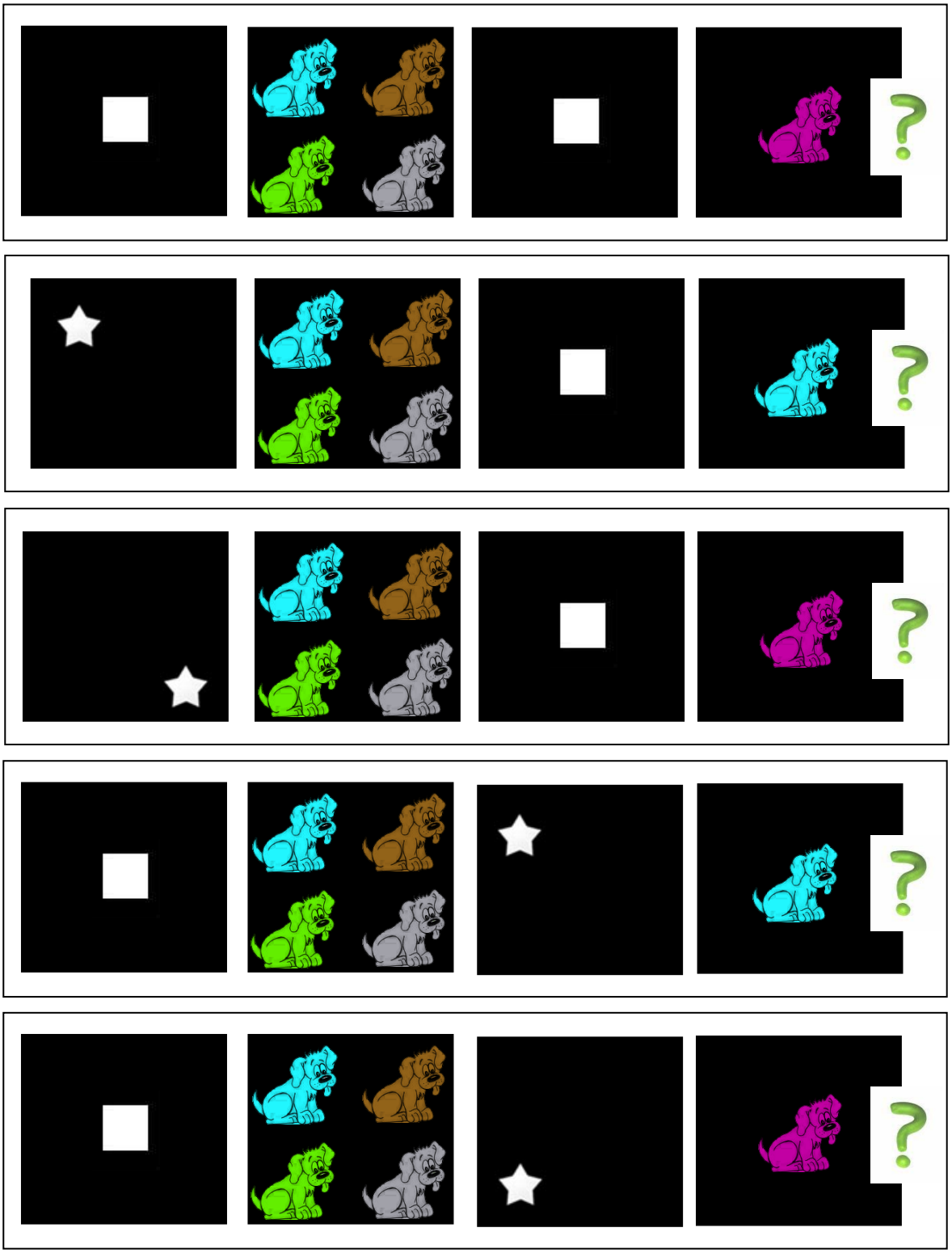


Figure C2. Instructions for Experiment 1C, 2-item task

Pinky and the Brain game



This is a memory game! It is easy and fun.

What is the game about?

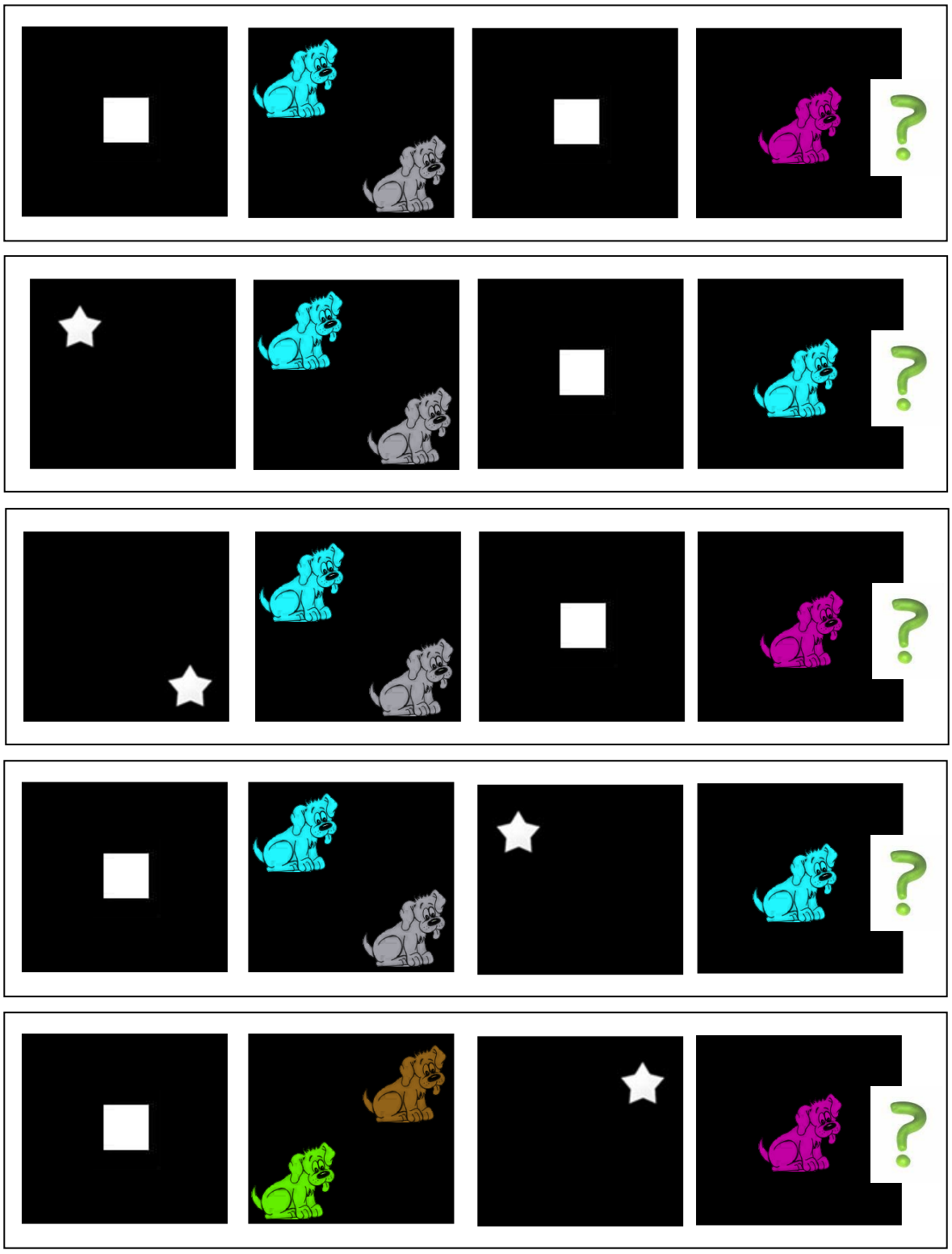
Meet Pinky and the Brain. Pinky is a very forgetful mouse, whereas the Brain is a very clever mouse. You will be helping Pinky remember colours. Every time, you will see two identical pictures of different colours: for example, you might see two differently coloured dogs. After a little while, another coloured dog will appear. Your task will always be to search your memory and decide *whether that last coloured dog was one of the two initial ones*: if it was, press the left mouse button (marked with "***yellow smiley face***"). If instead *the last dog was of a colour that was not one of the four initial dogs*, press the right button of the mouse (marked with *"**red smiley face***"). Spot old and new colours as well as you can: the more correct answers, the more points you'll win!

Sometimes, the Brain will give you a cue to help you do well. *The cue is a white asterisk and it will always mark the coloured dog out of the two that might re-appear next, so pay attention to it!* However, be careful! An asterisk does not mean that the coloured dog was definitely there: every now and again, an asterisk appears but the dog was not one of the initial two. Sometimes, the asterisk will appear before the two pictures, sometimes afterwards, but don't be confused by this – the Brain will tell you when the *helpful cues* will appear. When no asterisk appears, you will just see a white square in its place.

Remember, with either asterisks or squares your task is to remember whether the last coloured picture was one of the initial two or not. Asterisks are there to help you, so pay attention to them!

Before we start playing the game we will do some examples so that you understand the game well and win many points!

Figure C2. Illustrations of the example cards for Experiment 1C, 2-item task



APPENDIX D: Developmental differences between age groups, Experiment 6, Chapter 7

Behavioural results

Mean d-prime, *K*, and median RTs are reported in Table 24. D-prime and *K* analyses showed significant main effects of block [$F(1,29)=21.40$, $p<.001$, $\eta^2=.43$ and $F(1,29)=7.51$, $p=.01$, $\eta^2=.21$ for d-prime and *K* respectively], trial-type [$F(1,29)=127.89$, $p<.001$, $\eta^2=.82$ and $F(1,29)=79.94$, $p<.001$, $\eta^2=.72$ for d-prime and *K* respectively], and age-group [$F(1,29)=24.49$, $p<.001$, $\eta^2=.46$ and $F(1,29)=20.40$, $p<.001$, $\eta^2=.41$ for d-prime and *K* respectively], and a significant interaction of block x trial-type [$F(1,29)=54.51$, $p<.001$, $\eta^2=.65$ and $F(1,29)=37.41$, $p<.001$, $\eta^2=.56$ for d-prime and *K* respectively]. In addition, the *K* analysis showed interaction effects of block x age-group [$F(1,29)=57.49$, $p=.026$, $\eta^2=.16$] and block x trial-type x age-group [$F(1,29)=7.91$, $p=.009$, $\eta^2=.21$]. Results for the main effects of block and trial-type and the block x trial-type interaction were in agreement with the results reported in each age-group separately. Thus, for brevity only the block x trial-type x age-group interaction effect in *K* will be reported. Analyses of simple main effects showed that adults performed better than children in both cued and neutral trials in both pre-cue and retro-cue blocks ($p<.05$), and that both age-groups performed better in cued than in neutral trials in both blocks ($p<.01$). The interaction was driven by the children performing significantly better in cued trials of the pre-cue block than of the retro-cue block ($p<.001$) while adults performed equally well across the two blocks ($p>.05$). Both age-groups performed equally in neutral trials across the two blocks ($p>.05$). These results were supported by a difference score analysis that revealed a

significant main effect of block-benefit [$F(1,29)=37.41$, $p<.001$, $\eta^2=.56$], and a significant interaction of age-group x block-benefit [$F(1,29)=7.91$, $p=.009$, $\eta^2=.21$]. Simple main effects for the age-group x block-benefit interaction showed that both age-groups benefited more from pre-cues compared to retro-cues (M=1.54 and M=.61 respectively, $p<.001$ for children and M=1.17 and M=.83 respectively, $p=.03$ for adults) whereas no differences in benefits were found between the two age-groups. This was corroborated by the absence of an age-group main effect [$F(1,29)=.11$, $p=.74$, $\eta^2=.004$].

The analysis on median RT scores showed significant main effects of age-group, [$F(1,29)=39.51$, $p<.001$, $\eta^2=.58$], block [$F(1,29)=5.91$, $p=.02$, $\eta^2=.17$], and trial-type [$F(1,29)=53.15$, $p<.001$, $\eta^2=.65$], as well as significant interactions of age-group x block, [$F(1,29)=9.87$, $p=.004$, $\eta^2=.25$] and age-group x trial-type [$F(1,29)=7.10$, $p=.01$, $\eta^2=.20$]. Analyses of simple main effects for the age-group x block interaction showed that adults (M=642.18 and M=631.48 for pre- and retro-cue respectively) were faster than children (M=1027.53 and M=1111.43 for pre- and retro-cue respectively) in both blocks ($p<.001$ in both instances). The interaction was driven by children performing faster in the pre-cue than in the retro-cue block ($p<.001$), whereas adults did not differ in latency across the two blocks ($p>.05$). In addition, simple main effects for the age-group x trial-type interaction showed that adults (M=548.41 and M=725.25 for cued and neutral trials respectively) performed faster than children (M=879.19 and M=1259.77 for cued and neutral trials respectively) in both cued ($p<.001$) and neutral trials ($p<.001$), and both age-groups performed faster in cued than in neutral trials ($p<.001$ for children and $p=.004$ for adults). A subsequent difference score analysis was carried out to explore the

interaction independently of baseline differences on neutral trials. The analysis on block-benefits showed only a significant main effect of age-group [$F(1,29)= 7.10$, $p=.01$, $\eta^2=.20$], indicating overall greater benefits in children (M=380.57) compared to adults (M=176.84). However, when overall slowing was taken into account by treating RT differences as proportions of neutral RTs [(neutral-cued)/neutral], the main effect of age-group on scaled block-benefits did not remain significant ($p>.05$), suggesting that the large RT benefits depended on overall slowing in baseline responses by the children. Finally, the interactions of block x trial-type and age-group x block x trial-type did not reach significance ($p>.05$ in both instances).

Table 24. *D-prime, K, and RT scores for pre-cue, retro-cue, and neutral trials for 10-year-olds and adults. Standard deviations are reported in parentheses.*

	Pre-cue block		Retro-cue block	
	Cued	Neutral	Cued	Neutral
D-prime				
10-year-olds	3.11 (1.34)	1.14 (0.60)	1.79 (1.09)	1.19 (0.73)
Adults	4.22 (0.48)	2.10 (0.74)	3.50 (0.47)	2.26 (0.78)
K				
10-year-olds	3.10 (1.09)	1.56 (0.77)	2.25 (1.11)	1.63 (0.90)
Adults	3.83 (0.13)	2.66 (0.62)	3.62 (0.19)	2.80 (0.66)
RT (ms)				
10-year-olds	838.71 (223.30)	1216.35 (274.62)	919.68 (288.51)	1303.18 (318.06)
Adults	557.36 (135.01)	727.00 (146.26)	539.46 (144.84)	723.50 (147.02)

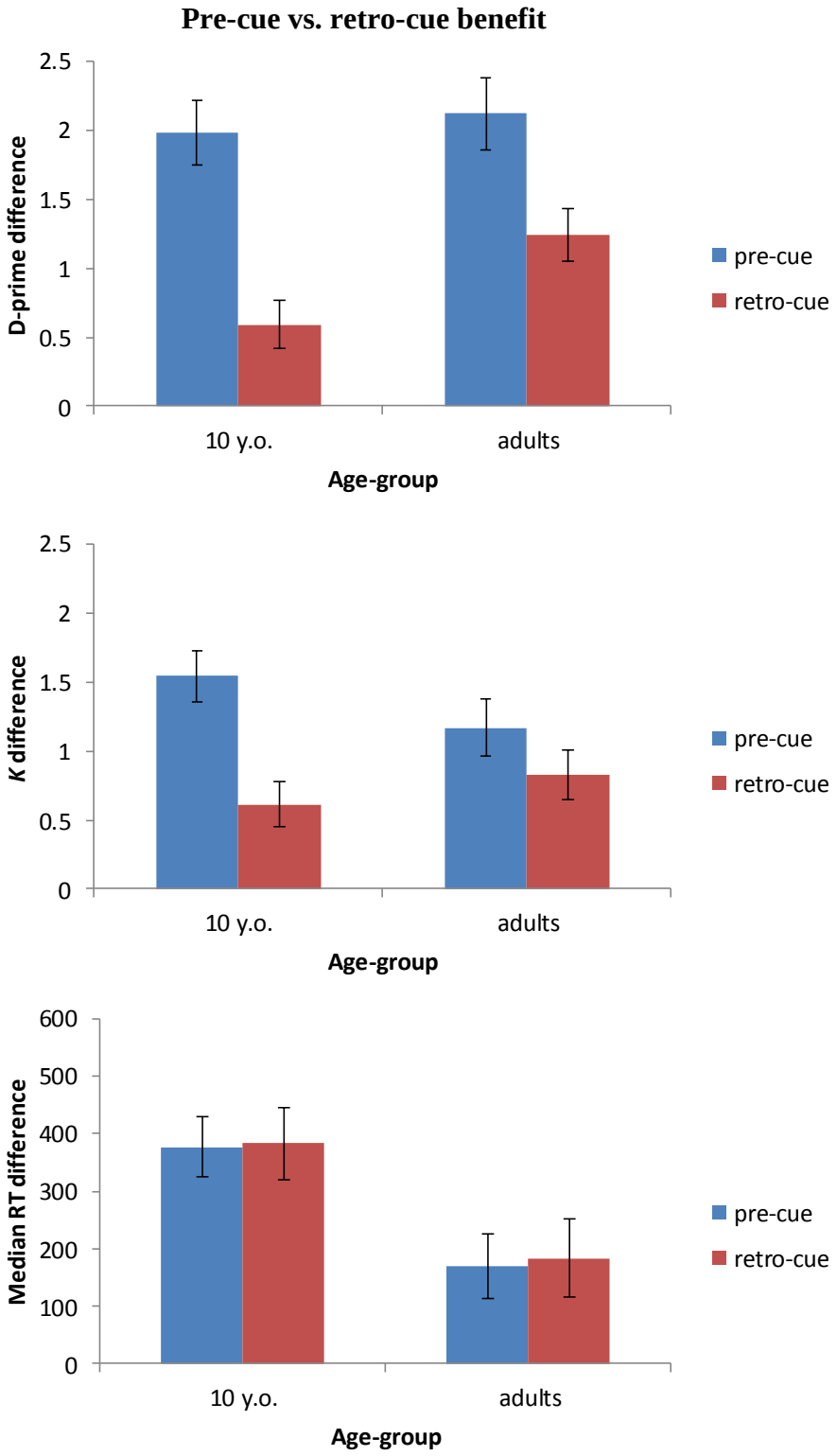


Figure 34. D-prime, *K*, and median RT difference scores from neutral baseline, comparing pre-cue and retro-cue blocks for 10-year-olds and adults. Error bars represent standard errors of the mean.