Towards an integrative model of visual short-term memory maintenance: evidence from the effects of attentional control, load, decay, and their interactions in childhood

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Abstract

Over the past decades there has been a surge of research aiming to shed light on the nature of capacity limits to visual short-term memory (VSTM). However, an integrative account of this evidence is currently missing. We argue that investigating parameters constraining VSTM in childhood suggests a novel integrative model of VSTM maintenance, and that this in turn informs mechanisms of VSTM maintenance in adulthood. Over 3 experiments with 7-year-olds and young adults (total N = 145), we provide evidence for multiple cognitive processes interacting to constrain VSTM performance. While age-related increases in storage capacity are undisputable, we replicate the finding that attentional processes control what information will be encoded and maintained in VSTM in the face of increased competition. Therefore, a central process to the current model is attentional refreshment, a mechanism that it is thought to reactivate and strengthen the signal of the visual representations. Critically, here we also show that attentional influences on VSTM are further constrained by additional factors, traditionally studied to the exclusion of each other, such as memory load and temporal decay. We propose that these processes work synergistically in an elegant manner to capture the adult-end state, whereas their less refined efficiency and modulations in childhood account for the smaller VSTM capacity that 7-year-olds demonstrate compared to older individuals. We conclude that going beyond the investigation of single cognitive mechanisms, to their interactions, holds the promise to understand both developing and fully developed maintenance in VSTM.

Keywords: visual short-term memory capacity; attentional control; memory load; temporal decay; integrative model

1.1. Introduction

Visual short-term memory (VSTM)[1] is a limited-resource system that allows the on-line storage and temporary maintenance of visual information, so that other cognitive processes can access and operate on it. Therefore, VSTM is vital to a broad range of cognitive abilities, e.g., it is correlated with fluid intelligence (e.g., Ackerman, Beier, & Boyle, 2002; Burgess, Gray, Conway, & Braver, 2011; Conway, Kane, & Engle, 2003; Cowan, Fristoe, Elliott, Brunner, & Saults, 2006; Engel de Abreu, Conway, & Gathercole, 2010; Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004; Kane, Hambrick, & Conway, 2005) and it is 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). Given its significance, a central topic of investigation across the cognitive sciences, for almost half a century now, has been the nature of VSTM, its core capacity limits, and its underlying neurocognitive mechanisms, although early conceptions date back to the 19th century (e.g., Williams, 1890).

An extensive and yet growing research body with adult and child populations has resulted in multiple accounts for memory maintenance and its constraints. These accounts range from pure storage capacity limitations (Cowan, 2001; Luck & Vogel, 1997) to decay (Barrouillet, Bernardin, & Camos, 2004; Burgess & Hitch, 1999; Ricker & Cowan, 2014; Towse, Hitch, & Hutton, 2000) and interference (Lewandowsky, Duncan, & Brown, 2004; Lewandowsky & Oberauer, 2009; Oberauer & Lewandowsky, 2008), both in the context of verbal short-term

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[1] With VSTM we refer to the capacity of individuals to maintain a small amount of information in mind for a short-term period. We note that in the literature this term has been used interchangeably with visual working memory (VWM, e.g., Cowan, 2001), even though the latter has specific connotations associated with dual processing tasks (e.g., Logie, 2011). However, to highlight that we do not use dual processing requirements here, and for consistency with our previous work, we use the former term, VSTM, throughout.

memory and VSTM. A noteworthy advancement in adult cognitive science is the recent emphasis on interactions between VSTM and selective attention (Awh, Vogel, & Oh, 2006; Chun & Turk-Browne, 2007; Chun, 2011; Gazzaley & Nobre, 2012; Gazzaley, 2011; Nobre & Stokes, 2011; Postle, 2006; Stokes & Nobre, 2011), in an attempt to shed light on the nature and flexibility of VSTM. The contribution of selective attention has also started to gain ground in understanding development (as detailed in section 1.4), but it remains debated (e.g., Cowan, Morey, AuBuchon, Zwilling, & Gilchrist, 2010) and has been treated mainly in isolation from other potential constraining mechanisms (e.g., Shimi, Nobre, Astle, & Scerif, 2014). This focus on isolated cognitive mechanisms is not warranted by the wealth of knowledge emerging from the field of developmental cognitive neuroscience: during development, improvement across multiple cognitive processes is associated with enhanced connectivity across networks (Fair et al., 2007; Solé-Padullés et al., 2016). Thus, it is theoretically counterproductive to attribute VSTM maintenance to a single mechanism without ruling out the contribution of other mechanisms through careful experimental control.

In the present study, we draw on both the adult and child literatures to integrate currently disparate accounts of VSTM maintenance. This attempt, we believe, highlights new directions that elucidate the nature of VSTM, its close interplay with attentional control from childhood, and most importantly the dynamic interplay of multiple non-mutually exclusive constraints on VSTM, in both the adult and child systems. We begin by overviewing the most influential models of WM, followed by a review of the current knowledge on the contribution of attentional control to VSTM for both the fully developed and developing systems. We then present three experiments with 7-year-olds and young adults investigating the effects of memory load and temporal decay on the interaction between attentional control and VSTM. We finally propose an integrative model, to offer a mechanistic description of the means by which attentional processes influence VSTM, and how these are further constrained by additional factors.

1.2. Theoretical models of short-term/working memory

VSTM is restricted in its capacity, i.e., recognised as a magic number 7 when studied with sequentially presented material (Miller, 1956) or limited to 4 items when studied with simultaneously presented materials (Cowan, 2001). Fundamental to preserving an efficient storage for adaptive behaviour have been the regulatory mechanisms gating access and keeping active in mind the information that is most relevant to current goals. A central role of attention is to select the information that is task-relevant and inhibit all else. Therefore, theoretical models of short- and working-memory (STM / WM) stipulate that attention controls the encoding of information into STM and its manipulation during maintenance in the form of executive processes (Baddeley & Hitch, 1974; Baddeley, 2002b, 2003; Cowan, 1999, 2005; Engle et al., 1999; Kane, Bleckley, Conway, & Engle, 2001; Kane et al., 2004). Specifically, the two most influential models of 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 a domain-general system, known as the *central executive*. This is an attentional system that regulates and acts upon two domain-specific systems, the *phonological loop* and the *visuo-spatial sketchpad*, that are specialised for the short-term storage of phonological and visual/spatial information respectively. The central executive is also responsible for co-ordinating the flow of information between the domain-specific systems and their communication with long-term memory (LTM) via the *episodic buffer* (Baddeley, 2000), a temporary storage system that is responsible for binding information originating from the two domain-specific systems and integrating them into chunks (Allen, Baddeley, & Hitch, 2006; Baddeley, Allen, & Hitch, 2011). Furthermore, the central executive is responsible for implementing a number of executive functions operating on the information stored in the domain-specific systems, such as attentional control (i.e., selecting incoming information), attentional focusing, attention switching, dual-task performance, and selecting and manipulating information in LTM (Baddeley & Hitch, 1974; Baddeley, 1998; Baddeley, 2002a, 2002b, 2003). Yet, the precise nature of the central executive remains somewhat elusive, as executive processes remain highly intercorrelated, albeit separable (Miyake et al., 2000). Furthermore, the original model does not offer a precise account of how these separable executive processes interact with the domain-specific systems (e.g., the visuo-spatial sketchpad) 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 they 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. 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 the two influential models above offer theoretical descriptions of a WM architecture (multicomponential vs. unitary respectively) and highlight a key role for attention in WM, both models exhibit limitations in providing mechanistic accounts of how attentional processes influence WM in the context of encoding and maintenance. For example, the multicomponential model (e.g., Baddeley & Hitch, 1974) does not detail precisely the encoding processes involved in WM, presumably because these operate on perceptual representations that fall within a cognitive domain that is distinguishable from memory. Nevertheless, this model explains the maintenance processes involved in STM by proposing on the one hand a verbal rehearsal mechanism maintaining the information stored in the phonological loop, and on the other an inner scribe mechanism maintaining the information in the visuo-spatial sketchpad (Logie, 2011; Logie, 1995, 2003). In contrast, the unitary model (e.g., Cowan, 1988) explains encoding in the context of activated features in LTM, but 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, but this process was studied only for verbal and sequentially presented material, leaving unexplored the specific maintenance mechanism responsible for visual and/or simultaneously presented material. Of note, it is essential for a comprehensive model of STM / WM to be able to account precisely for: a) how domain-general processes such as selective attention interact with domain-specific systems, such as storage capacity for verbal and visuo-spatial material; and b) how these factors influence different stages within the information processing stream, i.e., facilitating encoding and supporting maintenance. Understanding maintenance is especially important, because at any given moment our brain is required to resolve the competition arising from both external percepts and/or internal representations (Desimone & Duncan, 1995). Recent studies with both children and adults (see following sections) demonstrate that by understanding developmental similarities and differences in attentional influences on STM / WM, rich information about their dynamic relation emerges, ultimately fostering a better understanding of the basic mechanisms involved in VSTM / VWM.

1.3. Attentional contributions to VSTM in adulthood

It is now well-established that, in the adult system, attention and VSTM are closely intertwined (Chun & Turk-Browne, 2007; Corbetta, Kincade, & Shulman, 2002; Kiyonaga & Egner, 2013; LaBar, Gitelman, Parrish, & Mesulam, 1999; Olivers, 2008; Shimi, Woolrich, Mantini, & Astle, 2015). Nevertheless, it has been suggested that the nature of this relation depends on the specific forms of attention and VSTM processes involved and on the type of representations on which these processes operate (Awh et al., 2006; Chun, Golomb, & Turk-Browne, 2011; Chun & Johnson, 2011). For example, Chun and colleagues (Chun et al., 2011) proposed an organising taxonomy of distinguishable attentional processes operating on externally- vs. internally-focused representations. This distinction seems particularly fruitful in disentangling commonalities and differences in attentional effects, because it can drive hypotheses on how representations are encoded and/or held in VSTM at different time-points within the information processing stream.

An experimental paradigm that is ideally suited to applying this taxonomy to delineate the functional role of attentional control in encoding and maintaining information in VSTM has been the cueing partial-report paradigm, first pioneered in defining iconic memory (Sperling, 1960), and more recently extended to VSTM. In this paradigm, visuo-spatial cues precede ("pre-cues") or follow ("retro-cues") a complex array of items to be encoded into VSTM. Cues direct attention to one item in the memory array and participants are required to judge whether a subsequent probe item is the same as one of the previously presented array items. A wealth of studies adopting this paradigm have shown that visuo-spatial attention influences what information will be encoded and maintained in VSTM, facilitating VSTM performance (Griffin & Nobre, 2003; Kuo, Stokes, & Nobre, 2012; Landman, Spekreijse, & Lamme, 2003; Lepsien, Griffin, Devlin, & Nobre, 2005; Lepsien, Thornton, & Nobre, 2011; Makovski, Sussman, & Jiang, 2008; Matsukura, Cosman, Roper, Vatterott, & Vecera, 2014; Matsukura, Luck, & Vecera, 2007; Matsukura & Hollingworth, 2011; Murray, Nobre, & Stokes, 2011; Schmidt, Vogel, Woodman, & Luck, 2002; Woodman, Vecera, & Luck, 2003). Although these studies established that visuo-spatial attentional cues facilitate VSTM performance, the specific mechanisms through which orienting of spatial attention enhance VSTM performance remain debated. At an early stage in the memory stream, attentional orienting prioritises selected items over others for encoding into VSTM (Schmidt et al., 2002). At a later stage, multiple mechanisms have been proposed to account for the benefits of attentional orienting during maintenance: first, orienting may enhance the active maintenance of relevant items and/or suppresses the activation of irrelevant items (Lepsien & Nobre, 2006, 2007; Rerko & Oberauer, 2013; Souza, Rerko, & Oberauer, 2014b); second, it may 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; Pertzov, Bays, Joseph, & Husain, 2013; Shimi, Nobre, et al., 2014; van Moorselaar, Gunseli, Theeuwes, & Olivers, 2015); third, it may provide 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 the deployment of attention facilitates the maintenance of items in VSTM.

One possibility is that orienting of attention during maintenance functions as a simple process of refreshment of visual imagery. Raye and colleagues have shown that *refreshing* a just activated representation resuscitates, increases or prolongs its representation during maintenance (Raye, Johnson, Mitchell, Greene, & Johnson, 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 memoranda, thereby boosting its representation against the others. Yi, Turk-Browne, Chun, and Johnson (2008) found that directing selective attention in such a fashion modulates perceptual encoding into VSTM, whilst Souza, Rerko, and Oberauer (2014a) found that it improves recall from VSTM. Another possibility is that spatial cues presented during maintenance bias representations held in VSTM in the form of *spatial rehearsal*. Awh and colleagues 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 (Awh, Jonides, & Reuter-Lorenz, 1998; Awh & Jonides, 1998; Awh & Jonides, 2001). Although adult studies alone have failed to locate the precise stage and/or processes through which attention influences VSTM, they have enriched our knowledge with a number of possible accounts that developmentalists can draw on to understand VSTM development. At the same time, as discussed in the next section, by testing the adult framework against changes in attentional constraints on VSTM over childhood, developmental findings hold the powerful complementary promise of informing the adult literature [as first delineated by

Baddeley and Hitch (2000) in the domain of verbal memory], by pinpointing developmental dissociations (Hitch, 1990) in constraints on VSTM encoding and maintenance. For example, as we detail below, developmentally-informed designs allow researchers to investigate whether spatial attentional biases on encoding or maintenance in VSTM emerge at the same time-points in development, or differentiate in their trajectories.

1.4. Attentional contributions to VSTM over development

Developmental changes in VSTM are well documented (Cowan et al., 2005; Gathercole, 1999) and these changes have been attributed to an increase in storage capacity (Cowan, AuBuchon, Gilchrist, Ricker, & Saults, 2011; Cowan, Morey, AuBuchon, Zwilling, & Gilchrist, 2010; Cowan, Ricker, Clark, Hinrichs, & Glass, 2014; Riggs, McTaggart, Simpson, & Freeman, 2006). However, attentional mechanisms also enhance long-term retention of information (Amso & Johnson, 2006; see also Amso & Scerif, 2015 for a review on the neurocognitive mechanisms through which developing attention influences other cognitive processes) and developmental studies have started to examine the contribution of attentional control on changes in VSTM capacity (Blaser & Kaldy, 2010; Cowan et al., 2011; Markant & Amso, 2013, 2014; Olesen, Macoveanu, Tegnér, & Klingberg, 2007; Ross-Sheehy, Oakes, & Luck, 2011; Sander, Werkle-Bergner, & Lindenberger, 2011; Shimi, Nobre, & Scerif, 2015; Wendelken, Baym, Gazzaley, & Bunge, 2011). For example, Cowan, Morey, AuBuchon, Zwilling, and Gilchrist (2010) asked 7-year-olds, 12-year-olds, and adults to perform a simple change-detection task during which attention was directed non-spatially by asking participants to focus on coloured items of particular shapes, within an upcoming to-be-remembered array of variable load sizes, and ignore the coloured items of the other shape. While 7-year-olds had overall poorer capacity compared to

12-year-olds and adults, their performance did not differ from that of older participants when they allocated attention to small arrays. In contrast, with large arrays, younger participants 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. Of note, in that particular experiment attention was biased in a spatially non-specific way over a block of trials (e.g., direct attention to changes in shape over the full array), and a change could occur at any location in the memory array. As age-related differences in VSTM persisted even when allowing for slow encoding, the authors concluded that basic changes in storage capacity, rather than encoding speed or attentional filtering abilities, underpin developmental changes in VSTM capacity (Cowan, AuBuchon, Gilchrist, Ricker, & Saults, 2011). Similarly, children and high capacity adults did not differ in their filtering indices when selection bias depended on globally filtering out distractors of a particular colour (Astle et al., 2014).

However, although highly informative, these studies remain inconclusive about the role of other possible attentional constraints on VSTM in childhood because in these paradigms attention was always oriented to a non-spatial target dimension (e.g., shape) and in a sustained block-wise fashion, prior to encoding the to-be-remembered items. As already noted, the relation between attention and VSTM may depend on the distinguishable forms of attentional processes involved and on the type of representations these operate on (Chun et al., 2011). In these two studies, the distinct contributions of transient (rather than sustained) visuo-spatial (rather than featural) attentional biases to encoding and maintenance in VSTM could not be assessed.

Motivated by the methodological advances in the adult visuo-spatial cueing literature described above, recent findings indicated that, despite poorer overall memory in children, developmental differences in VSTM can be accounted for at least in part by age-related differences in how spatially-selective attentional control biases information, to facilitate later successful memory (Astle, Nobre, & Scerif, 2012; Shimi, Nobre, et al., 2014). By applying a developmental taxonomy of externally- vs. internally-focused representations, Shimi and colleagues showed that, while 7-year-olds benefited from visuo-spatial attention cues presented *prior to encoding* 4 items to the same degree as 11-year-olds and young adults, their ability to use visuo-spatial attention cues *during maintenance* of 4 items was not as efficient as that of older individuals. Furthermore, children's variable cueing benefits during the maintenance period predicted span on traditional VSTM and VWM measures over and above basic differences in capacity in the absence of cues, pointing to how individual differences in visuo-spatial attentional control contribute to VSTM/VWM capacity over development (Shimi, Nobre, et al., 2014). Electrophysiological findings corroborated these developmental differences by showing that children deploy neural pathways underpinning attentional control less efficiently than adults and differentially across the two attentional conditions, i.e., encoding vs. maintenance (Shimi, Kuo, Astle, Nobre, & Scerif, 2014). Thus, both behavioural and electrophysiological data indicated that these two processes in service of VSTM are behaviourally and neurally dissociated. Taken together, these results established that children are less efficient in recruiting visuo-spatial attentional control mechanisms to optimise *maintenance* compared to adults (even though they deploy other attentional filtering mechanisms efficiently, see Astle et al., 2014; Cowan et al., 2010), an important contribution to understanding young children's more limited VSTM capacity compared to older individuals. They also demonstrated that a careful and detailed attentional taxonomy can help us identify the functional role of distinguishable attentional control processes in service of VSTM from 6 years of age. Finally, they demonstrated that the cueing partial-report paradigm is theoretically- and experimentally-sound in studying and understanding the contribution of top-down spatial biases in service of VSTM in both childhood and adulthood.

1.5. Present study

Despite recent evidence of a differential role of attentional control in service of VSTM in childhood compared to adulthood (e.g., Shimi, Nobre, et al., 2014), no study to date has investigated whether visuo-spatial attentional mechanisms interact with other cognitive processes that may hinder or facilitate 7-year-old’s ability to optimise *VSTM maintenance*. Given the significance of VSTM in daily life, it is important to investigate whether multiple non-mutually exclusive processes constrain VSTM.

What possible constraining factors should be considered, then, in addition to attentional biases and hard capacity limits? Cowan et al.'s (2010) results, reviewed in the previous section, already hint to the potential effect of memory load on the effectiveness of attentional filtering, whereas temporal decay has long been part of models of cognitive development (e.g., Case, Kurland, & Goldberg, 1982; Cowan, Nugent, Elliott, & Saults, 2000). Here, we carried out a systematic investigation of the precise cognitive mechanisms and parameters through which visuo-spatial biases operate on VSTM in 7-year-olds and young adults: we began with the effects of memory load on the benefits drawn by visuo-spatial attentional biases, followed by the effects of temporal decay on these same benefits, and finally moved onto manipulating their interactions parametrically. We note here that we focus our experiments on 7-year-olds because, as reported in the previous section, earlier studies have shown that 7-year-olds are less able than adults to orient attention to information during VSTM maintenance, and in particular with four items (whereas 11-year-olds aligned themselves with adults, cf. Shimi, Nobre, et al., 2014; Shimi & Scerif, 2015), and poorer performance cannot be explained by older individuals' verbal recoding/rehearsal strategies (cf. Shimi & Scerif, 2015). Therefore, this age group holds promise as a tool to uncover multiple contributors to maintenance. Furthermore, we include an adult comparison sample for all of our experiments to test the generalizability of our results beyond childhood.

2. Experiment 1: Effects of memory load on attentional biases

Findings from studies with adults strongly advocate the presence of a highly limited VSTM capacity of about 4 items, with VSTM performance declining when the load of visual information exceeds this number (Alvarez & Cavanagh, 2004; Cowan, 2001; Luck & Vogel, 1997; Todd & Marois, 2004; Zhang & Luck, 2011). Furthermore, the effect of increasing load with up to 4 items is attenuated when spatial orienting and selection can take place on representations held internally in VSTM (Kuo et al., 2012; Lepsien et al., 2005; Souza, Rerko, & Oberauer, 2014b). This indicates that attentional biases are critical during the maintenance period for enhancing VSTM performance when the total number of items approaches capacity limits. For example, Nobre, Griffin, and Rao (2008) compared adults' VSTM performance following spatially informative attentional cues during maintenance ("retro-cues" henceforth) 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, when Matsukura, Luck, and Vecera (2007) compared adults' performance for memory arrays with 4 and 6 items, they found larger retro-cue benefits for set size 4 than set size 6 arrays. Together, these results seem to suggest that visuo-spatial attention cues during maintenance attenuate the detrimental effects of increasing memory load when the load of items approaches capacity limits, but when the load exceeds VSTM storage then benefits accrued from these visuo-spatial cues is weakened. Consistent with this suggestion, additional load manipulations with supra-VSTM-capacity arrays demonstrated that young adults cannot always rely on retro-cues to enhance memory recognition. Astle, Summerfield, Griffin, and Nobre (2011, see Experiment 3) presented participants with memory arrays that varied in load (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. Astle et al. also found no cue benefits with 2 items in the array, suggesting that when the load of information to be held in VSTM is low and well within capacity, individuals do not necessarily use the retro-cue to apply an attentional bias[2].

Shimi, Nobre, et al. (2014) 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

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[2] Other adult studies have suggested cueing effects on varying VSTM set sizes (e.g., Souza, Rerko, Lin, & Oberauer, 2014; Williams, Hong, Kang, Carlisle, & Woodman, 2013). However, these studies did not include control conditions with neutral cues as in our study and the study by Astle et al. Thus, direct comparisons with these studies with regards to cueing effects are inappropriate. Also, these studies employed continuous report measures, and work suggests that continuous colour report paradigms place different memory demands than the spatial cueing paradigm (Shimi & Scerif, in preparation), which might explain the differential cueing effects across studies.

developmental differences were clearly evident in participants' ability to use cues presented *during the maintenance* of information, with 7-year-olds demonstrating significantly smaller benefits than older individuals. These differences could not be explained by the symbolic nature of the cues or by the youngest children's inability to voluntarily guide their attention to selectively maintain and/or ignore competing information in VSTM. Building on the adult findings described above, an alternative account for the smaller cueing benefits during maintenance in 7-year-olds compared to the other two age groups is that a memory array of 4 items exceeds young children's capacity limits, resulting simply in fewer items being stored in VSTM compared to the older participants, and therefore less information to be selectively refreshed by retro-cues. Indeed, many developmental studies have documented the smaller storage capacity for younger children (approximately 1.5-3 items) compared to older children and adults (approximately 4-5 items, e.g., Cowan et al., 2005; Riggs, McTaggart, Simpson, & Freeman, 2006), and the diminished attentional filtering abilities for 7-year-olds compared to 12-year-olds and adults when 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 this hypothesis, we presented 7-year-olds and adults with 2 items and compared their performance to that with memory arrays of 4 items.

We hypothesized that if smaller cueing benefits during maintenance for 7-year-olds compared to older individuals depend on less information having been encoded in VSTM, simply because of lower storage capacity (as suggested for non-spatial and sustained attentional filtering biases, e.g., Cowan et al., 2010), then maintenance 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). If, to the converse, visuo-spatial attentional cues maximise encoding and maintenance in

VSTM at the limits of capacity, we would predict greater cueing benefits for 4, compared to 2-item arrays. We employed both visuo-spatial cues prior to encoding (pre-cues) and cues during maintenance (retro-cues) to allow for a direct comparison between these cues and for better understanding how the attentional processes that these cues enable (visuo-spatial attentional orienting prior to encoding in VSTM vs. attentional orienting during maintenance in VSTM) interact with storage capacity in 7-year-olds.

2.1. Method

2.1.1. Participants

Forty-one children (15 boys and 26 girls) between 6 and 7 years old (M=6.56 years old, SD=.50; “7-year-olds” henceforth) and forty-two young adults (16 males and 26 females) between 18 and 34 years old (M=24.48 years old, SD=3.80) participated in Experiment 1. The sample sizes were selected to provide sufficient statistical power to replicate previously demonstrated effects (Cowan et al., 2010, N= 30; Shimi, Nobre, et al., 2014, N=40 for the current target age groups): to achieve power of 0.95 to detect a medium effect size (even taking the lowest calculated effect size from these studies, d=0.50) with a significance level of $\alpha = .05$, the estimated required number of participants was 36. Children were recruited from local primary schools via an opt-in procedure and adults were recruited amongst university undergraduates and postgraduates. All participants were healthy, had normal or corrected-to-normal vision, and no hearing problems were reported by the parents or teachers of the child participants. Participants with neurological/psychiatric disorders were excluded from the study. Prior to testing, ethical approval from the appropriate Research Ethics Board was secured and permission for entry in schools was given by relevant local Educational Boards. Adult participants and parents/guardians of child participants signed informed consent forms and children also verbally assented to participate in the study. Twenty-one children (7 boys and 14 girls) and 22 adults (8 males and 14 females) completed the 2-item task and will be called as the “load-2 group” henceforth. The other twenty children (8 boys and 12 girls) and 20 adults (8 males and 12 females) completed the 4-item task and will be called as the “load-4 group” henceforth.

2.1.2. Apparatus

Attentional Orienting Task: The task is presented schematically in Figures 1A and 1B. In each trial, participants viewed briefly a memory array of either two or four (depending on the specific load group) peripheral coloured items, followed by a single central coloured probe item after a variable delay. Participants were instructed to indicate whether the probe was present in the preceding memory array by pressing a mouse button (left for present and right for absent). Central cues, that were fully informative (100% cue validity) of the location of a target probe should this appear in the memory array, either preceded (“pre-cues” henceforth) or followed (“retro-cues” henceforth) the memory array. In pre-cue trials, an informative spatial cue (a white arrow) preceded the memory array and guided children’s attention to one of the upcoming items of the array, while a spatially uninformative white filled square followed the array. In retro-cue trials, a white square preceded the memory array, while an informative spatial cue followed the array and guided children’s attention internally to the mental representation of one of the already encoded items of the array. The white squares presented at the un-cued time-point within each trial served the purpose of controlling for generic alerting effects that spatial cues may engender. In neutral baseline trials, uninformative white squares preceded and followed the memory array.

Stimuli were presented on a black background with E-Prime 1.2 (Psychological Software Tools, Inc). They comprised identical line drawings of cartoons/objects (e.g., little miss sunshine) presented in different colours, drawn from a set of seven colours: white, red, magenta, orange, yellow, green, and blue. They were symmetrically arranged, each centered at 2.87° lateral and 2.87° azimuthal eccentricity from a central fixation point from a viewing distance of 70cm. If the array consisted of 4 items, these were presented one in each quadrant. If the array consisted of 2 items, these were presented along a diagonal (i.e., top left – bottom right or bottom left – top right). Each item subtended 1.64° x 2.05° of visual angle. The fixation point subtended a visual angle of 0.16°. All cues (white arrows and white filled squares) were centrally presented at the location of the fixation point and subtended 0.82° x 0.82° of visual angle.

The task consisted of 2 practice blocks of 6 trials each. The first practice block was a slower version of the test blocks to ensure that children understood the task, whereas the second practice block employed the timing parameters of the test blocks. Practice blocks were followed by 4 test blocks of 48 trials in each, totalling 192 experimental trials; 128 probe-present (67%) and 64 (33%) probe-absent trials. Half of all trials were cued (equally likely to point to one of the two or four possible locations) and half were neutral. Of the probe-present trials, 32 were pre-cue trials, 32 were retro-cue trials, and 64 were neutral trials. Of the probe-absent trials, 16 were pre-cue trials and 16 were retro-cue trials, in order to ensure that cues did not signal a “present” response, and 32 were neutral trials. The task was split into 2 “pre-cue” blocks, containing pre-cue and neutral trials, and 2 “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 and were counterbalanced across participants. Cued and neutral trials were intermixed randomly within each block.

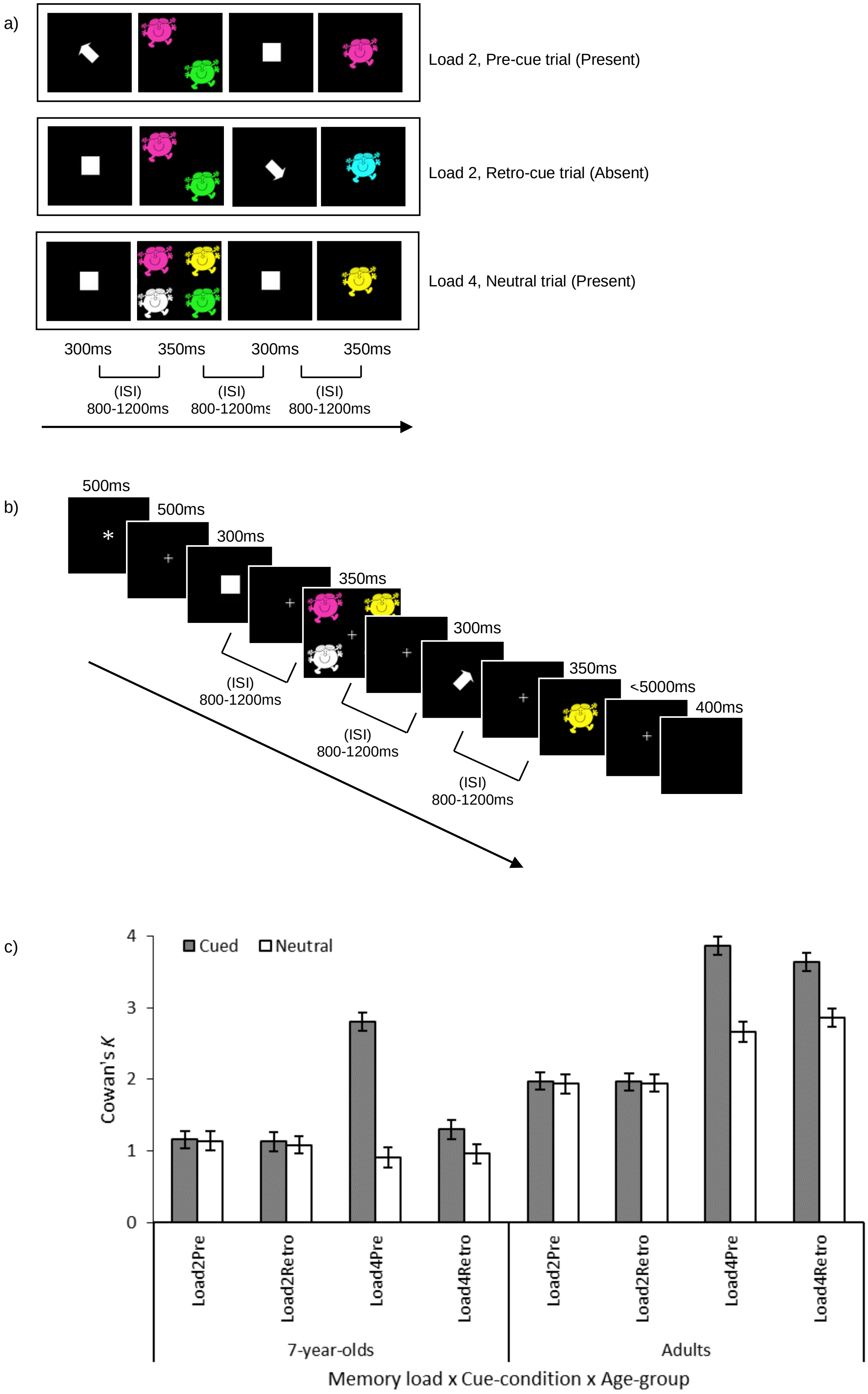
a)
Load 2, Pre-cue trial (Present)
Load 2, Retro-cue trial (Absent)
Load 4, Neutral trial (Present)
300ms
350ms
300ms
350ms
(ISI)
800-1200ms
(ISI)
800-1200ms
(ISI)
800-1200ms
b)
500ms
500ms
300ms
350ms
300ms
350ms
<5000ms
400ms
(ISI)
800-1200ms
(ISI)
800-1200ms
(ISI)
800-1200ms
c)
Cued
Neutral
Cowan's K
0
1
2
3
4
Load2Pre
Load2Retro
Load4Pre
Load4Retro
Load2Pre
Load2Retro
Load4Pre
Load4Retro
7-year-olds
Adults
Memory load x Cue-condition x Age-group

Figure 1: Experiment 1 task and results. a) Schematic illustration of the task, its two memory load conditions (load 2 vs. load 4), and the cue conditions across the trial-types. b) 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 which remained visible throughout the trial. Five hundred ms later, a cue (either a pre-cue or a neutral cue depending on the type of trial) appeared for 300ms. After a randomly varied fixation interval (~1000ms), the memory array with the 2/4 coloured items appeared for 350ms, followed by a randomly varied fixation interval (~1000ms). Depending on the type of trial, participants had to store in memory either only 1 item out of the two/four (pre-cue trials) or all 2/4 items (retro-cue and neutral trials). Subsequently, another cue (either a retro-cue or a neutral cue depending on the type of trial) appeared for 300ms. After a randomly varied fixation interval (~1000ms), 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. c) Cowan's *K* scores for cued and neutral trials, comparing 7-year-olds and adults' performance in pre-cue and retro-cue blocks, for load-2 and load-4 groups. Error bars represent standard errors of the mean.

2.1.3. Procedure

Participants were tested individually in a quiet room within their school or at the university and sat at a comfortable distance from the screen. The examiner explained the characteristics of the different types of trials of the task using examples presented on cards and emphasized that participants should pay attention to the attention cues, when available, as these would help them decide whether the probe was present 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 responded by placing the index finger of each hand on each mouse button while adults responded by holding the mouse in one hand. Participants received verbal feedback from the experimenter and visual feedback (correct, incorrect, no response) while performing the practice trials, in order to ensure that they understood the task. On experimental trials, they received feedback about the number of correct responses every 16 trials and at the end of each block.

2.1.4. Statistical design

Separate mixed-design Analyses of Variance (ANOVAs) were performed on mean Cowan's *K* and d-prime with the "cue-condition" (pre-cue, retro-cue) and the "trial-type" (cued, neutral) as the within-subject variables and the "memory load" (2 items, 4 items) and the age-group as the between-subject variables. Analyses for *K* and d' converged, thus for brevity we report statistics for *K* alone[3]. Cowan's *K* is a memory capacity measure that reflects the number of stored items in memory (Cowan, 2001; Pashler, 1988). Cowan's *K* was calculated using the

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[3] This applies to all the experiments reported in the paper. We opted to present *K* results to aid direct comparisons with the previous findings reported in the literature.

formula: *K* = S (set size of the initial array) × (hit rate – false alarm rate)[4]. Hit rate was defined as the conditional probability that the participants responded probe present when the probe was indeed present and false alarm rate was defined as the conditional probability that the participants responded probe present when in fact the probe was absent. Significant findings were subsequently followed by Bonferroni-corrected analyses of simple main effects.

2.2. Results

Figure 1C presents mean Cowan's *K* scores for the trial-types, the cue-conditions, and the memory loads across the age-groups. The analysis on *K* scores yielded significant main effects of cue-condition [F(1,79)=21.27, p<.001, η^2=.21], trial-type [F(1,79)=90.86, p<.001, η^2=.54], memory load [F(1,79)=66.23, p<.001, η^2=.46] and age-group [F(1,79)=160.34, p<.001, η^2=.67]. In addition, the memory load x cue-condition [F(1,79)=16.59, p<.001, η^2=.17], the memory load x trial-type [F(1,79)=81.28, p<.001, η^2=.51], the cue-condition x trial-type [F(1,79)=54.39, p<.001, η^2=.41], the age-group x memory-load [F(1,79)=20.89, p<.001, η^2=.21], and the age-group x cue-condition [F(1,79)=20.06, p<.001, η^2=.20] interactions reached significance. Similarly, the three-way interactions of memory load x cue-condition x trial-type [F(1,79)=54.91, p<.001, η^2=.41], age-group x memory-load x cue-condition [F(1,79)=15.77,

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[4] In a highly influential follow up to the original formula for *K*, Cowan and colleagues suggest different models for calculating *K* based on the position of the probe in the task (Cowan, Blume, & Saults, 2013). Following these recommendations would mean that one would apply the Reverse-Pashler formula (Model 2) to calculate *K* in neutral trials and the Cowan formula (Model 3) to calculate *K* in cued trials. Applying two different models to calculate *K* is statistically problematic for comparing cued and neutral trials within the same paradigm because the two models result in different ranges of values, with the Reverse-Pashler model returning larger capacity estimates; this eliminates true performance differences between cued and neutral trials, not because these do not exist, but rather because the two formulas cancel each other out. Given that Cowan and colleagues proposed these alternative models on the assumption that the resulting formula would be applied to all conditions within a paradigm and to be in line with the *K* formula used in all other published studies using the current paradigm (Astle et al., 2011; Kuo et al., 2012; Shimi, Nobre, et al., 2014; Shimi & Scerif, 2015), we applied Cowan's *K* formula to all our conditions. Of note, applying the two different formulae to cued and neutral trials would affect both the 2- and the 4-item conditions, therefore not undermining the differences we report here across levels of load. Furthermore, we note that employing the Reverse-Pashler formula in a new statistical analysis yielded the same results with those reported here employing Cowan's *K* formula.

$p<.001$, $\eta^2=.17$], and age-group x cue-condition x trial-type [$F(1,79)=16.26$, $p<.001$, $\eta^2=.17$] were significant. Importantly, the highest-order four-way interaction of age-group x memory load x cue-condition x trial-type [$F(1,79)=18.95$, $p<.001$, $\eta^2=.19$] was also significant.

Analyses of simple main effects for the four-way interaction revealed that adults had higher *K* scores than 7-year-olds across all conditions (ps<.001). Furthermore, with *4 items* in the array, all participants had higher *K* scores in cued than in neutral trials, both in pre-cue ($p<.001$ for 7-year-olds and adults) and retro-cue ($p=.01$ for 7-year-olds and $p<.001$ for adults) conditions, whereas with *2 items* in the array, participants had equal *K* scores for cued and neutral trials, both in pre-cue ($p=.88$ for 7-year-olds and $p=.79$ for adults) and retro-cue ($p=.73$ for 7-year-olds and $p=.90$ for adults) conditions, indicating the presence of benefits from pre-cues and retro-cues with 4 items, but not with 2 items in the array for both 7-year-olds and adults. Furthermore, with *4 items* in the array, all participants had higher *K* scores in the pre-cue condition than in the retro-cue condition in cued trials ($p<.001$ for 7-year-olds and $p=.05$ for adults), but not in neutral trials ($p=.69$ for 7-year-olds and $p=.06$ for adults), whereas with *2 items* in the array, participants had equal *K* scores across conditions both in cued ($p=.77$ for 7-year-olds and $p=.92$ for adults) and neutral trials ($p=.59$ for 7-year-olds and $p=.94$ for adults), 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 for all participants. Finally, in *cued trials of the pre-cue condition,* 7-year-olds had higher *K* scores with 4 items than with 2 items in the array ($p<.001$). In contrast, their *K* scores were equal between 4 items and 2 items in the array in *cued trials of the retro-cue condition* ($p=.36$) and in *neutral trials* of both pre-cue ($p=.25$) and retro-cue conditions ($p=.49$). Conversely, adults had higher *K* scores with 4 items compared with 2 items in the array across all conditions (p<.001). Table 1 (Appendix) presents *K* and d-prime mean scores for all cells[5].

In order to test cueing benefits in storage capacity independently of baseline differences in memory in neutral trials, difference scores were also calculated as the difference between cued and neutral trials. The analysis on difference scores yielded main effects of memory load [F(1,79)=81.28, p<.001, η^2=.51] and cue-benefit [F(1,79)=54.39, p<.001, η^2=.41], as well as significant interactions of memory load x cue-benefit [F(1,99)=54.91, p<.001, η^2=.41], age-group x cue-benefit [F(1,79)=16.26, p<.001, η^2=.17], and age-group x memory-load x cue-benefit [F(1,79)=18.95, p<.001, η^2=.19]. Simple main effects for the three-way interaction indicated greater *pre-cue benefits* in arrays with 4 items (M=1.89 for 7-year-olds and M=1.20 for adults) than with 2 items (M=.02, p<.001 for 7-year-olds and M=.04, p=.002 for adults) and, with *4 items* in the array, greater pre-cue than retro-cue (M=.34, p<.001) benefits. Importantly, there were differential cueing benefits between 7-year-olds and adults when the cues were presented in advance of encoding and during maintenance with *4 items* in the array (p=.001 for pre-cue and p=.02 for retro-cue) but not with 2 items in the array (p=.94 for pre-cues and p=.88 for retro-cues), suggesting 7-year-olds' difficulty in benefitting from cues during maintenance when the load was high.

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[5] We note that in the literature seven year-olds' *K* has been reported to be slightly higher than what we have found consistently across our experiments here. One reason for this discrepancy could be that earlier studies used the Pashler's formula to calculate *K* for full test arrays which yields slightly larger estimates than Cowan's formula (e.g., Riggs et al., 2006). Studies that used Cowan's formula reported the same capacity (~1.5 items) for 7-year-olds (e.g., Cowan et al., 2010) with what we found. To provide readers with an overall estimate of 7-year-olds accuracy performance, which we take into account when we interpret our results, we also present d-prime scores (Appendix). Similar discrepancies in *K* have also been reported in adult studies using lateralised vs. central memory arrays [cf. Emrich, Al-Aidroos, Pratt, & Ferber (2009)].

2.3. Discussion

Experiment 1 demonstrated that attentional biases in 7-year-olds, both prior to encoding and during maintenance, depend heavily on the number of items that young children are required to encode and maintain in VSTM, supporting the hypothesis that memory load modulates attentional cueing benefits. However, results were at odds with what was predicted according to a model that suggests a simple increase in storage capacity is the sole constraint to VSTM capacity. Children performed equally well for cued and neutral trials in terms of accuracy when the memory load was well within capacity limits and they demonstrated no reliable benefits from cues presented either prior to encoding or during maintenance of memory arrays with 2 items (consistent with, e.g., Cowan et al., 2010). In contrast, differences across cued and neutral trials were clearly evidenced when memory load was high (4 items), suggesting that, as a whole, transient but informative spatial attention cues facilitate VSTM when memory demands are high, a finding that was also evidenced in our adult sample and it is consistent with those reported for adults in other studies (e.g., Astle et al., 2011).

Of note, these benefits were largest following cues presented prior to encoding of visual information. These attentional benefits in function of encoding accentuated as memory load increased from 2 items to 4 items and attenuated the deleterious effects of increasing load. This result suggests that young children successfully recruit visuo-spatial 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. These robust attentional benefits on encoding are also consistent with the absence of developmental differences between 7-, 11-year-olds, and young adults (Shimi, Nobre, et al., 2014). 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, corroborates that pre-cues and retro-cues are behaviourally dissociated. In combination with the findings by Shimi, Nobre, et al. (2014), these findings suggest that visuo-spatial attentional biases supporting VSTM *fractionate*, emerging at different time-points in development.

The absence of cueing benefits when the memory load was low (i.e., 2 items) indicate that 7-year-olds did not use visuo-spatial attention cues, either for encoding or for maintaining the information, when they could easily retain in memory 2 items (cf. d-prime values in Table 1) and decide whether the probe was in the array without any help. Likewise, this finding was evidenced in our adult sample and it is consistent with results by Astle et al. (2011) who found no cue benefits for adults when maintaining 2 items in VSTM. Of note, the absence of cueing benefits at low load does not mean that attentional processes do not play a role in basic storage capacity, because benefits are clearly evident when load is high. Rather, it is possible that young children use visuo-spatial attention cues strategically, in a manner that is similar 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 or not. If the load approaches capacity limits, then it is advantageous to selectively encode into VSTM only one item out of four. If it does not, then retaining both items in memory until the probe appears is equally effective.

It remains to be determined why, when memory load is high, 7-year-olds show smaller attentional benefits during *maintenance*, in contrast to the large encoding benefits. One potential constraining factor is that, for 7-year-olds, information encoded in VSTM may be decaying at a faster rate (e.g., Cowan, Nugent, Elliott, & Saults, 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 (2010) results reporting inefficient attentional filtering for 7-year-olds compared to older children and adults with large memory arrays. Cowan et al. (2011) suggested that, in addition to a simple increase in memory capacity, these differences could depend on encoding speed of simultaneously presented items. By presenting memory items to 7-year-olds sequentially and at a slower pace, they demonstrated that capacity estimates in 7-year-olds are smaller than older children's and adults', even when encoding speed and simultaneous presentations are controlled for. However, no study to date has assessed the role of temporal decay parameters in modulating spatially-selective attentional benefits on VSTM maintenance for simultaneously presented items. And yet, these data are critical to assess the potential interactions between visuo-spatial attentional biases and time-based decay accounts of VSTM maintenance. We examine the hypothesis that 7-year-olds's faster decay of information might account for their reduced ability to draw attentional benefits in Experiment 2.

3. Experiment 2: Effects of decay on attentional biases

Theories of cognitive development have long proposed that temporal factors play a critical role in WM capacity in childhood (see Case, Kurland, & Goldberg, 1982; Case, 1985 for an early *resource-sharing* theory). For example, Towse, 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. In a series of studies, Towse et al. manipulated the concurrent task's difficulty while controlling for completion time and thus the retention interval duration (Towse & Hitch, 1995), as well as manipulating the retention interval duration while controlling for processing difficulty in counting, reading, and operation span tasks

(Towse, Hitch, & Hutton, 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 longer the time interval required by the concurrent processing task, the longer children switch away from remembering the items to-be-recalled. Towse 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, Towse 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), but perhaps more so for WM measures that do not require concurrent processing. Also, Towse and colleagues did not rule out the possibility that, in addition to decay, other processes may also be responsible for memory loss (Towse, Hitch, & Horton, 2007; Towse & Hitch, 1995; Towse et al., 1998).

More recently, Barrouillet and colleagues (Barrouillet et al., 2004; Barrouillet, De Paepe, & Langerock, 2012; Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; Barrouillet & Camos, 2001; Gaillard, Barrouillet, Jarrold, & Camos, 2011; Portrat, Camos, & Barrouillet, 2009) systematically investigated how factors influencing both time-based decay and attentional resources might 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 switch of attention towards them during concurrent processing. According to Barrouillet et al., older children are more efficient than younger children 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 interval available for refreshing the stored items, resulting in better item maintenance. Barrouillet et al. argue that while this refreshing activity operates as a rehearsal mechanism (similar to attentional refreshment mechanism discussed above, e.g., Raye, Johnson, Mitchell, Greene, & Johnson, 2007; Raye, Johnson, Mitchell, Reeder, & Greene, 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 to maintain them. As a result, traces decay to a greater degree in younger children, 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 developmental changes could account for a shift from passive to active maintenance. The authors proposed that up until 6 years of age (although the exact age boundary may depend on specific task demands) the task-switching model proposed by Towse et al. can explain WM span better than the TBRS model, whereas once active attentional refreshment mechanisms take hold, the TBRS model is a better account of WM span changes. Camos and Barrouillet concluded that WM span develops in 2 stages, merging the two models. Despite their differences, the two time-based accounts provide strong evidence that both attentional refreshment mechanisms and the decay of memory traces are significant predictors of WM span and suggest that the duration of the maintenance interval is a factor that should be considered when attempting to understand differences in memory performance, both in childhood and adulthood. It should be noted that both accounts were developed and tested mainly with *verbally- and sequentially- encoded* material, whereas their emerging hypotheses have not been tested in the context of *visually- and simultaneously presented items.*

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 current cueing paradigm, 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 of the array offset (e.g., 1000ms), their performance decreased significantly and did not differ from the condition in which no cue was provided. This finding suggested that representations degraded by the time the cue appeared (see also Averbach & Coriell, 1961). These seminal results, along with those from a number of studies that followed (e.g., Neisser, 1967; Pashler, 1988; Phillips, 1974) established the division of visual memory 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; Shimi, Kuo, et al., 2014; Shimi, Nobre, et al., 2014; Shimi & Scerif, 2015) 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 with adults that have manipulated the length of the maintenance interval prior to retro-cue presentation systematically showed that longer delays in presenting a cue result in poorer VSTM performance compared to shorter delays (Astle et al., 2011; Becker, Pashler, & Anstis, 2000; Kuo, Yeh, Chen, & D'Esposito, 2011; Sligte, Scholte, & Lamme, 2008; Sligte, Vandenbroucke, Scholte, & Lamme, 2010). These findings support the conclusion that memory traces decay as a function of time. However, whether smaller attentional cue benefits during maintenance for 7-

year-olds are influenced by temporal factors and whether their selection of a memory item via internal attentional orienting maybe facilitated by visual after-effects, i.e., IM, remains to be examined. This was the aim of Experiment 2.

Returning to developmental models of verbal WM, 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 information in memory. While these secondary tasks were employed to block rehearsal mechanisms, they might engage interfering processes that load STM differentially across age groups. These extraneous concurrent processing demands themselves could obscure the precise role of maintenance activities in early childhood, and the "simple" role of decay. Time-based decay as a factor constraining developmental differences in VSTM capacity, unconfounded by possibly variable ability to engage in concurrent processing, remains understudied.

Based on the existing time-based accounts outlined above, Experiment 2 examined further why 7-year-olds benefit only 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 maintain memoranda in VSTM. An alternative possibility, based on the model proposed by Towse and Hitch (1995), is that encoded representations decay faster in young children compared to older children and adults, so that more degraded representations are available to selectively refresh when they are given the opportunity to do so. To the best of our knowledge, only one study to date has examined pure time-based effects (i.e., with no interference from a concurrent task) during the maintenance of simultaneously presented visual items in 7-year-olds (Cowan et al., 2015; but see Káldy & Leslie, 2005 for relevant infant work). However, in this study all retention intervals were within VSTM limits (>1 sec.) and therefore VSTM representations were not pitted against iconic representations. In contrast, comparing the effects of IM and VSTM temporal parameters would provide insight to a potential decay from a rich IM system to a more limited VSTM system. Additionally and most importantly, the authors did not examine the effects of time decay on the efficacy of attentional biases themselves during VSTM maintenance.

In the study by Shimi, Nobre, et al. (2014) as well as in Experiment 1 here, all inter-stimulus intervals (ISIs) adopted VSTM parameters and 7-year-olds showed small cueing benefits during maintenance. In order to investigate whether the temporal decay accounts for 7-year-olds’ poor performance on retro-cue trials, we manipulated the duration of the maintenance interval between the memory array and the retro-cue. We also manipulated the duration of the retention interval between retro-cue and probe. We hypothesized that if young children benefitted little from retro-cues, both in Experiment 1 and in the study by Shimi, Nobre, et al. (2014), because memory representations had already decayed before they could apply a spatial bias, then we should observe better performance 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. Also, by shortening the cue – probe interval, we 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 long after the array offset, but the selected item continues to passively decay 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., a long array – cue VSTM interval; in contrast to the hypothesis above), provided the probe appears shortly after selection (i.e., short cue – probe interval). In contrast to Experiment 1, only spatial retro-cues following arrays of 4 items were employed here, since 7-year-olds showed clear benefits from cues presented prior to encoding and also did not rely on cues to retain 2 items in memory.

3.1. Method

3.1.1. 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) and 26 adults (8 males and 18 females) aged between 18 and 31 years old (M = 23.04 years old, SD = 2.92) participated in Experiment 2. Recruiting procedures were similar to those reported in Experiment 1. Ethical approval and informed consent was attained as in Experiment 1.

3.1.2. Apparatus

Attentional Orienting Task: Experiment 2 differed from the task used in Experiment 1: a) by including only retro-cue blocks of 4 items 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 the array – cue interval was shorter than that used in Experiment 1 and used the short temporal parameters presented in Figure 2A (“IM 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 again 2 trial-types, cued and neutral, but only one cue condition, retro-cue; retro-cue and neutral trials were randomly presented within a block.

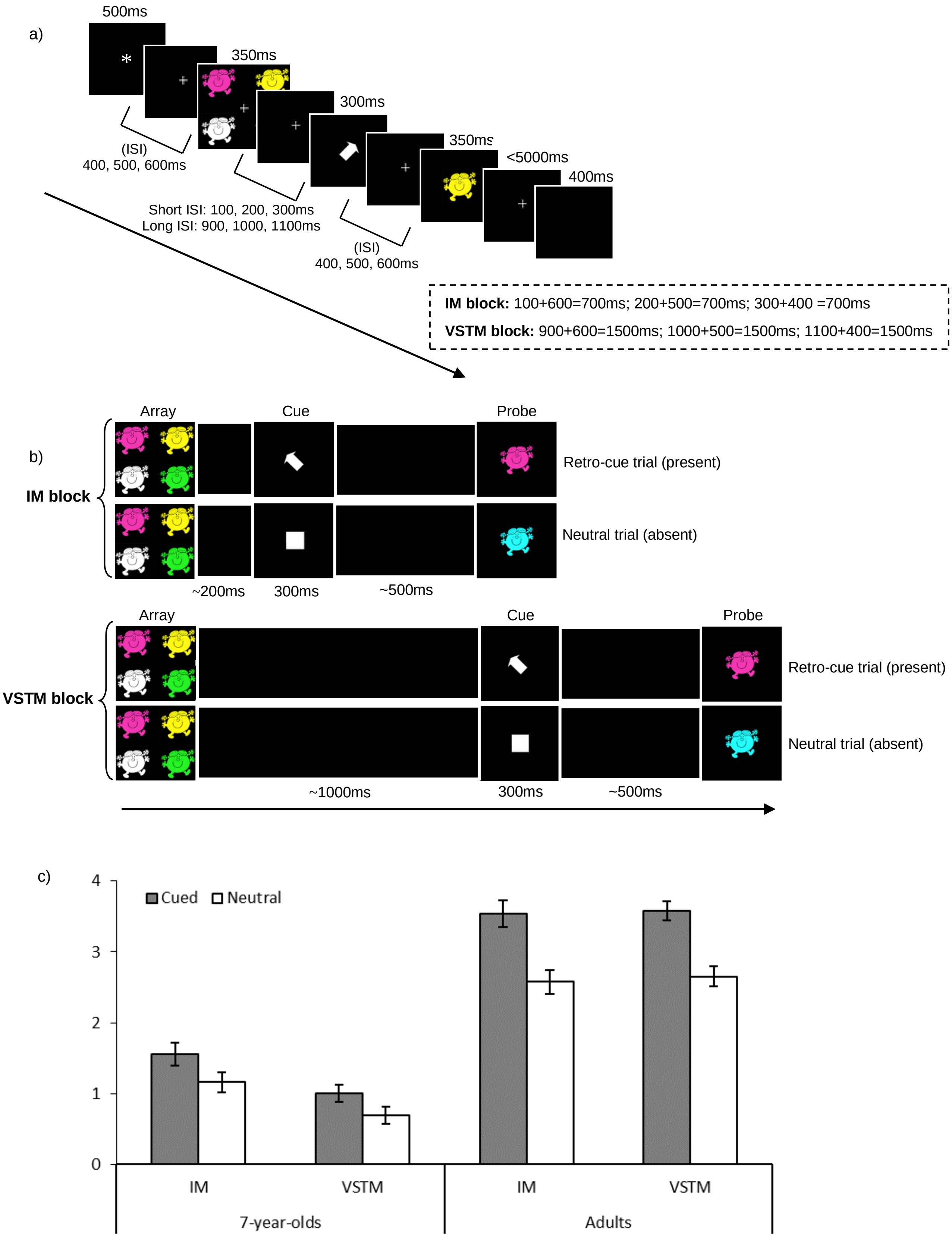
a)
500ms
350ms
300ms
350ms
<5000ms
400ms
(ISI)
400, 500, 600ms
Short ISI: 100, 200, 300ms
Long ISI: 900, 1000, 1100ms
(ISI)
400, 500, 600ms
IM block: 100+600=700ms; 200+500=700ms; 300+400 =700ms
VSTM block: 900+600=1500ms; 1000+500=1500ms; 1100+400=1500ms
b)
IM block
Array
Cue
Probe
Retro-cue trial (present)
Neutral trial (absent)
~200ms
300ms
~500ms
VSTM block
Array
Cue
Probe
Retro-cue trial (present)
Neutral trial (absent)
~1000ms
300ms
~500ms
c)
4
3
2
1
0
Cued
Neutral
IM
VSTM
IM
VSTM
7-year-olds
Adults

Figure 2: Experiment 2 task and results. a) 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 which remained visible throughout the trial. Approximately 500ms later, the memory array appeared for 350ms, followed by a randomly varied fixation interval whose time depended on delay manipulation, i.e., short ISI (~200ms) or long ISI (~1000ms). Subsequently, a cue appeared for 300ms, followed by a randomly varied fixation interval (400-600ms; the timing depended on the previous ISI so that the probe would always appear at the same time following the array). Finally, 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. ISI timings within each block were yoked to obtain a constant memory array to probe latency as explained in the text box. b) Temporal parameters for the two blocks, IM and VSTM. c) Cowan's *K* scores for cued and neutral trials, comparing 7-year-olds and adults' performance in IM and VSTM blocks. Error bars represent standard errors of the mean.

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 (Figure 2B). 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, attentional biases in the IM blocks are believed to operate on transient iconic representations.

Furthermore, the array – cue fixation intervals selected for Experiment 2 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 2B). 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 Experiment 1, 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 later 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.

3.1.3 Procedure

The procedure was identical to that of Experiment 1 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). There were two VSTM test blocks and two IM test blocks that alternated throughout the task and were counterbalanced across participants.

3.1.4. Statistical design

A repeated-measures ANOVA was performed on Cowan's *K* scores with "delay" (IM, VSTM) and "trial-type" (cued, neutral) as the within-subject variables and the age-group as the between-subject variable. This analysis was followed by an additional repeated-measures ANOVA to examine the a priori question of whether retro-cues can rescue a VSTM representation from fading further. Performance on neutral trials in IM blocks provides an indication for how good participants' baseline memory recognition is at the time the retro-cue appears, and therefore contrasting performance between neutral trials in IM blocks and retro-cue trials in VSTM blocks allows examining how effective a retro-cue is at that time-point.

3.2. Results

Figure 2C presents mean Cowan's *K* scores for the trial-types and the delay conditions across the age-groups. *K* scores yielded main effects of delay [F(1,59)=11.41, p=.001, η^2=.16], trial-type [F(1,59)=53.88, p<.001, η^2=.48], and age-group [F(1,59)=141.76, p<.001, η^2=.71], as well as significant interactions of age-group x delay [F(1,59)=17.90, p<.001, η^2=.23] and age-group x trial-type [F(1,59)=11.21, p=.001, η^2=.16]. Analyses of simple main effects for the age-group x delay interaction revealed higher *K* scores for adults than for 7-year-olds in both IM (M=3.06 and M=1.36 for adults and 7-year-olds respectively, p<.001) and VSTM conditions (M=3.12 and M=.84 for adults and 7-year-olds respectively, p<.001). The interaction was driven by significantly higher *K* scores in the IM block than in the VSTM block for 7-year-olds (p<.001). There were no significant differences in performance between the two delay conditions for adults (p=.58), suggesting that overall memory was greater with shorter maintenance intervals for 7-year-olds, whereas time did not affect adults' memory capacity. Analyses of simple main effects for the age-group x trial-type interaction yielded higher *K* scores in cued than in neutral trials for both children (M=1.28 and M=.92 respectively, p=.003) and adults (M=3.56 and M=2.61 respectively, p<.001), suggesting cue benefits across blocks for all participants. Importantly, there were higher *K* scores for adults than 7-year-olds in both cued and neutral trials (ps<.001), suggesting greater benefits drawn from retro-cues in adults than in children. Indeed, these results were corroborated by the analysis of difference scores [F(1,59)=11.21, p=.001, η^2=.16], which yielded greater cueing benefits in adults (M=.95) than in 7-year-olds (M=.35).

Results from the planned comparison between IM neutral trials and VSTM retro-cue trials revealed a trial x age-group significant interaction [F(1,59)=36.20, p<.001, η^2=.38]. Posthoc tests showed no significant differences between IM neutral trials (M=1.16) and VSTM retro-cue trials (M=1.00, p=.21) for 7-year-olds indicating that retro-cues rescued VSTM representations from fading further. Adults, on the other hand, had higher *K* scores in VSTM retro-cue trials (M=3.58) than in IM neutral trials (M=2.58, p<.001), which suggests that cues boosted the signal of an otherwise weakened VSTM representation even more.

Effects of time on VSTM maintenance and cue-dependent top-down bias deployment: Experiment 1 vs. Experiment 2

The previous analyses tested the effects of time intervening between encoding of memoranda and cues (i.e., prior to applying top-down biases) on VSTM maintenance. However, these analyses do not allow inferring whether information continues to decay following the offset of attentional cues and once top-down biases have been applied to internal representations. In order to examine this question, we compared directly performance of the Load 4 group in Experiment 1 with performance in the VSTM blocks in Experiment 2. In both instances, the memory array – retro-cue ISI was within VSTM limits (~1000ms), but the following retro-cue – probe ISI differed, in that it was shorter in Experiment 2 (~500ms) than in Experiment 1 (~1000ms). We hypothesized that if information continues to decay after it has been transferred to the VSTM system, then performance should be better in Experiment 2 compared with Experiment 1. In contrast, if information decays until it reaches VSTM but then it plateaus, performance should not differ between the two experiments.

There were only main effects of trial-type [F(1,97)=65.62, p<.001, η^2=.40] and age-group [F(1,97)=315.95, p<.001, η^2=.77], and a significant interaction of trial-type x age-group [F(1,97)=131.16, p<.001, η^2=.12] on Cowan's *K*, which was driven by larger cueing benefits in adults (M=.86) than in children (M=.32, p<.001). The main effect of Experiment [F(1,97)=2.92, p=.1, η^2=.03] and the interactions of trial-type x Experiment [F(1,97)=.18, p=.68, η^2=.002], age-group x Experiment [F(1,97)=.35, p=.55, η^2=.004], and age-group x trial-type x Experiment [F(1,97)=.39, p=.53, η^2=.004] did not reach significance, suggesting no greater decay of information after its refreshment by VSTM attentional cues neither for 7-year-olds nor for adults.

3.3. Discussion

In Experiment 2, we manipulated the duration of the period during which participants had to maintain all encoded items until cue presentation, as well as shortened the period during which participants had to retain the selected representation until response. Better accuracy for probes at cued locations were observed again for all participants and benefits from cues during maintenance were smaller for 7-year-olds than for adults again, as in Experiment 1. A key new finding in Experiment 2 is that 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. In contrast, adults performed equally well when retro-cues operated on iconic and VSTM representations. Also, 7-year-olds’ performance on baseline neutral trials became poorer when longer delays were imposed during maintenance (array – cue interval), whereas adults’ baseline performance did not deteriorate with time. Together with the findings of Experiment 1, the current findings suggest that applying attentional biases early in childhood depends heavily on temporal parameters during the maintenance period and confirm that memory traces decay as a function of time (consistent with Cowan, Nugent, Elliott, & Saults, 2000; Towse & Hitch, 1995; Towse et al., 1998). Complementing previous findings focused on the reliability of attentional cues (e.g., Shimi, Nobre et al., 2014), Experiment 2 provided evidence that temporal parameters are an additional important factor in understanding attentional mechanisms engendered by spatial cues in young children.

The time-based effects on the maintenance of memory were also evidenced in 7-year-olds' poorer recognition on baseline neutral trials with long compared to short delays until the memory probe. Of note, this evidence of time-based decay was obtained even in the absence of a concurrent processing task, as our paradigm requires simple maintenance; these pure time-based effects are in agreement with recent child findings (Cowan et al., 2015). Overall, these results support the predictions of time-based forgetting during maintenance and suggest that a greater degree of decay in 7-year-olds compared to older individuals accounts at least in part for their smaller ability to benefit from cues presented during VSTM maintenance. The findings 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. Furthermore, these results emphasize that constraining factors during maintenance should be taken into account when examining developmental differences in VSTM capacity.

A final key finding of Experiment 2 is that 7-year-olds benefited from retro-cues in a manner that was similar to Experiment 1. A temporally relevant difference between the two experiments is that Experiment 1 involved longer cue – probe interval durations (1000ms on average, vs. 500ms in Experiment 2). Therefore, the similarities in the benefits from retro-cues across experiments suggest that the length of the retention period following the selection of an item via the retro-cue is not as important for memory as it is for the retention period prior to selecting an item via the cue. The current results suggest that 7-year-olds 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, even though the representation is not as robust as when the cue appears at shorter delays. Critically, and in addition, the VSTM representation of the selected item is no longer subject to decay with time, so that when the probe finally appears, after a further maintenance period, the selected representation is not weaker. The latter was also mirrored in the adult results.

In summary, the presence of reliable cueing benefits in VSTM trials in the present experiment suggests that the small attentional benefits engendered by retro-cues in Experiment 1 should not be attributed solely to 7-year-olds' inability to orient attention internally, but also to a greater item fragility caused by the delay period until a retro-cue appears. This seems to be especially the case when items exceed 7-year-olds' VSTM capacity, as results from Experiment 1 showed that 7-year-olds do not rely on attention cues to maintain information when the memory load is within their VSTM capacity (i.e., 2 items).

Taken together, the results from Experiments 1 and 2 show that although 7-year-olds apply attentional biases when these are needed the most, these biases result in best performance when they operate on iconic representations, when decay is minimal and load exceeds their capacity. These results suggest that both the effects of memory load and decay on attentional biases during maintenance deserve further investigation using parametric manipulations of memory load and maintenance delays. With 2 items in memory (Experiment 1), 7-year-olds did not show retro-cue benefits, possibly because they could retain all items in VSTM until responses were required, whereas with 4 items in the array (Experiment 2), and in contrast to adults, they performed best when retro-cues operated on iconic traces. Attentional control may play a critical role when memory arrays contain intermediate memory load (i.e., 3 items) and when maintenance of the encoded information is required for a long period of time, a point to which we turn next.

4. Experiment 3: Attentional biases during maintenance: Parametric manipulations of memory load and maintenance delays

In the previous experiments, cueing benefits were examined in isolation for memory load (Experiment 1) and temporal decay (Experiment 2) effects on maintenance. As a whole, the findings demonstrated that cueing effects during maintenance change as a function of both load and temporal delay. Memory traces decay as a function of time even in the absence of interference from a concurrent processing task, and the number of simultaneously encoded items seems 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. However, further data are needed to determine whether, and if so, how, memory load, temporal delay and attentional biases operate in combination. Such an investigation would have implications for current theoretical models of WM, because these have tended to investigate each of these parameters in isolation (Baddeley & Hitch, 2000; Barrouillet et al., 2009; Cowan, 2014, 2015; Gaillard et al., 2011; Towse et al., 2002).

Based on these observations, a) we hypothesized that if representations decay before 7-year-olds can apply a spatial bias reliably at the limits of their capacity, we might observe more efficient attentional biases if memory load is intermediate (e.g., 3 items) compared to low (e.g., 2 items, in Experiment 1); b) although we expected decay from IM to VSTM systems, we hypothesized that we might not observe evidence of decay within the VSTM system, provided memory load is intermediate, even if we stretch the requirement to retain the information for longer; c) finally, we hypothesized that perhaps memory load is not the most critical constraint, but instead that temporal decay is, so that young children might be able to rescue representations held in memory, even when memory load is much higher (e.g., 6 items), provided cues are presented shortly after the memory array (within the IM range).

In order to investigate these complementary hypotheses, in Experiment 3 we presented participants with memory arrays containing 3 (“load 3” henceforth) or 6 (“load 6” henceforth) items. In the load 3 condition, we presented retro-cues either within an IM, a VSTM, or a longer VSTM interval. In the load 6 condition, we presented retro-cues for 7-year-olds only within an IM interval, to limit frustration, because 7-year-olds’ performance in the previous experiments and piloting suggested that they would be at floor with longer intervals in this more demanding condition. To generalize our child findings and emerging multi-factorial model of maintenance in VSTM to the adult population, in this experiment we varied the array – cue ISI in the load 6 condition for adults to include VSTM and long VSTM intervals in addition to the IM delay. To preview our findings, the pattern of our child results was replicated in adults.

4.1. Method

4.1.2. Participants

Thirty-two new children (19 boys and 13 girls) aged 6 and 7 years old (M = 6.5 years old, SD = .51, “7-year-olds” henceforth) and thirty adults (9 males and 21 females) aged 18 to 32 years old (M = 23.07 years old, SD = 4.47) participated in Experiment 3. Recruiting procedures were similar to those reported in Experiment 1. Ethical approval and informed consent was attained as in Experiment 1.

4.1.3. Apparatus

Attentional Orienting Task: Experiment 3 differed from the task used in Experiment 2: a) by presenting memory arrays with 3 and 6 items; and b) by manipulating the array – cue interval to IM, VSTM, and long VSTM timing parameters[6] (Figure 3A). In 7-year-olds, the array – cue interval was manipulated only for the 3-item arrays. There were 8 test blocks for children and 12 test blocks for adults of 36 trials in each, totalling 288 experimental trials for children and 432 experimental trials for adults; 192 probe-present (67%) and 96 (33%) probe-absent trials for children and 288 probe-present (67%) and 144 (33%) probe-absent trials for adults[7]. Half of all trials were cued (equally likely to point to one of the three or six possible locations) and half were neutral. For children, the task was split into 6 "load 3" blocks, with 2 blocks for each delay interval (IM, VSTM, long VSTM), and 2 "load 6" blocks adopting the IM interval only. For adults, the task was split into 6 "load 3" blocks and 6 "load 6" blocks, with 2 blocks for each delay interval (IM, VSTM, long VSTM). Similar to Experiment 2, we designed the task in such a way so that we could assess participants' baseline memory recognition at the time at which the retro-cue appeared in VSTM and longer VSTM blocks. Practice blocks, feedback, and recording procedures were identical to Experiment 1.

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[6] We used the specific timing parameters for long VSTM in Experiment 3 so that the difference in the array – retro-cue ISI between the VSTM and long VSTM conditions (800ms) is the same as between the IM and VSTM conditions in Experiments 2 and 3. Furthermore, a longer ISI for long VSTM would have increased the duration of each trial. For children to complete the whole task, we would need to decrease the number of trials in each block, reducing thus statistical power.

[7] The difference in the total number of experimental trials between children and adults is due to the absence of the 4 blocks testing VSTM and long VSTM with 6-item arrays in 7-year-olds. Children and adults completed the same number of experimental trials in all other conditions.

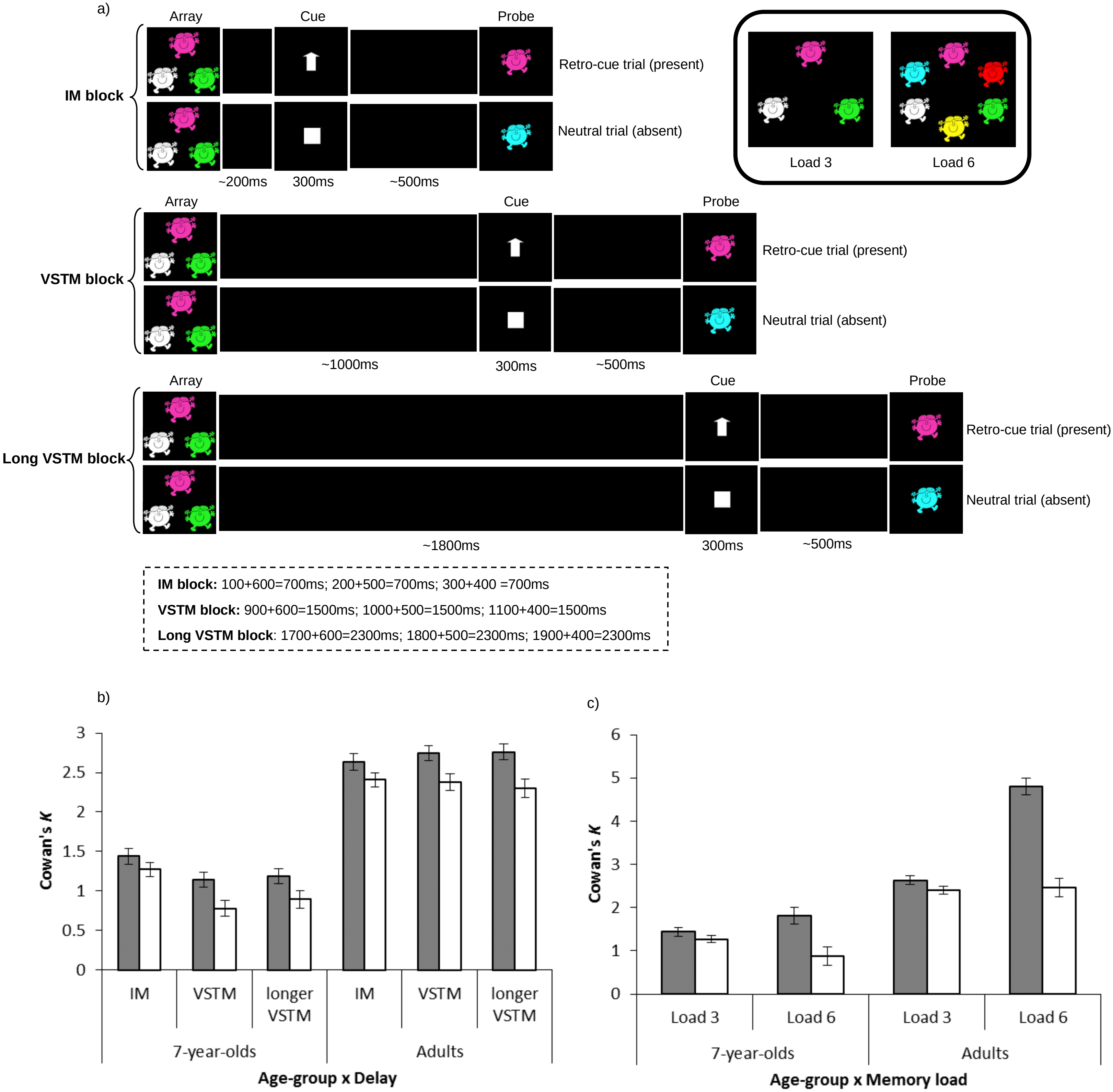
a)
Array
Cue
Probe
IM block
Retro-cue trial (present)
Neutral trial (absent)
~200ms
300ms
~500ms
Load 3
Load 6
VSTM block
~1000ms
300ms
~500ms
Long VSTM block
~1800ms
300ms
~500ms
IM block: 100+600=700ms; 200+500=700ms; 300+400 =700ms
VSTM block: 900+600=1500ms; 1000+500=1500ms; 1100+400=1500ms
Long VSTM block: 1700+600=2300ms; 1800+500=2300ms; 1900+400=2300ms
b)
Cowan's K
0
0.5
1
1.5
2
2.5
3
IM
VSTM
longer VSTM
IM
VSTM
longer VSTM
7-year-olds
Adults
Age-group x Delay
c)
Cowan's K
0
1
2
3
4
5
6
Load 3
Load 6
Load 3
Load 6
7-year-olds
Adults
Age-group x Memory load

Figure 3: Experiment 3 task and results. The sequence of events and their temporal parameters on each test trial were similar to Figure 2A, except that there was the additional long VSTM condition. ISI timings within each block were yoked to obtain a constant memory array to probe latency as explained in the text box. a) 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. b) Cowan's *K* scores for cued and neutral trials, comparing 7-year-olds and adults' performance in IM, VSTM, and long VSTM blocks, for load-3 arrays. Error bars represent standard errors of the mean. c) Cowan's *K* scores for cued and neutral trials, comparing 7-year-olds and adults' performance in load-3 and load-6 arrays, within an IM interval. Error bars represent standard errors of the mean.

4.1.4. Statistical design

We employed 2 different analytical strategies, given the absence of the two delay intervals (VSTM and long VSTM) in load 6 in children. The first analysis assessed the effects of time (i.e., IM vs. VSTM vs. long VSTM) on maintenance when memory load was intermediate (i.e., 3 items) and perhaps just within 7-year-olds' VSTM capacity limits (e.g., Cowan et al., 2005). The second analysis tested the effects of memory load (3 items vs. 6 items) on maintenance when the retro-cues were presented within an IM interval following the memory array. With regards to the first line of analysis, a repeated-measures ANOVA was performed on Cowan's *K* scores with the "delay" (IM, VSTM, long VSTM) and the "trial-type" (cued, neutral) as the within-subject variables for arrays with 3 items and the age-group as the between-subject variable. Additional planned comparisons contrasted: a) neutral IM trials with cued VSTM trials, noting that VSTM cues appeared at the same time-point at which memory was probed in neutral IM trials; and b) neutral VSTM trials with cued long VSTM trials, in which again cues appeared at the same time-point at which memory was cued in neutral VSTM trials. With regards to the second line of analysis, a repeated-measures ANOVA was performed on Cowan's *K* scores with the "memory load" (3 items, 6 items) and the "trial-type" (cued, neutral) as the within-subject variables for arrays that adopted the IM intervals and the age-group as the between-subject variable. For adults only, a full ANOVA with "memory load" (3 items, 6 items), "trial-type" (cued, neutral), and "delay" (IM, VSTM, long VSTM) as within-subject variables was also carried out.

4.2. Results

4.2.1. Effects of time on internal attentional orienting with intermediate memory load (3 items)

Figure 3B presents mean Cowan's *K* scores for the trial-types and the delay conditions for memory load 3 for children and adults. *K* scores yielded a main effect of trial-type [F(2,60)=5.74, p=.004, η^2=.09], with significantly better performance in cued (M=1.99) than in neutral trials (M=1.67) suggesting cue benefits across delays. There were also main effects of delay [F(2,120)=5.74, p=.004, η^2=.09] and age-group [F(1,60)=198.20, p<.001, η^2=.77], as well as a significant interaction of age-group x delay [F(2,120)=8.20, p<.001, η^2=.12]. Analyses of simple main effects for the interaction showed that adults had higher *K* scores than 7-year-olds across all delays (ps<.001). The interaction was driven by 7-year-olds' significantly higher *K* scores with IM delay (M=1.36) than VSTM (M=.96) and long VSTM (M=1.04) delays (ps<.001) suggesting decay of items between IM and VSTM delays. Their *K* scores between VSTM and long VSTM delays did not differ significantly (p=1.00) suggesting that decay reached a plateau when iconic representations were transferred to VSTM. In contrast, at this level of load (3 items), adults' *K* scores did not differ significantly across delay blocks (M=2.52 for IM; M=2.57 for VSTM; and M=2.53 for long VSTM, ps=1.00).

Furthermore, two ANOVAs contrasted performance between neutral trials in IM blocks and retro-cue trials in short VSTM blocks, and between neutral trials in short VSTM blocks and retro-cue trials in long VSTM blocks. These planned comparisons showed: 1) no significant differences between IM neutral trials (M=1.27) and short VSTM retro-cue trials (M=1.14, p=.18) for 7-year-olds indicating that retro-cues rescued VSTM representations from fading further; in contrast, adults had higher *K* scores in VSTM retro-cue trials (M=2.75) than in IM neutral trials (M=2.41, p=.001), suggesting that cues boosted the signal of an otherwise weakened VSTM representation; and 2) a statistically significant difference [F(1,60)= 23.39, p<.001] between short VSTM neutral trials (M=.77 for 7-year-olds and M=2.38 for adults) and long VSTM retro-cue trials (M=1.19 for 7-year-olds and M=2.76 for adults) indicating that long retro-cues boosted the signal of an otherwise weakened VSTM representation for all participants.

4.2.2. Effects of memory load (3 vs. 6 items) on internal attentional orienting to iconic representations

Figure 3C presents mean Cowan's *K* scores for the different trial-types and memory loads for IM for children and adults.

There were main effects of memory load [F(1,60)=39.45, p<.001, η^2=.40], trial-type [F(1,60)=70.15, p<.001, η^2=.54], and age-group [F(1,60)=124.27, p<.001, η^2=.67] as well as significant interactions of memory load x trial-type [F(1,60)=62.81, p<.001, η^2=.51], age-group x trial-type [F(1,60)=11.11, p=.001, η^2=.16] and age-group x memory load [F(1,60)=40.39, p<.001, η^2=.40]. The interaction of age-group x trial-type x memory load was also significant [F(1,60)=13.76, p<.001, η^2=.19].

Analyses of simple main effects for the 3-way interaction indicated that adults had higher *K* scores than 7-year-olds across cued and neutral trials and both with *3 items* in the array (7-year-olds: M=1.44 for cued and M=1.27 for neutral; adults: M=2.63 for cued and M=2.41 for neutral, ps<.001) and with *6 items* in the array (7-year-olds: M=1.82 for cued and M=.88 for neutral; adults: M=4.80 for cued and M=2.46 for neutral, ps<.001). Importantly, both age-groups had significantly greater cue benefits in arrays with 6 items than with 3 items (7-year-olds: M=.94 and M=.17 respectively, p=.004; adults: M=2.34 and M=.22 respectively, p<.001). The interaction was driven by significantly greater cue benefits in arrays with *6 items* for adults than for 7-year-olds. The magnitude of iconic cue benefits in load-3 arrays did not differ significantly between adults and 7-year-olds ($p=.70$).

4.2.3. Effects of attentional orienting, delay, and load in adults

Figure 4 presents mean Cowan's *K* scores for trial-types, delay conditions, and memory load levels for adults. The analysis on Cowan's *K* yielded main effects of memory load [$F(1,29)=33.20$, $p<.001$, $\eta^2=.53$], delay [$F(2,58)=12.25$, $p<.001$, $\eta^2=.30$], and trial-type [$F(1,29)=215.03$, $p<.001$, $\eta^2=.88$], as well as significant interactions of memory load x trial-type [$F(1,29)=82.77$, $p<.001$, $\eta^2=.74$] and memory load x delay [$F(2,58)=13.53$, $p<.001$, $\eta^2=.32$].

Analyses of simple main effects for the memory load x trial-type interaction indicated that adults had higher *K* scores in cued than in neutral trials both with *3 items* in the array ($M=2.71$ and $M=2.36$ respectively, $p<.001$) and with *6 items* in the array ($M=4.14$ and $M=2.12$ respectively, $p<.001$). The interaction was driven by higher *K* scores in *cued trials with 6 items* in the array than in *cued trials with 3 items* in the array ($p<.001$), whereas *K* scores did not differ between neutral trials across the two levels of load ($p=.11$) suggesting differential cueing benefits across memory load levels. Indeed, the analysis on difference scores yielded a main effect of memory load [$F(1,29)=82.77$, $p<.001$, $\eta^2=.74$] with greater cueing benefits with *6 items in the array* ($M=2.02$) than with *3 items in the array* ($M=.35$). Analyses of simple main effects for the memory load x delay interaction indicated that with *6 items in the array* adults had higher *K* scores in the IM blocks ($M=3.63$) than in the VSTM ($M=3.06$, $p=.002$) and in the long VSTM blocks ($M=2.70$, $p<.001$). Performance did not differ significantly between VSTM and long VSTM blocks ($p=.23$) suggesting that decay reached a plateau when the mental representations were transferred from IM to VSTM. With *3 items in the array*, there were no significant differences across delays ($M=2.52$ for IM; $M=2.57$ for VSTM; and $M=2.53$ for long VSTM, ps=1.00), suggesting that item representations did not decay when the load was within adults' VSTM capacity limits (Cowan, 2001).

Finally, four pair-wise t-tests contrasted performance between neutral trials in IM blocks and retro-cue trials in short VSTM blocks, and between neutral trials in short VSTM blocks and retro-cue trials in long VSTM blocks, for both intermediate and high memory loads. These planned comparisons showed statistically significant differences: 1) between IM neutral trials and short VSTM retro-cue trials for load 3 [M=2.41 and M=2.74 respectively; t(29)= -5.08, p<.001] and load 6 [M=2.46 and M=3.97 respectively; t(29)= -6.15, p<.001]; and 2) between short VSTM neutral trials and long VSTM retro-cue trials for load 3 [M=2.38 and M=2.76 respectively; t(29)= -4.83, p<.001] and load 6 [M=2.15 and M=3.65 respectively; t(29)= -6.02, p<.001], indicating that retro-cues boosted the signal of VSTM representations.

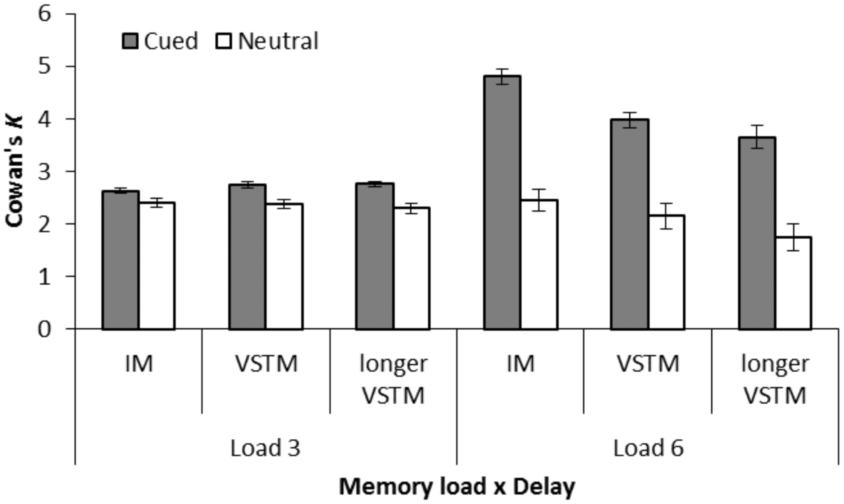

Figure 4: Cowan's *K* adult scores for cued and neutral trials, comparing IM, VSTM, and long VSTM blocks, for load-3 and load-6 arrays. Error bars represent standard errors of the mean.

4.3. Discussion

As expected, in contrast to Experiment 1 in which participants did not rely on retro-cues to aid maintenance when they only had to retain two items in VSTM, in this experiment we observed reliable cue benefits during VSTM maintenance when we increased the memory load to three items. Together with the findings of Experiment 2, this result suggests that when memory load taxes participants' VSTM capacity limits, then they strategically rely on retro-cues to facilitate maintenance. Furthermore, Experiment 3 showed again greater VSTM capacity for adults compared with 7-year-olds. Importantly, results indicated that item representations decay faster in its transfer from IM to VSTM for children compared with adults, even when memory load is intermediate (i.e., 3 items). This was indicated by 7-year-olds' better performance in IM blocks compared with VSTM blocks, whereas there was no observed decay in *K* between the two memory systems in adults. This finding points towards an additional mechanism responsible for less information being transferred from the IM system to the VSTM system for 7-year-olds. Of note, because prior manipulations of the retention interval across age groups employed retention intervals that lasted 1 seconds (e.g., Cowan et al., 2015), this age-related difference has not been previously reported. Furthermore, Experiment 3 showed again that, in contrast to adults, 7-year-olds' overall memory performance was better with IM maintenance intervals and when retro-cues were presented shortly after the memory array, thus operating on transient iconic traces rather than on VSTM representations. Also, replicating results from Experiment 2, 7-year-olds' performance on baseline neutral trials became poorer when longer delays were imposed during maintenance (i.e., from IM to VSTM). This result suggests again that memory traces decay as a function of time. Critically, however, and extending the results from Experiment 2, when we stretched the requirement to retain information for longer, there were no differences in baseline memory performance between shorter VSTM and longer VSTM maintenance intervals. This finding indicates that when memory load is intermediate, decay reaches a plateau once mental representations are transferred from the high-capacity but fragile IM system to the limited-capacity but durable VSTM system.

Another key finding in Experiment 3 is that iconic retro-cues rescued mental representations even when memory load was well beyond capacity limits (i.e., 6 items). This strongly suggests that memory load is not the only critical factor influencing the efficacy of attentional biases during maintenance. Instead, the efficacy of attentional biases in both age groups depends heavily on temporal parameters. Importantly, benefits from cues during maintenance were larger when participants had to retain a higher memory load (i.e., 6 items) than a lower memory load (i.e., 3 items), documenting that both 7-year-olds and adults recruit top-down attention in the face of increased visual competition and apply attentional biases when these are needed the most. However, adults' ability to do so was significantly better than 7-year-olds, even when the cue was presented shortly after the memory array, corroborating previous findings for age-related differences in the ability to deploy visuospatial attentional control during the maintenance period (Shimi, Nobre, et al., 2014; Shimi & Scerif, 2015). In addition, a striking finding in Experiment 3, replicating and extending Experiment 2, is that retro-cues rescue memory performance to a level that is equivalent (as in the comparison with uncued IM trials in 7-year-olds) or better (as in the comparison with uncued VSTM trials for all participants) than when memory that is probed, uncued, at the time when retro-cues are presented. These findings suggest that directed visuo-spatial attentional cues do not only protect selected memoranda from further decay, but they also boost their representations when they would be particularly weak (at long delays). The specific mechanisms for this enhancement remain open to further investigation, but we expand on how we conceptualize these in the General Discussion.

Our developmental results are in agreement with other adult findings demonstrating that retro-cues, presented shortly after a memory array whose load exceeded adults' capacity (≥8 items), boosted performance significantly (Astle et al., 2011; Sligte et al., 2008). Our findings suggest that retro-cues have their greatest effects, not only when memory load approaches capacity limits (as in the comparison between 2, 4, and now 3 items in the memory array), but also when retro-cues are presented shortly after the memory array.

In order to fully extend the pattern of questions and results addressed by 7-year-olds' data to the adult system, we examined the effects of time at all levels of load in a separate analysis on adults only. Findings demonstrated that adults' benefits from cues during maintenance were larger when participants had to retain a higher memory load (i.e., 6 items) than a lower memory load (i.e., 3 items), attesting that, similar to children, adults apply greater attentional biases when these are needed the most. Furthermore, when adults maintained items at a lower memory load (3 items), item representations did not decay as a function of time. In contrast, when they had to retain information at a higher memory load (6 items), their memory performance was significantly better with IM maintenance intervals than with longer maintenance intervals, indicating that memory performance was better for transient iconic traces rather than for VSTM representations. Finally, adults' performance did not become poorer with longer, compared with shorter, VSTM maintenance intervals, corroborating the implication from children's data that decay reaches a plateau when mental representations are transferred from IM to VSTM systems.

In conclusion, our systematic manipulations over the three experiments strongly suggest that both children and adults apply a spatial bias during maintenance when they need it the most;

however, developmentally this ability is further and differentially constrained by the number of items that participants at different ages have to retain in memory and by time-based decay.

5. General Discussion

There is ample evidence suggesting that the ability to maintain visual information improves dramatically during childhood (Brockmole & Logie, 2013; Cowan et al., 2005; Gathercole, Pickering, Ambridge, & Wearing, 2004; Isbell, Fukuda, Neville, & Vogel, 2015; Klingberg, Forssberg, & Westerberg, 2002; Logie & Pearson, 1997; Luciana, Conklin, Hooper, & Yarger, 2005). However, theoretical frameworks encompassing multiple constraints on VSTM maintenance and their interactions have lagged behind; this is especially the case for research examining temporary storage and maintenance of simultaneously encoded visual information. In this context, the role of attentional biases, time-based decay, and memory load on maintenance in VSTM have been studied in isolation. Here, we propose that developing an integrative theoretical framework to account for 7-year-olds' differing ability to maintain information in VSTM has repercussions for an understanding of the adult system.

We first highlight the key findings of our 3 experiments and subsequently we discuss how these findings contribute to existing models of VSTM/WM and of their cognitive development. Finally, we conclude with a novel integrative model of VSTM maintenance describing the means by which we think attentional processes influence VSTM and how these are further constrained by additional factors.

5.1. Overview of key findings

In Experiment 1, we examined whether memory load itself may influence the deployment of attentional biases in service of VSTM. Specifically, one hypothesis following from the finding that 7-year-olds benefit less from attention cues during VSTM maintenance than older individuals (e.g., Shimi, Nobre, et al., 2014), was that having to encode and maintain a set of 4 items may have exceeded their capacity limits, thus compromising 7-year-olds's ability to recruit top-down attentional control to refresh and enhance an internal representation. By contrast, the alternative hypothesis was that, if even 7-year-olds can deploy attentional biases when they are needed most, the biggest benefits of cues should emerge for large (4 items) rather than small (2 items) sets. Therefore, we compared 7-year-olds and adults' ability to apply attentional biases and VSTM performance when having to encode and retain memory loads of 2 and 4 items. Results demonstrated no reliable benefits from cues presented either prior to encoding or during maintenance with a memory set size of 2 items neither for adults nor for children, indicating that, when set size is within capacity limits (Cowan et al., 2005; Riggs et al., 2006; Riggs, Simpson, & Potts, 2011), participants 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 and these were to a similar magnitude to adults' cueing benefits. Cues during maintenance, on the other hand, resulted in reliable but smaller benefits of attentional cues compared to cues before encoding and also compared with adults, replicating previous results with 4 items (Shimi et al., 2014). This in turn indicates that 7-year-olds can voluntarily orient their attention to support VSTM, but that their ability to bias information in VSTM is modulated by memory load.

Given that higher memory load calls for top-down attention mechanisms, we subsequently investigated whether additional non-attentional factors, such as the temporal demands of the task, interact with the recruitment of voluntary attention during VSTM maintenance. In Experiment 2, we manipulated the duration of the interval between encoding and cue presentation to be short or long, so that participants 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. Previous models, developed to account for the effects of time on the maintenance of sequentially presented verbal material, debated the role of passive decay (Towse et al., 1998) and active refreshment mechanisms (Barrouillet et al., 2009). Here, to our knowledge for the first time in the visual domain, we see evidence of both decay and active refreshment. This is because, in contrast to adult results, 7-year-olds' performance on uncued trials declined over time, suggesting passive decay of memory traces as a function of time (consistent with Cowan, Nugent, Elliott, & Saults, 2000; Towse & Hitch, 1995; Towse et al., 1998) even in the absence of interference from a concurrent task (Cowan et al., 2015; Ricker & Cowan, 2010). However, performance on cued trials suggests that active refreshment mechanisms influenced these representations equally well, boosting performance significantly, whether they were in the form of IM or VSTM representations, albeit to a smaller degree for 7-year-olds than for adults. Together, the findings of Experiments 1 and 2 documented how attentional cueing benefits in 7-year-olds depend heavily on both memory load and on temporal decay over the maintenance period. When memory load exceeds 7-year-olds' capacity, attentional biases are more effective when they operate on iconic traces, as has been previously shown in adults with supra-VSTM capacity arrays (Astle et al., 2011; Sligte et al., 2008, 2010).

In Experiment 3 we investigated interactions between load and decay by manipulating memory load parametrically to well beyond participants' capacity limits and by extending the duration of the interval between encoding and retro-cue presentation. Results corroborated the findings of Experiment 2, i.e., that retrospective orienting during maintenance in 7-year-olds operates most efficiently on transient iconic traces, rather than on VSTM representations. When attentional biases operate on iconic representations, they can boost 7-year-olds' performance significantly even when memory load well exceeds their capacity (6 items): 7-year-olds can apply attentional biases during maintenance to rescue iconic representations from fading. Importantly, Experiment 3 also indicated that when memory load is intermediate (3 items), internal representations decay from IM to VSTM. However, once these are transferred to the less-fragile VSTM system, decay reaches a plateau, highlighting a distinction between the two memory systems and the effects of time on 7-year-olds' retention and retrieval of mental representations from these two systems.

Furthermore, Experiment 3 extended these findings to the adult system and showed that, similarly to children, adults apply greater attentional biases during maintenance when these are needed the most: attentional biases can boost adults' performance significantly when memory load is high (6 items). Like in children, in adults we observed, first, evidence of decay (from IM to VSTM), and, second, evidence for a plateau when adults' mental representations were transferred from IM to VSTM. Of note, in adults this non-linear change was observed only under high memory load. In contrast to 7-year-olds, when load was intermediate, item representations did not decay as a function of time. Direct age-related comparisons confirmed these results.

Critically, age-group comparisons showed that, in addition to adults' more refined ability to orient attention internally to select an item to facilitate maintenance and later recognition, item representations decay faster in 7-year-olds compared with adults even when the load of information is intermediate (3 items). Going beyond the developing ability to deploy visuospatial attentional control during the maintenance period (Shimi, Kuo, et al., 2014; Shimi, Nobre, et al., 2014; Shimi & Scerif, 2015), this effect suggests a cognitive mechanism that is responsible for the successful transfer of iconic representations to VSTM and changes between 7 years of age and adulthood.

Overall, current results confirm the functional significance of top-down attentional biases in VSTM encoding and maintenance in both 7-year-olds and adults: they indicated that deploying attentional control can facilitate the accurate retrieval of information from VSTM, corroborating a close coupling between attentional control and memory from childhood (Astle et al., 2012; Markant & Amso, 2013, 2014; Ross-Sheehy et al., 2011; Shimi, Nobre, et al., 2014). Critically, here we show that visuo-spatial attentional orienting interacts with multiple other critical factors (temporal decay, memory load) to influence later retrieval.

5.2. Implications for theoretical models of short-term/working memory

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, Allen, & Hitch, 2011; Salway & Logie, 1995; Ueno, Allen, Baddeley, Hitch, & Saito, 2011; Vandierendonck, Kemps, Fastame, & Szmalec, 2004). Indeed, influential models of WM ascribe a fundamental role to "attentional control" in their architecture either as a "central executive" responsible for controlling and manipulating representations stored in modality-specific systems and for ensuring the communication of these systems with LTM via the episodic buffer (Baddeley & Hitch, 1974; Baddeley, 1998; Baddeley, 2002a, 2002b, 2003) 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 and their later active maintenance also takes place via attentional refreshment, 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).

5.3. Implications for theories of VSTM and VWM development

Current accounts of VSTM development emphasise simple changes in the capacity to store more items in VSTM/VWM over changes in encoding efficiency or attentional filtering abilities (Cowan et al., 2011, 2010). While unarguably children have a more limited storage capacity that follows a monotonic increase with development (Cowan et al., 2011, 2010; Riggs et al., 2006; Simmering, 2012), here we show that, first, both children and adults are able to use visuo-spatial attention cues to maintain information in VSTM and, second, that adults do so in a way that allows them to access that information more accurately than children. Consistent with suggestions from the verbal domain (Barrouillet et al., 2009), here we show that attentional refreshment mechanisms influence WM abilities differentially for the two age groups: the smaller attentional benefits for 7-year-olds compared with adults corroborate the suggestion that changes in attentional refreshment mechanisms are also relevant to understanding changing in VSTM maintenance.

The smaller benefits for younger children are also consistent with time-based forgetting models proposing that memory traces in childhood decay fast with time (Hitch et al., 2001; Towse & Hitch, 1995; Towse et al., 2002; Towse et al., 1998), again primarily developed to account for maintenance of sequentially presented information. Here we provide complementary evidence that decay occurs for simultaneously presented information and in the absence of a concurrent secondary task. Importantly though, a simple decay account is not sufficient: decay seems to be modulated by the number of items that needs to be encoded and maintained in memory, as decay is faster when the number of items exceeds the limits of VSTM capacity and when the items are difficult to refresh (Shimi & Scerif, 2015). This indicates that time available for maintenance, although important, cannot alone account for 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 is active, rather than passive, and engages broad attentional processes[8].

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[8] We note that in the adult literature there is an ongoing debate on decay vs. interference and we clarify that we do not argue against the possibility of interference influencing performance in subsequent stages within the information processing stream (cf. adult results in Exp.3). In fact, we have previously suggested shared controlled mechanisms for avoiding interference (Shimi, Nobre, et al., 2014) and we are currently exploring further whether feature interference at test might constrain VSTM performance from early childhood to adulthood (Shimi & Scerif, in preparation). However, here we propose that decay in the early stages within the information processing stream should be taken into account when trying to understand 7-year-olds limited VSTM performance compared to adults.

5.4. Proposed model of VSTM maintenance: attention, time, and load all matter

A question that arises from the current experiments and is important for theories of cognitive development is why information decays to a greater extent in 7-year-olds when it exceeds VSTM capacity. This issue seems to relate to the mechanisms responsible for transferring memory representations from the rich and transient iconic system to the limited and durable VSTM system when the number of items exceeds the limits of VSTM capacity. We propose that this limitation can be explained by a model that incorporates more explicitly how and when visual attentional refreshment operates, potentially explaining why fewer and/or more degraded representations are transferred from IM to VSTM in 7-year-olds compared to adults. 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 rapidly 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. Here we propose that, first, older individuals are more efficient in using attention mechanisms to transfer a larger number of items from iconic to VSTM before they decay. An additional (and separable) source of age-related difference is the ability to then use top-down attentional control to selectively maintain a representation that has already been transferred to VSTM. It may be for example that once individuals are presented with a memory array, they can reactivate the representation of all items to prevent their loss, and adults implement this first process most efficiently. This re-activation process may occur via an attentional 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. Age-group differences in storage capacity may reflect, at least in part, immaturity in this early attentional re-activation mechanism. The more refined and faster this mechanism is, the fewer traces will decay and more robust representations will be transferred to durable VSTM. Figure 5 illustrates the information processing steps of the proposed integrative model.

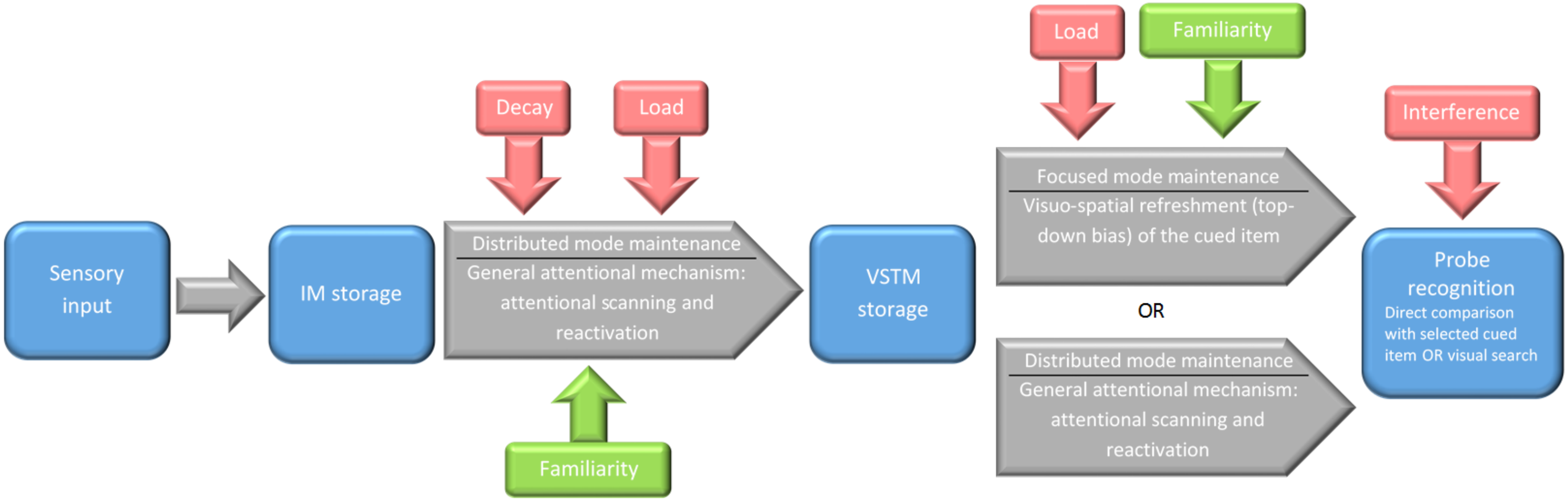

Figure 5: Figure 5 illustrates the information processing steps of the proposed integrative model. Sensory input is stored in the high-capacity IM system. Information is transferred to the limited-capacity VSTM system via a general attentional mechanism of item scanning and reactivation. Memory load constrains this maintenance process. Compared with a low memory load, a higher memory load requires longer scanning and reactivation, and due to decay fewer representations are transferred from IM to VSTM (cf. Experiments 1 and 3). Memoranda characteristics (e.g., familiarity) also constrain or enhance attentional reactivation further. The more difficult items (e.g., unfamiliar items) allow for less efficient scanning and attentional reactivation from long-term memory representations, allowing fewer items to be transferred to the durable VSTM system from the fragile IM system (cf. Shimi & Scerif,

2015). Once representations are transferred to VSTM, they are maintained via the general attentional mechanism (uncued trials) or via visuo-spatial attentional refreshment of the cued item (retro-cue trials; cf. Experiments 1-3; Shimi, Nobre, et al., 2014). Here, memoranda and memory load influence the magnitude and reliability of visuospatial attentional refreshment. Blue colour represents the cognitive stages within the information processing stream, i.e., sensory input, storage systems, and recognition. Grey colour represents the cognitive mechanisms taking place between the systems and during maintenance. Pink and green colours represent the cognitive and non-cognitive factors that influence the cognitive mechanisms. Developmental changes in the general attentional mechanism of item scanning and reactivation between IM and VSTM and between VSTM and probe recognition, as well as developmental changes in the mechanism of visuo-spatial attentional refreshment of the cued item, result in the behavioural differences in VSTM performance observed between 7-year-olds and adults.

Beyond this first iconic stage, representations transferred to VSTM also need to be maintained in VSTM until probe response. Adults are more efficient in re-activating these (transferred) durable representations via a scanning and refreshing mechanism either until probe response [(e.g., in neutral trials) – reflecting 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 the benefits of 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 reactivated enough and thus has degraded to a great extent, then top-down biasing and attentional refreshment via a retro-cue is not as successful. According to this account, the number of items that will be transferred to VSTM equals the number of items that participants have reactivated before these representations have degraded. In other words, fewer items during encoding allow more items to be reactivated and transferred before decay even in 7-year-olds whose early refreshment mechanism is less developed, whereas more items during encoding allow fewer items to be reactivated and transferred with remaining traces becoming lost due to decay. In light of the current results, it may be the case that *when memory load is low* and therefore within capacity limits, 7-year-olds are able to reactivate all the representations stored in IM before they decay by mentally scanning and attentionally refreshing rapidly all items; in this way 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 7-year-olds have the chance to reactivate all representations via this mental memory scanning and refreshing process. As a whole, therefore, our proposed account emphasises the importance of investigating generalised attention mechanisms, temporal parameters, and directed attentional spatial mechanisms as constraints on the ability to transfer to and maintain information in VSTM.

Additional factors that were not studied here could also be integrated into this multi-componential framework. For example, the memoranda characteristics will also constrain or enhance maintenance further (Cowan et al., 2015; Ricker & Cowan, 2010; Shimi & Scerif, 2015). 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. In contrast, familiar items will facilitate the reactivation rate because there are multiple mental codes (visual, semantic, etc.) that participants can rely on to internally scan and recall an item (Shimi & Scerif, 2015). Additional adult findings support the significance of the interval between IM and VSTM in forming robust VSTM representations. In a series of experiments, Logie, Brockmole, and Jaswal (2011) showed that randomizing task-irrelevant features of visual items between study and test at short iconic intervals (e.g., 500ms) had a disruptive effect on VSTM performance compared to items with unchanged features, whereas performance between randomized and unchanged conditions did not differ if randomization occurred at longer study-test intervals (>1000ms), implying decay of high-fidelity iconic traces during the first second following the test offset, followed by formation of stable task-relevant bound features in VSTM.

Most importantly, and perhaps most explicitly for the first time, the current model highlights that there are distinguishable and complementary attentional mechanisms to be involved in VSTM: the first one is a “general” *attentional scanning and reactivation mechanism* that operates in a distributed mode and that is responsible for transferring information across memory systems and for retaining information when no cues are available. Neutral, baseline trials or the first maintenance interval between the memory array and the retro-cue in cued trials operate in a distributed mode. We consider this mechanism to function rather rapidly with attention being allocated transiently. For example, using a change-detection paradigm, Vogel, Woodman, and Luck (2006) found that adults needed about 50ms per item to encode and consolidate items in VSTM and for larger arrays, participants required more uninterrupted processing time than for smaller arrays in order to create durable VSTM representations. Similarly, using a variety of traditional STM paradigms (e.g., Sternberg item recognition), Vergauwe and Cowan (2014) found that adults retrieved items during the maintenance period at a speed of ~40ms per item pointing to high-speed retrieval underlying memory search and refreshing. Comparable processing rates have been estimated for attentional scanning in visual search tasks (e.g., Woodman & Luck, 1999). In contrast, differential rates in the ability to focus attention have been observed between high and low WM span individuals (Heitz & Engle, 2007). At the neural level, reactivation is assumed to be achieved via persistent neuronal firing during the delay period in the gamma frequency range. For example, gamma-band neural oscillations have been implicated in the maintenance of VSTM/VWM information (Palva, Kulashekhar, Hämäläinen, & Palva, 2011; Roux, Wibral, Mohr, Singer, & Uhlhaas, 2012). However, further neuroscience research is needed to investigate precisely the implication of a reactivation mechanism of mental representations during simultaneous maintenance, similar to how multiple sequential items are neurally coded and stored in STM (Lisman & Idiart, 1995; Lisman & Jensen, 2013; Usher, Haarman, Cohen, & Horn, 2001).

The second mechanism in our model is a “specialised” *visuo-spatial refreshment mechanism* that operates in a focused mode and that is responsible for applying top-down biases internally. Retro-cues operate in a focused mode and they refresh a spatially selected internal representation by triggering spatiotopic access to it (Myers, Walther, Wallis, Stokes, & Nobre, 2015) and boost its signal via sustained, elevated neural firing during the cue – probe interval (LaRocque, Lewis-Peacock, Drysdale, Oberauer, & Postle, 2013; Lewis-Peacock, Drysdale, Oberauer, & Postle, 2012). This shift in the mode of attentional refreshment following retro-cue onset is also supported by evidence of modulation of alpha-band neural oscillations, after retro-cues, enabling maintenance of the cued item (Myers et al., 2015; Poch, Campo, & Barnes, 2014). Similarly, pre-cues operate in a focused mode although they act as a prioritization mechanism (Schmidt et al., 2002) whereas retro-cues act as a protection mechanism either from decay (current results) or interference at least during the maintenance period (Shimi, Nobre, et al., 2014). Based on our model, we estimate that 7-year-olds require more time (>50ms) than adults to scan an item and therefore iconic representations decay faster before children can reactivate them all and generate robust VSTM representations. Further research is needed to investigate precise retrieval rates for visual items across different age groups. Moreover, additional research is needed to examine whether in addition to degradation of the quantity of representations (i.e., number of items), the quality (i.e., resolution) of 7-year-olds’ representations is poorer compared to adults. It may be, for example, that the precision by which individuals retain memory items changes 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.

6. Conclusions

The main aim of this paper was to go beyond the investigation of single mechanisms, such as broad attentional control or VSTM storage capacity, which may all constrain 7-year-olds' ability to maintain items in VSTM, in an attempt to understand in depth the *multiple* processes contributing to VSTM maintenance and their interactions. Current results led us to suggest an integrative model that describes the mechanisms gating transfer into and maintenance of information in VSTM, for both 7-year-olds and adults. Jonides and colleagues stated that "A proper theory (of VSTM) must articulate the processes that create and operate on representations … including encoding and maintenance operations, …, shifts of attention …, and retrieval mechanisms" (Jonides et al., 2008, pp. 195). We believe that an integrative theoretical framework taking into account multiple processes and their interactions holds the promise to study and understand developing VSTM, but also the developed adult state.

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References

Ackerman, P. L., Beier, M. E., & Boyle, M. O. (2002). Individual differences in working memory within a nomological network of cognitive and perceptual speed abilities. *Journal of Experimental Psychology: General*, *131*(4), 567–589. http://doi.org/10.1037/0096-3445.131.4.567

Allen, R. J., Baddeley, A. D., & Hitch, G. J. (2006). Is the binding of visual features in working memory resource-demanding? *Journal of Experimental Psychology: General*, *135*(2), 298–313. http://doi.org/10.1037/0096-3445.135.2.298

Alvarez, G. A., & Cavanagh, P. (2004). The Capacity of Visual Short-Term Memory is Set Both by Visual Information Load and by Number of Objects. *Psychological Science*, *15*(2), 106–111. http://doi.org/10.1111/j.0963-7214.2004.01502006.x

Amso, D., & Johnson, S. P. (2006). Learning by selection: visual search and object perception in young infants. *Developmental Psychology*, *42*(6), 1236–1245. http://doi.org/10.1037/0012-1649.42.6.1236

Amso, D., & Scerif, G. (2015). The attentive brain : insights from developmental cognitive neuroscience. *Nature Reviews Neuroscience*, *16*(10), 606–619. http://doi.org/10.1038/nrn4025

Astle, D. E., Harvey, H., Stokes, M., Mohseni, H., Nobre, A. C., & Scerif, G. (2014). Distinct neural mechanisms of individual and developmental differences in VSTM capacity. *Developmental Psychobiology*, *56*(4), 601–610. http://doi.org/10.1002/dev.21126

Astle, D. E., Nobre, A. C., & Scerif, G. (2012). Attentional control constrains visual short-term memory: Insights from developmental and individual differences. *The Quarterly Journal of Experimental Psychology*, *65*(2), 277–294. http://doi.org/10.1080/17470218.2010.492622

Astle, D. E., Summerfield, J., Griffin, I., & Nobre, A. C. (2011). Orienting attention to locations in mental representations. *Attention, Perception & Psychophysics*, *74*(1), 146–162. http://doi.org/10.3758/s13414-011-0218-3

Averbach, E., & Coriell, A. S. (1961). Short-term memory in vision. *Bell Systems Technical Journal*, *40*, 309–328.

Awh, E., & Jonides, J. (1998). Spatial selective attention and spatial working memory. In R. Parasuraman (Ed.), *The Attentive Brain* (pp. 353–380). Cambridge: MA: MIT Press.

Awh, E., & Jonides, J. (2001). Overlapping mechanisms of attention and spatial working memory. *Trends in Cognitive Sciences*, *5*(3), 119–126. http://doi.org/10.1016/S1364-6613(00)01593-X

Awh, E., Jonides, J., & Reuter-Lorenz, P. A. (1998). Rehearsal in spatial working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(3), 780–790.

Awh, E., Vogel, E. K., & Oh, S.-H. (2006). Interactions between attention and working memory. *Neuroscience*, *139*(1), 201–208. http://doi.org/10.1016/j.neuroscience.2005.08.023

Baddeley, A. (2000). The episodic buffer: a new component of working memory? *Trends in*

Cognitive Sciences, *4*(11), 417–423. http://doi.org/10.1016/S1364-6613(00)01538-2

Baddeley, A. D. (1998). The central executive: a concept and some misconceptions. *Journal of the International Neuropsychological Society*, *4*, 523–526.

Baddeley, A. D. (2002a). Fractionating the Central Executive. In D. Stuss & R. T. Knight (Eds.), *Principles of the Frontal Lobe Function* (Vol. 44, pp. 246–260). New York: Oxford University Press.

Baddeley, A. D. (2002b). Is Working Memory Still Working? *European Psychologist*, *7*(2), 85–97. http://doi.org/10.1027//1016-9040.7.2.85

Baddeley, A. D. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience*, *4*, 829–839. http://doi.org/10.1038/nrn1201

Baddeley, A. D., Allen, R. J., & Hitch, G. J. (2011). Binding in visual working memory: The role of the episodic buffer. *Neuropsychologia*, *49*(6), 1393–400. http://doi.org/10.1016/j.neuropsychologia.2010.12.042

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. *Science*, *255*(5044), 556–559. http://doi.org/10.1126/science.1736359

Baddeley, A. D., & Hitch, G. J. (2000). Development of working memory: should the Pascual-Leone and the Baddeley and Hitch models be merged? *Journal of Experimental Child Psychology*, *77*(2), 128–137. http://doi.org/10.1006/jecp.2000.2592

Baddeley, A. D., & Logie, R. H. (1999). Working memory: The multiple-component model. In A. Miyake & P. Shah (Eds.), *Models of Working Memory: Mechanisms of Active Mainenance and Executive Control* (pp. 28–61). Cambridge, UK: Cambridge University Press.

Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General*, *133*(1), 83–100. http://doi.org/10.1037/0096-3445.133.1.83

Barrouillet, P., & Camos, V. (2001). Developmental Increase in Working Memory Span: Resource Sharing or Temporal Decay? *Journal of Memory and Language*, *45*(1), 1–20. http://doi.org/10.1006/jmla.2001.2767

Barrouillet, P., De Paepe, A., & Langerock, N. (2012). Time causes forgetting from working memory. *Psychonomic Bulletin & Review*, *19*(1), 87–92. http://doi.org/10.3758/s13423-011-0192-8

Barrouillet, P., Gavens, N., Vergauwe, E., Gaillard, V., & Camos, V. (2009). Working memory span development: A time-based resource-sharing model account. *Developmental Psychology*, *45*(2), 477–490. http://doi.org/10.1037/a0014615

Becker, M. W., Pashler, H., & Anstis, S. M. (2000). The role of iconic memory in change-detection tasks. *Perception*, *29*, 273–286. http://doi.org/10.1068/p3035

Blaser, E., & Kaldy, Z. (2010). Infants get five stars on iconic memory tests: A partial-report test of 6-month-old infants' iconic memory capacity. *Psychological Science*, *21*(11), 1643–1645. http://doi.org/http://dx.doi.org/10.1177/0956797610385358

Brockmole, J. R., & Logie, R. H. (2013). Age-related change in visual working memory: A study of 55,753 participants aged 8-75. *Frontiers in Psychology*, *4*(JAN), 1–5. http://doi.org/10.3389/fpsyg.2013.00012

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching, and working memory. *Developmental Neuropsychology*, *19*(3), 273–293.

Burgess, G. C., Gray, J. R., Conway, A. R. a., & Braver, T. S. (2011). Neural mechanisms of interference control underlie the relationship between fluid intelligence and working memory span. *Journal of Experimental Psychology: General*, *140*(4), 674–692. http://doi.org/10.1037/a0024695

Burgess, N., & Hitch, G. J. (1999). Memory for serial order: A network model of the phonological loop and its timing. *Psychological Review*, *106*(3), 551–581. http://doi.org/10.1037//0033-295X.106.3.551

Burnett Heyes, S., Zokaei, N., van der Staaij, I., Bays, P. M., & Husain, M. (2012). Development of visual working memory precision in childhood. *Developmental Science*, *15*(4), 528–539. http://doi.org/10.1111/j.1467-7687.2012.01148.x

Camos, V., & Barrouillet, P. (2011). Developmental change in working memory strategies: from passive maintenance to active refreshing. *Developmental Psychology*, *47*(3), 898–904. http://doi.org/10.1037/a0023193

Case, R. (1985). *Intellectual development: Birth to adulthood*. New York: Academic Press.

Case, R., Kurland, M., & Goldberg, J. (1982). Operational efficiency and the growth of short-term memory span. *Journal of Experimental Child Psychology*, *33*, 386–404.

Chun, M. M. (2011). Visual working memory as visual attention sustained internally over time. *Neuropsychologia*, *49*(6), 1407–1409. http://doi.org/10.1016/j.neuropsychologia.2011.01.029

Chun, M. M., Golomb, J. D., & Turk-Browne, N. B. (2011). A taxonomy of external and internal attention. *Annual Review of Psychology*, *62*, 73–101. http://doi.org/10.1146/annurev.psych.093008.100427

Chun, M. M., & Johnson, M. K. (2011). Memory: Enduring traces of perceptual and reflective attention. *Neuron*, *72*(4), 520–535. http://doi.org/10.1016/j.neuron.2011.10.026

Chun, M. M., & Turk-Browne, N. B. (2007). Interactions between attention and memory. *Current Opinion in Neurobiology*, *17*(2), 177–184. http://doi.org/10.1016/j.conb.2007.03.005

Conway, A. R. A., Kane, M. J., & Engle, R. W. (2003). Working memory capacity and its relation to general intelligence. *Trends in Cognitive Sciences*, *7*(12), 547–552. http://doi.org/10.1016/j.tics.2003.10.005

Corbetta, M., Kincade, J. M., & Shulman, G. L. (2002). Neural systems for visual orienting and their relationships to spatial working memory. *Journal of Cognitive Neuroscience*, *14*(3), 508–523. http://doi.org/10.1162/089892902317362029

Cowan, N. (1988). Evolving Concenptions of Memory Storage, Selective Attention, and their Mutual Constraits Within the Human Information-Processing System. *Psychological Bulletin*, *104*(2), 163–191.

Cowan, N. (1992). Verbal Memory Span and the Timing of Spoken Recall. *Journal of Memory and Language*, *684*(5), 668–684. http://doi.org/10.1016/0749-596X(92)90034-U

Cowan, N. (1999). An embedded-processes model of working memory. In P. Shah (Ed.), *Models of Working Memory: Mechanisms of Active Mainenance and Executive Control* (pp. 62–101). Cambridge, UK: Cambridge University Press.

Cowan, N. (2001). The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *The Behavioral and Brain Sciences*, *24*, 87–185.

Cowan, N. (2005). *Working Memory Capacity*. Hove, UK: Psychology Press.

Cowan, N. (2011). The focus of attention as observed in visual working memory tasks: making sense of competing claims. *Neuropsychologia*, *49*(6), 1401–1406. http://doi.org/10.1016/j.neuropsychologia.2011.01.035

Cowan, N. (2014). Short-term and working memory in childhood. In P. J. Bauer & R. Fivush (Eds.), *The Wiley Handbook on the Development of Children's Memory* (pp. 202–229). West Sussex, UK: Wiley-Blackwell. http://doi.org/10.1002/9781118597705.ch10

Cowan, N. (2015). Working Memory Maturation: Can We Get At the Essence of Cognitive Growth? *Perspectives on Psychological Science*.

Cowan, N., Aubuchon, A. M., Gilchrist, A. L., Ricker, T. J., & Saults, J. S. (2011). Age differences in visual working memory capacity: not based on encoding limitations. *Developmental Science*, *14*(5), 1066–1074. http://doi.org/10.1111/j.1467-7687.2011.01060.x

Cowan, N., Blume, C. L., & Saults, J. S. (2012). Attention to Attributes and Objects in Working Memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(3), 731–747. http://doi.org/10.1037/a0029687

Cowan, N., Elliott, E. M., Scott Saults, J., Morey, C. C., Mattox, S., Hismjatullina, A., & Conway, A. R. a. (2005). On the capacity of attention: its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology*, *51*(1), 42–100. http://doi.org/10.1016/j.cogpsych.2004.12.001

Cowan, N., Fristoe, N. M., Elliott, E. M., Brunner, R. P., & Saults, J. S. (2006). Scope of attention, control of attention, and intelligence in children and adults. *Memory & Cognition*, *34*(8), 1754–1768. http://doi.org/10.3758/BF03195936

Cowan, N., Morey, C. C., AuBuchon, A. M., Zwilling, C. E., & Gilchrist, A. L. (2010). Seven-year-olds allocate attention like adults unless working memory is overloaded. *Developmental Science*, *13*(1), 120–133. http://doi.org/10.1111/j.1467-7687.2009.00864.x

Cowan, N., Nugent, L. D., Elliott, E. M., & Saults, J. S. (2000). Persistence of memory for ignored lists of digits: areas of developmental constancy and change. *Journal of Experimental Child Psychology*, *76*, 151–172. http://doi.org/10.1006/jecp.1999.2546

Cowan, N., Ricker, T. J., Clark, K. M., Hinrichs, G. A., & Glass, B. A. (2015). Knowledge cannot explain the developmental growth of working memory capacity. *Developmental Science*, *18*(1), 132–145. http://doi.org/10.1111/desc.12197

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience*, *18*(1), 193–222. http://doi.org/10.1146/annurev.ne.18.030195.001205

Dick, A. (1974). Iconic memory and its relation to perceptual processing and other memory mechanisms. *Perception & Psychophysics*, *16*(3), 575–596. http://doi.org/10.3758/BF03198590

Emrich, S. M., Al-Aidroos, N., Pratt, J., & Ferber, S. (2009). Visual Search Elicits the Electrophysiological Marker of Visual Working Memory. *PLoS ONE*, *4*(11). http://doi.org/10.1371/journal.pone.0008042

Engel de Abreu, P. M. J., Conway, A. R. A., & Gathercole, S. E. (2010). Working memory and fluid intelligence in young children. *Intelligence*, *38*(6), 552–561. http://doi.org/10.1016/j.intell.2010.07.003

Engle, R., Tuholski, S., Laughlin, J., & Conway, A. R. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology: General*, *128*, 309–331.

Fair, D. A., Dosenbach, N. U. F., Church, J. A., Cohen, A. L., Brahmbhatt, S., Miezin, F. M., … Schlaggar, B. L. (2007). Development of distinct control networks through segregation and integration. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(33), 13507–12. http://doi.org/10.1073/pnas.0705843104

Gaillard, V., Barrouillet, P., Jarrold, C., & Camos, V. (2011). Developmental differences in working memory: Where do they come from? *Journal of Experimental Child Psychology*, *110*(3), 469–479. http://doi.org/10.1016/j.jecp.2011.05.004

Gathercole, S. E. (1999). Cognitive approaches to the development of short-term memory. *Trends in Cognitive Sciences*, *3*, 410–419.

Gathercole, S. E., Pickering, S. J., Ambridge, B., & Wearing, H. (2004). The structure of working memory from 4 to 15 years of age. *Developmental Psychology*, *40*, 177–190. http://doi.org/10.1037/0012-1649.40.2.177

Gazzaley, A. (2011). Influence of early attentional modulation on working memory. *Neuropsychologia*, *49*(6), 1410–1424. http://doi.org/10.1016/j.neuropsychologia.2010.12.022

Gazzaley, A., & Nobre, A. C. (2012). Top-down modulation: bridging selective attention and working memory. *Trends in Cognitive Sciences*, *16*(2), 129–135. http://doi.org/10.1016/j.tics.2011.11.014

Gilchrist, A. L., & Cowan, N. (2011). Can the focus of attention accommodate multiple, separate items? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*(6), 1484–1502. http://doi.org/10.1037/a0024352

Griffin, I. C., & Nobre, A. C. (2003). Orienting attention to locations in internal representations. *Journal of Cognitive Neuroscience*, *15*(8), 1176–1194. http://doi.org/10.1162/089892903322598139

Heitz, R. P., & Engle, R. W. (2007). Focusing the Spotlight: Individual Differences in Visual Attention Control. *Journal of Experimental Psychology: General*, *136*(2), 217–240. http://doi.org/10.1037/0096-3445.136.2.217

Hitch, G. J. (1990). Developmental fractionation of working memory. In *Neuropsychological impairment of short-term memory* (pp. 221–246). Cambridge, UK: Cambridge University Press.

Hitch, G. J., Towse, J. N., & Hutton, U. (2001). What limits children's working memory span? Theoretical accounts and applications for scholastic development. *Journal of Experimental Psychology: General*, *130*, 184–198. http://doi.org/10.1037//0096-3445.130.2.184

Isbell, E., Fukuda, K., Neville, H. J., & Vogel, E. K. (2015). Visual working memory continues to develop through adolescence. *Frontiers in Psychology*, *6*(May), 1–10. http://doi.org/10.3389/fpsyg.2015.00696

Jonides, J., Lewis, R. L., Nee, D. E., Lustig, C. A., Berman, M. G., & Moore, K. S. (2009). The mind and brain of short-term memory. *Annual Review of Psychology*, *59*(5), 193–224. http://doi.org/10.1146/annurev.psych.59.103006.093615

Káldy, Z., & Leslie, A. M. (2005). A memory span of one? Object identification in 6.5-month-old infants. *Cognition*, *97*(2), 153–177. http://doi.org/10.1016/j.cognition.2004.09.009

Kane, M. J., Bleckley, M. K., Conway, A. R. A., & Engle, R. W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General*, *130*(2), 169–183.

Kane, M. J., Hambrick, D. Z., & Conway, A. R. A. (2005). Working memory capacity and fluid intelligence are strongly related constructs: Comment on Ackerman, Beier, and Boyle (2005). *Psychological Bulletin*, *131*(1), 66–71. http://doi.org/10.1037/0033-2909.131.1.66

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: a latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General*, *133*(2), 189–217. http://doi.org/10.1037/0096-3445.133.2.189

Kiyonaga, A., & Egner, T. (2013). Working memory as internal attention: toward an integrative account of internal and external selection processes. *Psychonomic Bulletin & Review*, *20*(2), 228–242. http://doi.org/10.3758/s13423-012-0359-y

Klingberg, T., Forssberg, H., & Westerberg, H. (2002). Increased brain activity in frontal and parietal cortex underlies the development of visuospatial working memory capacity during childhood. *Journal of Cognitive Neuroscience*, *14*(1), 1–10. http://doi.org/10.1162/089892902317205276

Kuo, B.-C., Stokes, M. G., & Nobre, A. C. (2012). Attention modulates maintenance of representations in visual short-term memory. *Journal of Cognitive Neuroscience*, *24*(1), 51–60. http://doi.org/10.1162/jocn_a_00087

Kuo, B.-C., Yeh, Y.-Y., Chen, A. J.-W., & D'Esposito, M. (2011). Functional connectivity during top-down modulation of visual short-term memory representations. *Neuropsychologia*, *49*, 1589–1596. http://doi.org/10.1016/j.neuropsychologia.2010.12.043

LaBar, K. S., Gitelman, D. R., Parrish, T. B., & Mesulam, M. (1999). Neuroanatomic overlap of working memory and spatial attention networks: a functional MRI comparison within subjects. *NeuroImage, 10*(6), 695–704. http://doi.org/10.1006/nimg.1999.0503

Landman, R., Spekreijse, H., & Lamme, V. A. F. (2003). Large capacity storage of integrated objects before change blindness. *Vision Research*, *43*, 149–164.

LaRocque, J. J., Lewis-Peacock, J. A., Drysdale, A. T., Oberauer, K., & Postle, B. R. (2013). Decoding attended information in short-term memory: an EEG study. *Journal of Cognitive Neuroscience*, *25*(1), 127–142. http://doi.org/10.1162/jocn_a_00305

Lepsien, J., Griffin, I. C., Devlin, J. T., & Nobre, A. C. (2005). Directing spatial attention in mental representations: Interactions between attentional orienting and working-memory load. *NeuroImage*, *26*(3), 733–743. http://doi.org/10.1016/j.neuroimage.2005.02.026

Lepsien, J., & Nobre, A. C. (2006). Cognitive control of attention in the human brain: insights from orienting attention to mental representations. *Brain Research*, *1105*, 20–31. http://doi.org/10.1016/j.brainres.2006.03.033

Lepsien, J., & Nobre, A. C. (2007). Attentional modulation of object representations in working memory. *Cerebral Cortex*, *17,* 2072–2083. http://doi.org/10.1093/cercor/bhl116

Lepsien, J., Thornton, I., & Nobre, A. C. (2011). Modulation of working-memory maintenance by directed attention. *Neuropsychologia*, *49*(6), 1569–1577. http://doi.org/10.1016/j.neuropsychologia.2011.03.011

Lewandowsky, S., Duncan, M., & Brown, G. D. A. (2004). Time does not cause forgetting in short-term serial recall. *Psychonomic Bulletin & Review*, *11*(5), 771–790.

Lewandowsky, S., & Oberauer, K. (2009). No evidence for temporal decay in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(6), 1545–1551. http://doi.org/10.1037/a0017010

Lewis-Peacock, J. A., Drysdale, A. T., Oberauer, K., & Postle, B. R. (2012). Neural evidence for a distinction between short-term memory and the focus of attention. *Journal of Cognitive Neuroscience*, *24*(1), 61–79. http://doi.org/10.1162/jocn_a_00140

Lisman, J. E., & Idiart, M. A. (1995). Storage of 7 +- 2 Short-Term Memories in Oscillatory Subcycles. *Science*, *267*(5203), 1512–1515. http://doi.org/10.1126/science.7878473

Lisman, J. E., & Jensen, O. (2013). The Theta-Gamma Neural Code. *Neuron*, *77*(6), 1002–1016. http://doi.org/10.1016/j.neuron.2013.03.007

Logie, R. H. (1995). *Visuo-spatial Working Memory*. Hove, UK: Lawrence Erlbaum Associates.

Logie, R. H. (2003). Spatial and visual working memory: A mental workspace. In D. E. Irwin & B. H. Rossion (Eds.), *Cognitive Vision: The Psychology of Learning and Motivation* (pp. 37–38). San Diego: Academic Press.

Logie, R. H. (2011). The Functional Organization and Capacity Limits of Working Memory. *Current Directions in Psychological Science*, *20*(4), 240–245. http://doi.org/10.1177/0963721411415340

Logie, R. H., Brockmole, J. R., & Jaswal, S. (2011). Feature binding in visual short-term memory is unaffected by task-irrelevant changes of location, shape, and color. *Memory & Cognition*, *39*(1), 24–36. http://doi.org/10.3758/s13421-010-0001-z

Logie, R. H., & Pearson, D. G. (1997). The inner eye and the inner scribe of visuo-spatial working memory: Evidence from developmental fractionation. *European Journal of Cognitive Psychology*, *9*(3), 241–257.

Luciana, M., Conklin, H. M., Hooper, C. J., & Yarger, R. S. (2005). The development of nonverbal working memory and executive control processes in adolescents. *Child Development*, *76*(3), 697–712. http://doi.org/10.1111/j.1467-8624.2005.00872.x

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279–281. http://doi.org/10.1038/36846

Makovski, T., & Jiang, Y. V. (2007). Distributing versus focusing attention in visual short-term memory. *Psychonomic Bulletin & Review*, *14*(6), 1072–1078.

Makovski, T., Sussman, R., & Jiang, Y. V. (2008). Orienting attention in visual working memory reduces interference from memory probes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(2), 369–380. http://doi.org/10.1037/0278-7393.34.2.369

Markant, J., & Amso, D. (2013). Selective memories: infants' encoding is enhanced in selection via suppression. *Developmental Science*, *16*(6), 926–940. http://doi.org/10.1111/desc.12084

Markant, J., & Amso, D. (2014). Leveling the playing field: attention mitigates the effects of intelligence on memory. *Cognition*, *131*(2), 195–204. http://doi.org/10.1016/j.cognition.2014.01.006

Matsukura, M., Cosman, J. D., Roper, Z. J. J., Vatterott, D. B., & Vecera, S. P. (2014). Location-specific effects of attention during visual short-term memory maintenance. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(3), 1103–1116. http://doi.org/10.1037/a0035685

Matsukura, M., & Hollingworth, A. (2011). Does visual short-term memory have a high-capacity stage? *Psychonomic Bulletin & Review*, 1098–1104. http://doi.org/10.3758/s13423-011-0153-2

Matsukura, M., Luck, S. J., & Vecera, S. P. (2007). Attention effects during visual short-term memory maintenance: protection or prioritization? *Perception & Psychophysics*, *69*(8), 1422–1434. http://doi.org/10.3758/BF03192957

McElree, B. (2001). Working memory and focal attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*, 817–835.

McElree, B. (2006). Accessing recent events. *Psychology of Learning and Motivation*, *46*, 155–200. http://doi.org/10.1016/S0079-7421(06)46005-9

Miller, G. A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review*, *63*(2), 81–97. http://doi.org/10.1037/h0043158

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “Frontal Lobe” tasks: a latent variable analysis. *Cognitive Psychology*, *41*(1), 49–100. http://doi.org/10.1006/cogp.1999.0734

Murray, A. M., Nobre, A. C., & Stokes, M. G. (2011). Markers of preparatory attention predict visual short-term memory performance. *Neuropsychologia*, *49*, 1458–1465. http://doi.org/10.1016/j.neuropsychologia.2011.02.016

Myers, N. N. E., Walther, L., Wallis, G., Stokes, M. G., & Nobre, A. C. (2015). Temporal dynamics of attention during encoding versus maintenance of working memory: complementary views from event-related potentials and alpha-band oscillations. *Journal of Cognitive Neuroscience*, *27*(3), 492–508. http://doi.org/10.1162/jocn

Neisser, U. (1967). *Cognitive Psychology*. New York: Appleton-Century-Crofts.

Nobre, A. C., Griffin, I. C., & Rao, A. (2008). Spatial attention can bias search in visual short-term memory. *Frontiers in Human Neuroscience*, *1*(4), 1–9. http://doi.org/10.3389/neuro.09.004.2007

Nobre, A. C., & Stokes, M. G. (2011). Attention and short-term memory: crossroads. *Neuropsychologia*, *49*(6), 1391–1392. http://doi.org/10.1016/j.neuropsychologia.2011.04.014

Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*(3), 411–421. http://doi.org/10.1037//0278-7393.28.3.411

Oberauer, K. (2003). Selective Attention to Elements in Working Memory. *Experimental Psychology*, *50*, 257–269. http://doi.org/10.1027//1618-3169.50.4.257

Oberauer, K., & Bialkova, S. (2009). Accessing information in working memory: can the focus of attention grasp two elements at the same time? *Journal of Experimental Psychology: General*, *138*(1), 64–87. http://doi.org/10.1037/a0014738

Oberauer, K., & Lewandowsky, S. (2008). Forgetting in immediate serial recall: decay, temporal distinctiveness, or interference? *Psychological Review*, *115*(3), 544–576. http://doi.org/10.1037/0033-295X.115.3.544

Olesen, P. J., Macoveanu, J., Tegnér, J., & Klingberg, T. (2007). Brain activity related to working memory and distraction in children and adults. *Cerebral Cortex*, *17*, 1047–1054. http://doi.org/10.1093/cercor/bhl014

Olivers, C. N. L. (2008). Interactions between visual working memory and visual attention. *Frontiers in Bioscience: A Journal and Virtual Library*, *13*, 1182–1191.

Palva, S., Kulashekhar, S., Hämäläinen, M., & Palva, J. M. (2011). Localization of cortical phase and amplitude dynamics during visual working memory encoding and retention. *The Journal of Neuroscience*, *31*(13), 5013–5025. http://doi.org/10.1523/JNEUROSCI.5592-

10.2011

Pashler, H. (1988). Familiarity and visual change detection. *Perception & Psychophysics*, *44*(4), 369–378.

Pertzov, Y., Bays, P. M., Joseph, S., & Husain, M. (2013). Rapid forgetting prevented by retrospective attention cues. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(5), 1224–1231. http://doi.org/10.1037/a0030947

Phillips, W. A. (1974). On the distinction between sensory storage and short-term visual memory. *Perception & Psychophysics*, *16*, 283–290.

Poch, C., Campo, P., & Barnes, G. R. (2014). Modulation of alpha and gamma oscillations related to retrospectively orienting attention within working memory. *European Journal of Neuroscience*, *40*(2), 2399–2405. http://doi.org/10.1111/ejn.12589

Portrat, S., Camos, V., & Barrouillet, P. (2009). Working memory in children: a time-constrained functioning similar to adults. *Journal of Experimental Child Psychology*, *102*(3), 368–74. http://doi.org/10.1016/j.jecp.2008.05.005

Postle, B. R. (2006). Working memory as an emergent property of the mind and brain. *Neuroscience*, *139*, 23–38. http://doi.org/10.1016/j.neuroscience.2005.06.005

Raye, C. L., Johnson, M. K., Mitchell, K. J., Greene, E. J., & Johnson, M. R. (2007). Refreshing: A minimal executive function. *Cortex*, *43*, 135–145.

Raye, C. L., Johnson, M. K., Mitchell, K. J., Reeder, J. a, & Greene, E. J. (2002). Neuroimaging a single thought: dorsolateral PFC activity associated with refreshing just-activated information. *NeuroImage*, *15*, 447–453. http://doi.org/10.1006/nimg.2001.0983

Rerko, L., & Oberauer, K. (2013). Focused, unfocused, and defocused information in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*(4), 1075–96. http://doi.org/10.1037/a0031172

Ricker, T. J., & Cowan, N. (2010). Loss of visual working memory within seconds: the combined use of refreshable and non-refreshable features. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(6), 1355–1368. http://doi.org/10.1037/a0020356

Ricker, T. J., & Cowan, N. (2014). Differences between presentation methods in working memory procedures: a matter of working memory consolidation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(2), 417–428. http://doi.org/10.1037/a0034301

Riggs, K. J., McTaggart, J., Simpson, A., & Freeman, R. P. J. (2006). Changes in the capacity of visual working memory in 5- to 10-year-olds. *Journal of Experimental Child Psychology*, *95*(1), 18–26. http://doi.org/10.1016/j.jecp.2006.03.009

Riggs, K. J., Simpson, A., & Potts, T. (2011). The development of visual short-term memory for multifeature items during middle childhood. *Journal of Experimental Child Psychology*, *108*(4), 802–809. http://doi.org/10.1016/j.jecp.2010.11.006

Ross-Sheehy, S., Oakes, L. M., & Luck, S. J. (2011). Exogenous attention influences visual short-term memory in infants. *Developmental Science*, *14*(3), 490–501. http://doi.org/10.1111/j.1467-7687.2010.00992.x

Roth, J. K., Johnson, M. K., Raye, C. L., & Constable, R. T. (2009). Similar and dissociable mechanisms for attention to internal versus external information. *NeuroImage*, *48*, 601–608. http://doi.org/10.1016/j.neuroimage.2009.07.002

Roux, F., Wibral, M., Mohr, H. M., Singer, W., & Uhlhaas, P. J. (2012). Gamma-Band Activity in Human Prefrontal Cortex Codes for the Number of Relevant Items Maintained in Working Memory. *Journal of Neuroscience*, *32*(36), 12411–12420. http://doi.org/10.1523/JNEUROSCI.0421-12.2012

Salway, A. F. S., & Logie, R. H. (1995). Visuospatial working memory, movement control and executive demands. *British Journal of Psychology*, *86*(2), 253–269. Retrieved from http://onlinelibrary.wiley.com/doi/10.1111/j.2044-8295.1995.tb02560.x/abstract

Sander, M. C., Werkle-Bergner, M., & Lindenberger, U. (2011). Contralateral Delay Activity Reveals Life-Span Age Differences in Top-Down Modulation of Working Memory Contents. *Cerebral Cortex*, *21*(12), 2809–2819. http://doi.org/10.1093/cercor/bhr076

Schmidt, B. K., Vogel, E. K., Woodman, G. F., & Luck, S. J. (2002). Voluntazy and automatic attentional control of visual working memory. *Perception & Psychophysics*, *64*(5), 754–763.

Shimi, A., Kuo, B.-C. B., Astle, D. D. E., Nobre, A. C. A., & Scerif, G. (2014). Age Group and Individual Differences in Attentional Orienting Dissociate Neural Mechanisms of Encoding and Maintenance in Visual STM. *Journal of Cognitive Neuroscience*, *26*(4), 864–877. http://doi.org/10.1162/jocn_a_00526

Shimi, A., Nobre, A. C., Astle, D., & Scerif, G. (2014). Orienting attention within visual short-term memory: development and mechanisms. *Child Development*, *85*(2), 578–592. http://doi.org/10.1111/cdev.12150

Shimi, A., Nobre, A. C., & Scerif, G. (2015). ERP markers of target selection discriminate children with high vs. low working memory capacity. *Frontiers in Systems Neuroscience*, *9*(November), 1–10. http://doi.org/10.3389/fnsys.2015.00153

Shimi, A., & Scerif, G. (2015). The interplay of spatial attentional biases and mental codes in VSTM: Developmentally informed hypotheses. *Developmental Psychology*, *51*(6), 731–743. http://doi.org/10.1037/a0039057

Shimi, A., Woolrich, M. W., Mantini, D., & Astle, D. E. (2015). Memory load modulates graded changes in distracter filtering. *Frontiers in Human Neuroscience*, *8*(January), 1–9. http://doi.org/10.3389/fnhum.2014.01025

Sligte, I. G., Scholte, H. S., & Lamme, V. A. F. (2008). Are there multiple visual short-term memory stores? *PloS ONE*, *3*, e1699. http://doi.org/10.1371/journal.pone.0001699

Sligte, I. G., Vandenbroucke, A. R. E., Scholte, H. S., & Lamme, V. A. F. (2010). Detailed sensory memory, sloppy working memory. *Frontiers in Psychology*, *1*(175), 1–10. http://doi.org/10.3389/fpsyg.2010.00175

Smyth, M. M., & Scholey, K. A. (1994). Interference in immediate spatial memory. *Memory & Cognition*, *22*(1Smyth, M. M., Scholey, K. A. (1994). Interference in immediate spatial memory. Memory & Cognition, 22(1), 1–13. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/9080789), 1–13.

Solé-Padullés, C., Castro-Fornieles, J., De La Serna, E., Calvo, R., Baeza, I., Moya, J., … Sugranyes, G. (2016). Intrinsic connectivity networks from childhood to late adolescence: Effects of age and sex. *Developmental Cognitive Neuroscience*, *17*, 35–44. http://doi.org/10.1016/j.dcn.2015.11.004

Souza, A. S., Rerko, L., Lin, H.-Y., & Oberauer, K. (2014). Focused attention improves working memory: implications for flexible-resource and discrete-capacity models. *Attention, Perception & Psychophysics*, 2080–2102. http://doi.org/10.3758/s13414-014-0687-2

Souza, A. S., Rerko, L., & Oberauer, K. (2014a). Refreshing memory traces: thinking of an item improves retrieval from visual working memory. *Annals of the New York Academy of Sciences*, n/a-n/a. http://doi.org/10.1111/nyas.12603

Souza, A. S., Rerko, L., & Oberauer, K. (2014b). Unloading and reloading working memory: attending to one item frees capacity. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(3), 1237–1256. http://doi.org/10.1037/a0036331

Sperling, G. (1960). The information available in brief visual presentation. *Psychological Monographs*, *74*, 1–29.

St Clair-Thompson, H. L., & Gathercole, S. E. (2006). Executive functions and achievements in school: Shifting, updating, inhibition, and working memory. *Quarterly Journal of Experimental Psychology*, *59*(4), 745–759. http://doi.org/10.1080/17470210500162854

Stevens, C., & Bavelier, D. (2012). The role of selective attention on academic foundations: A cognitive neuroscience perspective. *Developmental Cognitive Neuroscience*, *2S*(SUPPL. 1), S30–S48. http://doi.org/10.1016/j.dcn.2011.11.001

Stokes, M., & Nobre, A. C. (2011). Top-Down Biases in Visual Short-Term Memory. In G. R. Mangun (Ed.), *Neuroscience of Attention* (pp. 209–228). New York: Oxford University Press.

Todd, J. J., & Marois, R. (2004). Capacity limit of visual short-term memory in human posterior parietal cortex. *Nature*, *428*, 751–754. http://doi.org/10.1038/nature02466

Towse, J. N., & Hitch, G. J. (1995). Is there a Relationship between Task Demand and Storage Space in Tests of Working Memory Capacity? *The Quarterly Journal of Experimental Psychology Section A: Human Experimental Psychology*, *48*(1), 108–124. http://doi.org/10.1080/14640749508401379

Towse, J. N., Hitch, G. J., & Horton, N. (2007). Working memory as the interface between processing and retention: A developmental perspective. *Advances in Child Development and Behavior*, *35*, 219–251.

Towse, J. N., Hitch, G. J., & Hutton, U. (1998). A Reevaluation of Working Memory Capacity in Children. *Journal of Memory and Language*, *39*(2), 195–217. http://doi.org/10.1006/jmla.1998.2574

Towse, J. N., Hitch, G. J., & Hutton, U. (1999). The Resource King is dead! Long live the Resource King! *Behavioral and Brain Sciences*, *22*(1), 111.

Towse, J. N., Hitch, G. J., & Hutton, U. (2000). On the interpretation of working memory span in adults. *Memory & Cognition*, *28*(3), 341–348. http://doi.org/10.3758/BF03198549

Towse, J. N., Hitch, G. J., & Hutton, U. (2002). On the nature of the relationship between processing activity and item retention in children. *Journal of Experimental Child Psychology*, *82*(2), 156–84.

Ueno, T., Allen, R. J., Baddeley, A. D., Hitch, G. J., & Saito, S. (2011). Disruption of visual feature binding in working memory. *Memory & Cognition*, *39*(1), 12–23. http://doi.org/10.3758/s13421-010-0013-8

Usher, M., Haarman, H., Cohen, J. ., & Horn, D. (2001). Neural mechanism for the magical number 4: competitive interactions and non-linear oscillations. *Behavioral and Brain Sciences*, *24*, 151–152.

van Moorselaar, D., Gunseli, E., Theeuwes, J., N. L. Olivers, C., & N L Olivers, C. (2015). The time course of protecting a visual memory representation from perceptual interference. *Frontiers in Human Neuroscience*, *8*(January), 1–9. http://doi.org/10.3389/fnhum.2014.01053

Vandierendonck, A., Kemps, E., Fastame, M. C., & Szmalec, A. (2004). Working memory components of the Corsi blocks task. *British Journal of Psychology*, *95*(Pt 1), 57–79. http://doi.org/10.1348/000712604322779460

Vergauwe, E., & Cowan, N. (2014). A common short-term memory retrieval rate may describe many cognitive procedures. *Frontiers in Human Neuroscience*, *8*(March), 1–7. http://doi.org/10.3389/fnhum.2014.00126

Vogel, E. K., Woodman, G. F., & Luck, S. J. (2006). The time course of consolidation in visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(6), 1436–1451. http://doi.org/10.1037/0096-1523.32.6.1436

Wendelken, C., Baym, C. L., Gazzaley, A., & Bunge, S. A. (2011). Neural indices of improved attentional modulation over middle childhood. *Developmental Cognitive Neuroscience*, *1*(2), 175–186. http://doi.org/10.1016/j.dcn.2010.11.001

Williams, J. (1890). *The Principles of Psychology*. New York: Holt.

Williams, M., Hong, S. W., Kang, M.-S., Carlisle, N. B., & Woodman, G. F. (2013). The benefit of forgetting. *Psychonomic Bulletin & Review*, *20*(2), 348–55. http://doi.org/10.3758/s13423-012-0354-3

Woodman, G. F., & Luck, S. J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. *Nature*, *400*(6747), 867–869. http://doi.org/10.1038/23698

Woodman, G. F., Vecera, S. P., & Luck, S. J. (2003). Perceptual organization influences visual working memory. *Psychonomic Bulletin & Review*, *10*, 80–87.

Yi, D.-J., Turk-Browne, N. B., Chun, M. M., & Johnson, M. K. (2008). When a thought equals a look: refreshing enhances perceptual memory. *Journal of Cognitive Neuroscience*, *20*(8), 1371–1380. http://doi.org/10.1162/jocn.2008.20094

Zhang, W., & Luck, S. J. (2009). Sudden death and gradual decay in visual working memory. *Psychological Science*, *20*, 423–428. http://doi.org/10.1111/j.1467-9280.2009.02322.x

Zhang, W., & Luck, S. J. (2011). The Number and Quality of Representations in Working Memory. *Psychological Science*, 1–8. http://doi.org/10.1177/0956797611417006