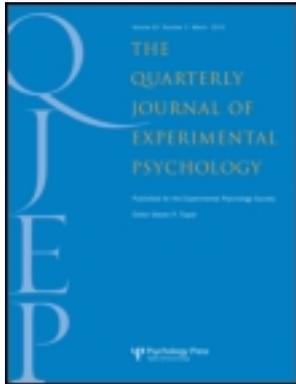


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Attentional control constrains visual short-term memory: Insights from developmental and individual differences

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The mechanisms by which attentional control biases mnemonic representations have attracted much interest but remain poorly understood. As attention and memory develop gradually over childhood and variably across individuals, assessing how participants of different ages and ability attend to mnemonic contents can elucidate their interplay. In Experiment 1, 7-year-olds, 10-year-olds, and adults were asked to report whether a probe item had been part of a previously presented four-item array. The initial array could either be uncued, be preceded (“precued”), or followed (“retrocued”) by a spatial cue orienting attention to one of the potential item locations. Performance across groups was significantly improved by both cue types, and individual differences in children’s retrospective attentional control predicted their visual short-term and working memory span, whereas their basic ability to remember in the absence of cues did not. Experiment 2 imposed a variable delay between the array and the subsequent orienting cue. Cueing benefits were greater in adults than in 10-year-olds, but they persisted even when cues followed the array by nearly 3 seconds, suggesting that orienting operated on durable short-term representations for both age groups. The findings indicate that there are substantial developmental and individual differences in the ability to control attention to memory and that in turn these differences constrain visual short-term memory capacity.

Keywords: Attentional control; Visual short-term memory; Development; Individual differences.

Attentional control biases the processing of incoming input to select information appropriately in the face of competing stimuli and/or responses (e.g., Desimone & Duncan, 1995; Mesulam, 1999; Miller & Cohen, 2001; Nobre, 2001). Following the work of Posner and colleagues (Posner, 1980; Posner & Cohen, 1984), the control of attention has been investigated by studying the effects of

spatial orienting cues, and extensive evidence demonstrates benefits of these attentional biases in selecting upcoming perceptual stimuli for further processing. Indeed, the use of spatial information to bias the processing of some stimuli over others is one of the most basic, and frequently studied, mechanisms by which we can control our processing of the visual environment. Of

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course, this selection could be driven bottom-up by a particularly salient stimulus in the environment and not involve any sort of “executive” process. Alternatively, this selection could be driven by endogenous top-down biases operating on multiple visual areas, depending upon the spatial location of task-relevant stimuli (Desimone & Duncan, 1995). More recently, similar spatial attentional biases have been applied to information held in memory (e.g., Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003; Sligte, Scholte, & Lamme, 2008). A high degree of overlap is thought to exist between those mechanisms by which we bias the processing of visual representations and those mechanisms by which we selectively bias aspects of remembered representations, but the precise mechanisms through which the latter processes might operate remain relatively uncharted.

In a now classical study, Sperling (1960) presented participants with an array of items to be later recalled (e.g., variably coloured letters). Following their disappearance, he cued participants’ attention to a subset of the items (for example, by directing them to attend to a specific row of items within the memory array). When the delay between the array and the cue was very brief, the partial report condition resulted in near-perfect recall for the cued row compared to the condition when participants were required to report the array in full, suggesting that cued information was selected from a large-capacity but transient (“iconic”) form of memory. Although this original experiment was not designed with spatial attentional orienting effects in mind, benefits suggested that information in iconic memory can be successfully selected on the bases of attentional cues and biased for efficient recall (Reeves & Sperling, 1986). More recently, multiple studies (Griffin & Nobre, 2003; Lepsien, Griffin, Devlin, & Nobre, 2005; Lepsien & Nobre, 2007; Nobre et al., 2004; Nobre, Griffin, & Rao, 2008; Ruff, Kristjansson, & Driver, 2007; Sligte et al., 2008) have addressed directly the role of spatial attentional biases on both iconic and visual short-term memory (VSTM). Spatial cues oriented participants’ attention to the location of

items within an array held in memory (spatial “retro-cues”). Decisions regarding items at the cued location were more accurate and faster than uncued performance, and benefits of retro-cues were equivalent to those attained with more traditional spatial cues preceding the array to be encoded in memory (“precues”). Moreover, directing attention retrospectively to representations held in memory and prospectively to incoming perceptual information to be later remembered engages overlapping brain areas (Lepsien et al., 2005; Lepsien & Nobre, 2006, 2007; Nobre et al., 2004; Ruff et al., 2007) and temporal dynamics (Kuo, Rao, Lepsien, & Nobre, 2009; Nobre et al., 2008), although orienting attention to memory recruits additional areas of prefrontal cortex (Lepsien et al., 2005; Ruff et al., 2007) and is characterized by distinct early event-related potentials over frontal electrodes (Griffin & Nobre, 2003). At least in adults, it therefore seems that the neurocognitive mechanisms involved in directing attention to incoming percepts and to representations held in memory are heavily related.

However, the close coupling of retrospective and prospective attentional control on memory, evident in adults’ behaviour, might emerge over developmental time, rather than being a stable property of attentional biases. It may depend, for example, on how efficiently different age groups deploy attentional control to information that is being maintained in working memory (rather than to incoming visual input as yet to be encoded) to facilitate performance and/or on how well established their basic memory abilities are. Therefore, children’s developing attention holds promise for revealing the mechanisms underpinning various constraints on memory. Nonetheless, as we detail below, much of the published developmental literature has focused, quite separately, on developmental changes in controlled attention as either the executive coordination of domain-specific memory stores in the context of working memory (e.g., Alloway, Gathercole, & Pickering, 2006), or as the driver of visuospatial orienting effects (e.g., Ristic & Kingstone, 2009), and not on relationships across these constructs.

It seems clear that children's ability to attend to relevant stimuli in their visual environment displays protracted modifications. By six years of age children's orienting of attention in response to cues affects the speed and accuracy of their manual responses in both detection and discrimination tasks, but these change into adolescence and adulthood (e.g., Akhtar & Enns, 1989; Brodeur & Boden, 2000; Brodeur & Enns, 1997; Enns & Brodeur, 1989; Goldberg, Maurer, & Lewis, 2001; Iarocci, Enns, Randolph, & Burack, 2009; Ristic & Kingstone, 2009; Schul, Townsend, & Stiles, 2003; Wainwright & Bryson, 2002, 2005). For example, Iarocci et al. (2009) assessed orienting to peripheral flashes and centrally presented arrow cues in 5-, 7-, and 9-year-olds, young adults, and younger and older seniors. All age groups oriented attention reflexively to flashes and used arrow cues strategically, but both the youngest and the eldest participants were poorest at controlling the effects of peripheral cues, unpredictable of upcoming target locations, when these were juxtaposed with predictive central arrows. This literature indicates a fine and changing balance in the ability to control visuospatial attention over development, but to our knowledge no published study has addressed the question of whether, and if so, how, spatial attentional orienting can bias children's representations in visual memory and improve performance, either prospectively or retrospectively.

A parallel but distinct tradition has focused instead on how the development of controlled attention constrains encoding and/or retrieval of information from working memory, because a critical component of multiple working memory models is the ability to direct attention to domain-specific information in memory for rehearsal and retrieval purposes. An influential model of working memory (Baddeley & Hitch, 1974) conceptualizes it as a system comprising distinct limited-capacity domain-specific elements (the phonological loop and the visuospatial sketchpad) and a domain-general component (the central executive) responsible for the control of attention and processing across domains and modalities. Furthermore, it has long been suggested that the

central executive is most likely composed of multiple dissociable but interrelated executive functions (e.g., Baddeley, 1996), and the distinction between the mechanisms supporting short-term storage and controlled attention mechanisms is also present in several other models of working memory (e.g., Cowan, 2001; Engle, Tuholski, Laughlin, & Conway, 1999; Kane, et al., 2004).

Changes in attentional control have indeed long been postulated to play a role in the development of working memory. For example, Hitch and Halliday (1983) proposed that developmental change in short-term memory capacity may depend on improvements in active mechanisms supporting maintenance and/or resistance to decay of relevant information in either the verbal or the visual format. More recently, multiple factor analyses of performance by large cohorts of 4- to 11-year-olds indicated that individual differences in domain-general executive resources limit the processing component of working memory tasks across this developmental period (Alloway et al., 2006; Alloway, Gathercole, Willis, & Adams, 2004). Moreover, children with low working memory scores display clear difficulties in controlling attention and avoiding attentional lapses in many everyday situations (Alloway, Gathercole, Kirkwood, & Elliott, 2009; Gathercole et al., 2008a; Gathercole, Durling, Evans, Jeffcock, & Stone, 2008b). Of note, tasks employed to investigate executive aspects of working memory are, by definition, complex and require coordinating multiple processes. Recent evidence from adults indicates that individuals with low working memory capacity differ from those with high capacity on a variety of very simple and basic measures of attentional control such as retaining relevant information while ignoring distractors and simple change detection (Fukuda & Vogel, 2009; Vogel, McCollough, & Machizawa, 2005), indicating that individual differences in attentional control may allow one to select relevant information appropriately and ignore distraction, facilitating encoding and retrieval in VSTM (Kane, Bleckley, Conway, & Engle, 2001; Vogel & Awh, 2008). What is much less well understood is whether simple markers of specific attentional processes

and their development predict performance on traditional measures of working memory.

To summarize then, as attentional control and memory develop gradually and variably over childhood, assessing how participants of different ages and ability orient attention to aid memory can elucidate the interplay between attention and memory in two ways. First, age-related differences can reveal whether controlling attention to memory prospectively and retrospectively dissociates developmentally. Second, individual differences in attentional control can reveal how basic attentional markers relate to memory ability. Although visual attentional biases in memory have been investigated in adults, children's simple orienting skills in this context remain relatively unexplored. Moreover, it remains unclear whether, and if so how, attentional orienting relates to measures of working memory capacity, which demonstrate increases in capacity over childhood (such as the traditionally used progressive span measures; e.g., Alloway, 2007).

In Experiment 1, we asked how attentional control modulates access to incoming and remembered information in adults and children and how children's individual differences in prospective and retrospective attentional control relate to traditional measures of working memory. In Experiment 2 we instead assessed whether benefits of attentional cues operate on durable short-term memory representations, rather than transient iconic traces, for both children and adults.

EXPERIMENT 1

Similarities and differences between the mechanisms supporting spatial attentional biases on perceptual input and VSTM may depend on the fact that, although both cue types provide a way to bias memory for later accurate recognition of the probe, precues select stimuli at the encoding stage, whereas retrocues operate on information already stored and to be maintained in memory. Indeed, orienting attention to information already stored in memory seems to select task-relevant features of objects differently from the attentional

selection of features as yet to be perceived, even when those stimuli are perceptually identical (Astle, Scerif, Kuo, & Nobre, 2009). As differences in the efficiency of precues and retrocues may depend on how representations in memory are established and/or how they are actively maintained, younger participants, for whom selective encoding, active maintenance, and basic memory ability vary, become of interest as a way of understanding the interplay between changing attentional control and memory. There is a growing literature exploring the relationship between controlled attention and working memory capacity in adults (e.g., Kane et al., 2001). However, whilst controlled attention has been explored in isolation in the context of visuospatial orienting or working memory in children (e.g., Robert, Borella, Fagot, Lecerf, & de Ribaupierre, 2009; Wainwright & Bryson, 2002), demonstrating their gradual development through the primary school years, we know of no studies that have attempted to examine their interplay through development. Furthermore, studying these mechanisms in development is likely to be advantageous: selective attention (Brodeur & Enns, 1997) and working memory capacity (Robert et al., 2009) are both more variable in childhood than in adulthood, making a developmental design ideal to examine the relationship between the two.

Experiment 1 aimed to validate a child-friendly but reliable way of assessing both prospective and retrospective orienting of spatial attention to memory and to investigate their relationships to validated measures of individual and developmental differences of working memory. We predicted that younger children would display poorer efficiency in the ability to orient attention prospectively and retrospectively to memory than would older children and adults. Furthermore, children's individual differences in these attentional control skills should predict visual (but not verbal) short-term memory abilities over and above their basic ability to remember visual information from memory and individual differences in general intelligence. The reason for this domain-specific prediction about the relationship between short-term memory and attentional control stems from the

adult literature. There have been both modelling suggestions (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001) and recent empirical demonstrations (Fukuda & Vogel, 2009) that behavioural measures of attentional control significantly correlate with behavioural measure of visual short-term memory capacity and that this relationship is largely unaffected by articulation (Makovski, Sussman, & Jiang, 2008). In addition, this association is particularly strong in young school-aged children (Alloway et al., 2006; Cowan et al., 2005) and may presumably be even stronger when assessing spatially controlled attention.

Method

Participants

Three groups of participants, 76 in total, completed our experimental task. These comprised a group of 6–7-year-olds ($N = 40$; 17 females; mean age = 7 years 5 months, $SD = 3.4$ months: “7-year-olds” henceforth), a group of 9–11-year-olds ($N = 24$; 15 females; mean age = 10 years 4 months, $SD = 10.31$ months: “10-year-olds” henceforth), and a group of young adults ($N = 12$; 10 females; mean age = 26.0 years, $SD = 39.8$ months: “adults” henceforth). All participants had normal or corrected-to-normal vision. The study was approved by the Central University Research Ethics Committee of the University of Oxford, UK.

Materials and stimuli

The experimental task was programmed in E-Prime 1.2 (Psychological Software Tools) and was presented on a 15" PC laptop widescreen. All participants were presented with an array of four items, selected from a set of highly familiar fruit and vegetables from the coloured set of images published by Rossion and Pourtois (2004). From a 60-cm viewing distance each item subtended 3.4 degrees angle, and it appeared at 7 degrees eccentricity and 4.5 degrees elevation. At the end of each trial, participants were presented with a probe stimulus (a single item, drawn from the same set of eight). Participants' task was to decide whether this probe stimulus was one of the original four array items or not

and report its presence/absence using a serial response mouse, with the left button indicating “present” and the right “absent”. Throughout the duration of the experiment, a cartoon character was presented at fixation (subtending 3.8 degrees angle), and all participants were asked to keep their eyes on him. On cued trials, either before (“precue”) or after (“retrocue”) the array, the character pointed to the location of one of the items in the array, with the pointing gesture extending clearly in the direction of one of the items. Participants received engaging auditory feedback on the accuracy and speed of their response after each trial (see Figure 1 for further details).

In addition, all children completed four subscales of the Automated Working Memory Assessment (AWMA, Alloway, 2007), a computerized battery of working memory measures (described in full below), and four subscales of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999), to provide a full scale IQ measure and to assess whether individual differences in attention and working memory related to general intelligence.

Procedure

Participants were tested individually in a quiet and well-lit room either at school or at university. They were given written as well as verbal instructions about task requirements, and the experimenter ensured that child participants recognized the test stimuli at the beginning of the experimental task. Each trial started with the presentation of a cartoon character at fixation for 150–300 ms, and this character remained static at fixation for neutral trials. On precue trials this was replaced for 300 ms with an image of the cartoon character pointing to the upper-left, upper-right, lower-left, or lower-right portions of the screen. After 800–1,200 ms the array of four items appeared and was presented for 300 ms. The items then disappeared for 300–700 ms, and they were followed by a cue in the retrocue condition, which was identical to the precue condition, for 300 ms. In the precue condition this 300-ms gap simply featured the same static image of the cartoon character. After a final delay of 800–1,200 ms the probe

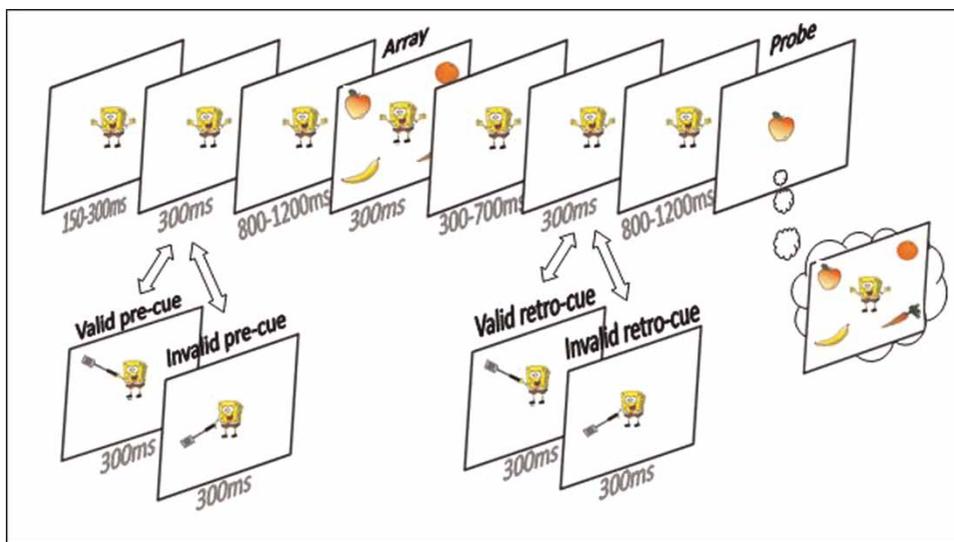


Figure 1. Experiment 1: Trial schematic. On “neutral” trials (central row of images), participants were simply presented with a four-item array and were later asked to report whether a probe item had been part of the array. The probe was present in the current example. On “precue” trials, the array was preceded by spatial cues (represented by the cartoon character at fixation trying to “help” the participants by pointing to the location of the item in the array that he thought would subsequently be the probe item) orienting attention to one of the four array locations, where the probe item, if present, would be (in “valid” trials) or at one of the other three locations (on “invalid” trials). On “retrocue” trials, cues followed the array. The final probe item remained visible until a response was made. Feedback for responses was provided in the form of engaging auditory inputs: If participants responded correctly they heard one of the following, depending upon the speed of response: >1,000 ms “Good!”, 800–1,000 ms “Great!”, 600–800 ms “Super-spectacular!”, and <600 ms “You’re on fire!”. Incorrect responses resulted in the voice of the cartoon character saying “Oops!” To view a colour version of this figure, please see the online issue of the Journal.

stimulus appeared at fixation. This was presented until the participants made a response (see Figure 1 for the trial order schematic).

Participants completed 14 practice trials before the experimental trials began. Each participant completed at least 10 blocks of 20 experimental trials, for half of which the probe item was present in the array. A total of 85% trials were cued (including either a “precue” or a “retrocue”). On the remaining 15% of trials participants were not presented with a cue and simply had to retain the four items in memory as well as they could (“neutral” trials). The cued trials were divided into validly cued trials (75%), in which the cued item was the subsequent probe item, and invalidly cued trials (25%), in which the probe item had been present in the array but at a location different from the cued one. All five trial types were randomly interleaved within the

blocks. Participants were given feedback after each trial and at the end of each block, when they were given a score out of 20 and were encouraged to try and improve their performance. For the youngest children the session could take as long as an hour.

In a separate session lasting approximately one hour, all children performed four measures from the AWMA (Alloway, 2007). These four measures were: (a) digit recall, requiring the child to repeat a list of heard numbers, a task designed to index verbal short-term memory storage; (b) dot matrix, requiring the child to remember the position of a red dot within a 4×4 grid and then recall its position in order, a task designed to tap spatial short-term memory; (c) backwards digit recall, requiring the child to repeat a list of heard numbers in backwards order, a task thought to index verbal working memory; and (d) spatial recall, requiring the child

to perform a series of mental rotations, whilst retaining the changing location of a dot, the ordered locations of which were to be recalled at the end of the sequence, geared to assess spatial working memory. Each became progressively harder, with the quantity of information (whether dot locations or digits) to be retained gradually increasing until the child's accuracy fell below a two-thirds criterion, at which point the test was terminated. Both groups of children also completed four subscales of the WASI (Wechsler, 1999) in a fixed order: the Vocabulary, Similarities, Block Design, and Matrix Reasoning.

Results

Developmental differences in prospective and retrospective attentional cueing

Developmental differences were investigated by calculating sensitivity (d -prime) and median reaction times to probes correctly identified as present in the array. The d -prime scores for each trial type and age group are reported in Table 1. They were derived by subtracting the normalized (z -score) proportion of "false alarms" from the normalized proportion of "correct hits" for each trial type. The advantage of this comparison is that it takes into account any response biases (such as young children always hitting the "target-present" button) and instead tests participants' sensitivity to the presence of a particular stimulus, relative to chance. These d -prime values were submitted to a 3 (age group: 7-year-olds, 10-year-olds, adults) \times

5 (trial type: valid precue, invalid precue, neutral, valid retrocue, invalid retrocue) analysis of variance (ANOVA), with the between-subject factor of group and the within-subject factor of trial-type. Here and henceforth, violations of sphericity were Greenhouse–Geisser corrected. There were significant main effects of group, $F(2, 70) = 19.26$, $MSE = 2.78$, $p < .001$, $\eta_p^2 = .355$, and trial type, $F(2.1, 150.1) = 42.70$, $MSE = 2.85$, $p < .001$, $\eta_p^2 = .379$. These main effects were moderated by a statistically significant interaction effect between trial type and group, $F(8, 280) = 2.23$, $MSE = 2.85$, $p = .026$, $\eta_p^2 = .060$. This was driven by simple main effects of group for: valid precues, $F(2, 70) = 3.38$, $MSE = 2.19$, $p = .040$, $\eta_p^2 = .088$, with adults displaying significantly higher d -prime scores ($M = 3.206$) than 7-year-olds ($M = 2.019$, $p = .018$) and 10-year-olds producing intermediate scores ($M = 2.647$); valid retrocues, $F(2, 70) = 20.96$, $MSE = 1.72$, $p < .001$, $\eta_p^2 = .375$, with adults displaying significantly higher d -prime scores ($M = 3.987$) than either 10-year-olds ($M = 1.714$, $p < .001$) or 7-year-olds ($M = 1.188$, $p < .001$) who did not differ from each other; and neutral trials, $F(2, 70) = 13.61$, $MSE = 1.13$, $p < .001$, $\eta_p^2 = .280$, with adults displaying higher d -prime scores ($M = 2.045$) than 10-year-olds ($M = 1.223$, $p = .035$), in turn higher than 7-year-olds ($M = .328$, $p = .002$). Furthermore, for all groups valid pre- and retrocues resulted in significantly higher d -prime scores than did neutral trials ($ps < .03$, except for retrocues for 10-year-olds, $p = .146$), whereas invalid cues of

Table 1. Mean d' and median reaction times to the probe for neutral, valid, and invalid precue and retrocue trials, for 7-year-olds, 10-year-olds, and adults, Experiment 1

		d'			Median reaction time (ms)		
		7-year-olds	10-year-olds	Adults	7-year-olds	10-year-olds	Adults
Neutral trials		0.33 (0.17)	1.22 (0.27)	2.04 (0.31)	2,067.66 (145.68)	1,661.25 (162.87)	780.24 (206.02)
Precue trials	Valid	2.02 (0.24)	2.65 (0.31)	3.21 (0.43)	1,503.84 (95.05)	1,117.18 (106.26)	621.55 (134.42)
	Invalid	-0.13 (0.23)	0.097 (0.30)	0.66 (0.41)	1,931.69 (136.61)	1,604.65 (152.73)	774.95 (193.19)
Retrocue trials	Valid	1.19 (0.21)	1.71 (0.28)	3.99 (0.38)	1,655.31 (87.01)	1,197.4 (97.28)	598.5 (123.05)
	Invalid	0.03 (0.22)	0.55 (0.29)	1.05 (0.39)	1,814.56 (88.93)	1,533.59 (99.43)	819.95 (125.77)

Note: Standard errors of the mean (SEM) are reported in parentheses.

both types resulted in poorer d -prime than did neutral for 10-year-olds and adults ($p < .05$), but not for 7-year-olds ($p = .06$ for invalid precues and $.247$ for invalid retrocues compared to neutral). However, groups did not differ significantly in d -prime following invalid pre- and retrocues, $F(2, 70) = 1.46$, $MSE = 1.99$, $p = .239$, $\eta_p^2 = .040$, and $F(2, 70) = 2.875$, $MSE = 1.87$, $p = .063$, $\eta_p^2 = .076$, respectively, with the latter trend driven by higher d -prime following invalid retrocues for adults than for 7-year-olds and 10-year-olds, who produced intermediate scores.

Given the group differences in d -prime in neutral trials, we calculated separately the degree of benefit and cost that participants derived from valid and invalid cues, by subtracting their performance on the neutral trials from their performance on the valid trials (see Figure 2). For cueing benefits, difference scores in d -prime between valid and neutral trials were submitted to 2 (cue type: precue, retrocue) \times 3 (age group) ANOVAs with cue type as a within-subject factor and age group as the between-subject factor. There was a main effect of cue type, $F(1, 70) = 4.88$, $MSE = 0.64$, $p = .03$, $\eta_p^2 = .065$, but this was moderated by a significant interaction between age group and cue type, $F(2, 70) = 10.75$, $MSE = 0.64$, $p < .001$, $\eta_p^2 = .235$. An analysis of simple main effects revealed that valid precues resulted in greater d -prime benefits than valid retrocues for 7-year-olds (precues $M = 1.691$, retrocues $M = 0.861$,

$p < .001$, $\eta_p^2 = .231$, and 10-year-olds (precues $M = 1.423$, retrocues $M = 0.490$, $p < .001$, $\eta_p^2 = .177$, whereas adults benefited to a greater degree from valid retrocues ($M = 1.943$) than from precues ($M = 1.161$, $p = .019$, $\eta_p^2 = .076$). In addition, adults benefited from retrocues significantly more, $F(2, 70) = 3.41$, $MSE = 2.45$, $p < .039$, $\eta_p^2 = .089$, than did 10- and 7-year-olds ($p = .012$ and $.040$, respectively). Cueing costs were computed as the difference in d -prime between neutral trials and invalid pre- and retrocues and were analysed in the same manner. These revealed a significant main effect of cue type, with significantly greater costs following invalid precues ($M = -0.989$) than following invalid retrocues ($M = -0.655$, $F(1, 70) = 6.39$, $MSE = 0.51$, $p = .014$, $\eta_p^2 = .084$, but there was no significant main effect of age group or an interaction of age group and cue type (lowest $p = .169$).

Median reaction times in responding accurately to the probe when it was present are also reported in Table 1. There was no statistically significant interaction between trial type and group, but there was a main effect of group, $F(2, 43) = 26.82$, $MSE = 719,132$, $p < .001$, $\eta_p^2 = .555$, and one of trial-type, $F(4, 172) = 10.25$, $MSE = 142,224$, $p < .001$, $\eta_p^2 = .192$. The 7-year-olds were slower than 10-year-olds ($M = 1,794.62$ and $M = 1,422.82$, respectively, $p = .006$), who in turn were slower than adults ($M = 719.04$, $p < .001$). In addition, and for all groups, reaction times following valid precues ($M = 1,080.86$) and retrocues ($M = 1,150.41$) did not significantly differ from each other ($p = .063$), but were significantly faster than those following invalid precues ($M = 1,437.10$), invalid retrocues ($M = 1,389.37$), and neutral trials ($M = 1,503.05$; $p < .002$), suggesting benefits of valid cueing on reaction time (RT), but not RT costs. Indeed, the last three conditions did not differ significantly from each other (lowest $p = .259$).

In order to assess benefits in reaction time while taking age-related differences in response speed into account, reaction time differences between validly cued and neutral trials were computed. In addition, these difference scores were scaled by participants' median RT on neutral trials. As the

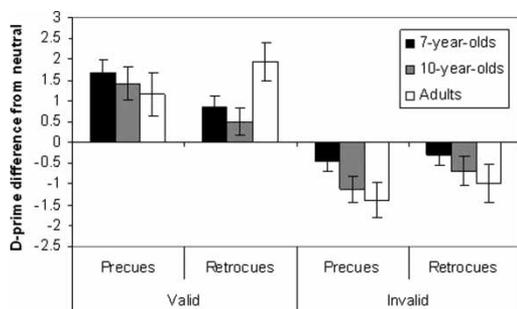


Figure 2. Experiment 1: Mean d -prime benefits and costs following valid and invalid precues and retrocues for 7-year-olds, 10-year-olds, and adults. Benefits and costs were calculated as the difference in d -prime scores between cued trials and neutral trials.

statistics for scaled and unscaled difference scores were consistent with each other, here we report the unscaled values for clarity. A 3 (age group) \times 2 (cue type) ANOVA revealed a statistically significant main effect of cue type, $F(1, 62) = 5.74$, $MSE = 26,895$, $p = .02$, $\eta_p^2 = .085$, and a significant interaction of cue type and age group, $F(2, 62) = 3.164$, $MSE = 26,895$, $p = .049$, $\eta_p^2 = .093$. An analysis of simple main effects revealed that 7-year-old children showed greater RT benefits from pre- ($M = 602.60$ ms) than from retrocues ($M = 430.59$ ms), $F(1, 62) = 18.70$, $p < .001$, $\eta_p^2 = .232$, whereas the two older age groups did not differ in their RT benefits from either type of cue (lowest $p = .134$). In contrast to the developmental differences in RT cueing benefits, there were no statistically significant effects of group or cue type, or an interaction of the two factors on costs in reaction time (lowest $p = .572$).

Individual differences in attentional control and memory

We assessed whether individual differences in attentional orienting related to differing memory abilities across children in our sample. As

memory measures are all unsped, we selected d' -prime scores rather than reaction times as our attentional predictor variables. This approach was also justified by preliminary null correlations between reaction times to the probe and memory span measures. In addition, we considered age as a continuous variable, rather than a categorical one, to evaluate fully the relative contribution of age and individual differences in predicting memory ability.

Preliminary bivariate and partial correlations across measures of attentional orienting, chronological age, IQ (WASI), and memory span performance (raw scores from the four AWMA subscales) are presented in Table 2. Values above the diagonal represent bivariate correlations across all measures, whereas those below the diagonal represent correlations between attentional orienting measures and memory measures, partialling out variability in age, IQ, and performance on neutral (uncued) trials. In summary, performance following valid retrocues related significantly to spatial short-term memory scores (as indexed by the Dot Matrix task) and spatial working memory span (measured by the Spatial Span task), even when the variability associated with

Table 2. Relationships between chronological age, IQ, attentional control measures, and raw scores for short-term and working memory span, Experiment 1

	IQ	d' neutral	d' valid precues	d' invalid precues	d' valid retrocues	d' invalid retrocues	Dot matrix	Spatial span	Forw. digit span	Back. digit span
Age	-.165	.406**	.098	.136	.179	.139	.656***	.621***	.516***	.505***
IQ		-.150	.065	.045	.106	-.010	-.018	.073	.251	.175
d' neutral			.164	.342**	.392**	.286*	.265*	.367**	.139	.340**
d' valid precues				-.199	.678***	-.092	.233	.164	.045	-.015
d' invalid precues				-.378	.070	.747***	.092	.085	.043	.192
d' valid retrocues				.695**	-.068	.129	.418**	.322*	.225	.167
d' invalid retrocues				-.161	.738***	-.016	.151	.070	.012	.169
Dot matrix				.234	-.008	.430**	.071	.588***	.560***	.502***
Spatial span				.176	-.071	.325*	-.079	.298*	.495***	.597***
Forward digit span				-.012	-.053	.197	-.075	.344*	.198	.635***
Backward digit span				-.047	.079	.157	.070	.343*	.481**	

Note: Values above the diagonal indicate bivariate correlations (Pearson's r) across measures, whereas values below the diagonal indicate partial correlations controlling for chronological age, IQ, and d' on neutral trials. IQ: Wechsler Abbreviated Scale of Intelligence (WASI), standard scores; attentional control measures: d' scores; raw scores for short-term: Dot Matrix, Automated Working Memory Assessment (AWMA); raw scores for working memory span: Spatial Span, AWMA.

* $p < .05$. ** $p < .01$. *** $p < .001$.

uncued trials (effectively, measuring how accurately participants could remember whether the probe item was part of the array) was taken into account. These relationships were specific to visual memory, as they did not hold for verbal short-term (Forward Digit span) and verbal working memory scores (Backward Digit span). The latter correlated instead with performance on neutral trials, when participants had to remember whether the probe was one of four familiar and verbalizable objects.

As preliminary correlations highlighted relationships between specific experimental variables (d -prime with valid retrocues and d -prime on neutral trials) and visual memory span scores, hierarchical regression analyses were carried out to test the extent to which they would account for individual differences in span, over and above differences in age and IQ. Model statistics and coefficients for the different predictor variables are reported in Table 3. These show that chronological age and d -prime scores following valid retrocues significantly predicted variance for both

visual short-term and visual working-memory span, whereas d -prime scores on neutral trials (i.e., uncued performance) and IQ did not.

Discussion

All three groups of participants derived a significant benefit from attentional cues validly orienting spatial attention both prospectively and retrospectively to the to-be-remembered material, compared to when arrays were uncued. This can be seen most obviously in the d -prime scores across conditions and groups, although in the case of 10-year-olds, for valid retrocues only, this was evident in the median RT data, not d -prime. Invalid cues also affected accuracy and speed performance in broadly similar ways across age groups. Critically, there were a number of age-related differences in the relative benefits of valid pre- and retrocues. First, cueing children's attention to incoming perceptual input improved their ability to remember this information more than cueing equivalent representations already held in

Table 3. Hierarchical regression model statistics predicting children's scores on the Dot Matrix task and on the Spatial Span task of the AWMA, Experiment 1

		Model summary				Coefficients		
		Adjusted R ²	R ² change	F change	p	Standardized β	t	p
Dot Matrix	Step 1	.376	.398	18.149	.000			
						.641	6.015	.000
						.083	0.779	.439
	Step 2	.472	.111	6.002	.004			
						.612	5.919	.000
						.037	0.372	.711
Spatial Span						.339	3.465	.001
						-.030	-0.292	.772
	Step 1	.368	.390	17.561	.000			
						.633	5.905	.000
						.171	1.593	.117
	Step 2	.443	.092	4.710	.013			
					.553	5.207	.000	
					.155	1.519	.135	
					.252	2.505	.015	
					.165	1.556	.126	

Note: Dot Matrix task: indexing visual short-term memory; Spatial Span task: visual working memory. AWMA: Automated Working Memory Assessment (Alloway, 2007).

memory, and this difference between prospective and retrospective attentional orienting was also reflected in younger children's speeded responses. In contrast, adults' *d*-prime scores benefited from retrospective cueing to a greater degree than from precues, and more so than children's. Secondly, children's individual differences in retrospective (but not prospective) attention orienting following valid cues predicted their visual short-term and visual working memory span, even when differences in chronological age and baseline memory on neutral trials were taken into account. Rather than viewing spatial short-term and working memory as being fixed and the stable consequences of prior selection, we suggest that the contents of spatial short-term memory are available for attentional biasing and modulation. Moreover, our data suggest that it is this ability to selectively bias part of the contents of visual short-term memory, and not the ability to simply maintain/retrieve the contents per se, that best predicts traditional measures of "capacity". In short, it could be that variability in apparent storage capacity in fact stems from variability in attentional control and not differences in the amount that can be stored as such (Fukuda & Vogel, 2009). Notably, simply searching for an item in memory (as indexed by performance on uncued trials) did not significantly predict these measures of span but it related to verbal working memory span.

The finding that attentional cueing can significantly improve memory across all age groups is entirely consistent with the effects reported for adults (Griffin & Nobre, 2003; Landman et al., 2003) and with predictions from the role of attentional control in more complex short-term and working memory span performance (e.g., Alloway et al., 2006). In addition, the developmental dissociation between prospective and retrospective orienting fits neatly with the observation that, although highly overlapping, the two processes also differ at the neurocognitive level (Aston et al., 2009; Lepsien et al., 2005; Lepsien & Nobre, 2007): younger children benefited to a greater degree from attentional cues biasing information as yet to be encoded than from information they already hold in memory, whereas the opposite was

true for adults. Indeed, it was the ability to orient attention retrospectively that most closely related to more traditional measures of visual short-term and working memory span (AWMA, Alloway, 2007). The latter finding could not easily be accounted for by difference in basic memory ability and therefore pinpoints the need to further investigate how these basic attentional biases operate.

A plausible alternative interpretation for greater benefits of precues in children is that children may have produced a larger number of overt saccades to cued locations than have adults. Although we did not explicitly measure eye movements, these are unlikely to explain why age groups differed as they could not account for disparities in retrospective orienting of attention. A further outstanding question is whether the attentional orienting effects elicited by retrocues in Experiment 1, for both children and adults, operate on short-lived memory akin to visual after-effects ("iconic memory"), or whether they bias more established and durable representations held in short-term memory, a topic of extensive investigation in adults (e.g., Sperling, 1960).

EXPERIMENT 2

In Experiment 2, we asked whether children's benefits of attentional orienting to memory operate on durable but gradually decaying short-term representations, rather than perhaps only on short-lived representations akin to iconic memory—that is, essentially priming low level after images. The precise timing of decay from iconic memory is influenced by a variety of factors, including individual differences in expertise and strategy deployment (Gegenfurtner & Sperling, 1993), so it is plausible that the retrocue effects measured in Experiment 1 could have been driven by short array–cue intervals orienting to transient iconic traces. Substantial evidence, nonetheless, indicates that, at least in adults, retrocues can operate on more durable representations. Sligte et al. (2008) manipulated the interval between the memory array and retrocues to investigate when cueing benefits would disappear.

In adults, benefits persisted even when cues appeared 4 s after stimulus offset, placing the effects firmly in the realm of short-term memory. Further studies have also demonstrated cueing benefits with intervals between memory arrays and cues extending well over 10 seconds (Lepsien et al., 2005; Lepsien & Nobre, 2007).

Regardless of the findings obtained with adult participants and the significant relationships of retrospective attentional cueing with visual short-term and working abilities in Experiment 1, it remains possible that the retrospective cueing benefits displayed by children may be much more transient than those measured in adults. There are indeed very good reasons to predict developmental differences in these effects, both from the attentional orienting literature and from the working memory literature. For example, Ristic and Kingstone (2009) demonstrated more labile effects of attentional orienting in response to central cues in preschoolers than in adults when the interval between cues and targets lengthened. Furthermore, Hitch, Towse, and colleagues (e.g., Hitch, Towse, & Hutton, 2001; Towse, Hitch, & Hutton, 1998) established that an important factor underpinning developmental differences in working memory capacity is the time-based decay of information to be later recalled.

We therefore aimed to assess whether the temporal characteristics of attentional cueing effects differ in children and adults. If retrospective attentional orienting operates on durable short-term memory representations in both children and adults, retrocues should result in better performance than performance in uncued trials of equivalent duration, even when retrocues follow arrays by long intervals.

Method

Participants

A sample of 52 new participants contributed to Experiment 2. A group of 10-year-old children ($N = 26$; mean age = 10 years 6 months, $SD = 3.4$ months; all males: “10-year-olds” henceforth) and a group of young healthy adults ($N = 26$; mean age = 20 years 4 months, $SD = 7.3$

months; all males: “adults” henceforth) participated in the task. Again, all participants had normal or corrected-to-normal vision. Here we focused on a single group of children as, in contrast to adults, all children in Experiment 1 had displayed smaller benefits from retrospective attentional cues than from prospective ones, and retrocuing benefits could presumably depend on iconic traces, rather than working memory. In addition, and surprisingly, 10-year-olds had only shown retrocuing benefits in reaction time. A single group of 10-year-olds would allow us to assess more reliably whether retrocuing effects in children, if they are present and however small, could be modulated by increasing the retention delay.

Apparatus and stimuli

Experimental equipment and stimuli were the same as those in Experiment 1.

Procedure

The procedure was identical to that employed for retrocue and neutral trials in Experiment 1, except for the experimental modifications detailed below and for the fact that participants were not assessed using the AWMA and WASI. Each trial began with the fixation stimulus (500 ms), followed by the four-item array for 300 ms. After equiprobable retention intervals of either 700 ms (short delay) or 2,700 ms (long delay), on retrocue trials the central character pointed to the location of one of the items in the memory array. On neutral trials, the fixation cartoon character remained static throughout. Retrocues were always valid, in that, if the probe was present in the array, they correctly directed participants' attention to its location within the array. These stimuli were followed by a further interval of 1,200 ms and then by the probe. As in Experiment 1, the probe remained on screen until participants indicated whether it had been present in the four-item initial array or not (see Figure 3 for trial schematic).

There were therefore four trial types of interest, randomly interleaved across the experiment: neutral trials with a short interval between the onset of the array and the probe (2,500 ms, “short

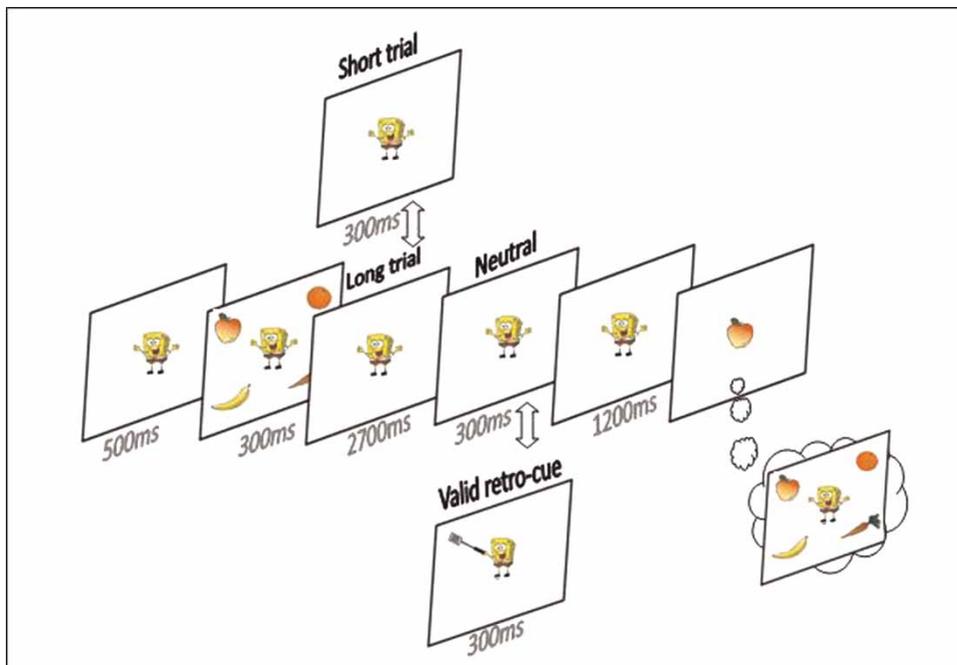


Figure 3. Experiment 2: Trial schematic. As in Experiment 1, participants reported whether the probe item had been present in the initial array. On “neutral” trials, the probe was presented either 2,500 (“short neutral trials”) or 4,500 ms (“long neutral trials”) after the onset of the array. On “retrocue” trials, the array was followed by a spatial cue presented either 700 ms (“short retrocue trials”) or 2,700 ms after array offset (“long retrocue trials”). Retrocues always indicated the location of the probe accurately if this was present in the array. To view a colour version of this figure, please see the online issue of the Journal.

neutral trials”), retrocue trials also lasting 2,500 ms with a cue appearing shortly after the array (700 ms, “short retrocue trials”), neutral trials with a long interval between the array and the probe (4,500 ms, “long neutral trials”), and validly cued trials also lasting 4,500 ms and a long delay between the array and the cue (2,700 ms, “long retrocue trials”, see Figure 3 for trial sequence). The task included eight blocks, each containing 20 trials, resulting in a total 160 trials, equally subdivided into trials in which the probe was present or absent in the array. The experiment took approximately 30 minutes to complete.

Results

Mean d -prime scores by 10-year-olds and adults across conditions were calculated as for Experiment 1 and are reported in Table 4. A 2 (group: 10-year-olds, adults) \times 2 (trial type:

neutral, valid) \times 2 (trial duration: short, long) ANOVA revealed statistically significant main effects of trial type, $F(1, 50) = 26.47$, $MSE = 1.53$, $p < .001$, $\eta_p^2 = .335$, trial duration, $F(1, 50) = 12.49$, $MSE = 1.27$, $p < .001$, $\eta_p^2 = .201$, and age group, $F(1, 50) = 19.10$, $MSE = 6.87$, $p < .001$, $\eta_p^2 = .328$. Main effects were moderated by an interaction effect of trial type and age group, $F(1, 50) = 5.063$, $MSE = 1.53$, $p = .029$, $\eta_p^2 = .078$, driven by a significant difference between retrocue and neutral trials for both 10-year-olds (neutral $M = 0.640$, retrocue $M = 1.137$), $F(1, 50) = 4.19$, $p = .046$, and adults (neutral $M = 1.841$, retrocue $M = 3.110$), $F(1, 50) = 27.34$, $p < .001$, and between groups for both neutral, $F(1, 50) = 13.25$, $MSE = 1.41$, $p = .001$, and retrocue trials, $F(1, 50) = 18.21$, $MSE = 2.78$, $p < .001$, although the cueing benefit was numerically greater for adults. None of the other effects reached statistical significance, lowest $p = .116$

Table 4. Mean d' and median reaction times to the probe for neutral and retrocue trials of short and long duration, for 10-year-olds and adults, Experiment 2

Trials		d'		Reaction time (ms)	
		10-year-olds	Adults	10-year-olds	Adults
Short	Neutral	0.70 (0.20)	2.07 (0.36)	987.65(74.12)	896.07(40.86)
	Retrocue	1.50 (0.28)	3.57 (0.44)	803.15(68.30)	619.13(34.38)
Long	Neutral	0.58 (0.07)	1.62 (0.33)	944.96(79.93)	954.65(46.74)
	Retrocue	0.78 (0.25)	2.65 (0.48)	779.13(55.24)	672.88(38.45)

Note: Standard errors of the mean (*SEM*) are reported in parentheses.

for the interaction of trial duration and trial type. These effects were also supported by a 2 (group) \times 2 (trial duration) ANOVA on d' -prime differences (represented in Figure 4) in cued compared to neutral trials, revealing a main effect of group, $F(1, 50) = 5.06$, $MSE = 3.06$, $p = .029$, $\eta_p^2 = .078$, with a greater benefit for adults ($M = 1.269$) than for 10-year-olds ($M = 0.497$). There were no significant main effect of trial duration and interaction of trial duration with age group on d' -prime benefits (lowest $p = .116$).

Median reaction times for 10-year-olds and adults across the four trial types are also presented in Table 4. A 2 (age group) \times 2 (trial type) \times 2 (trial duration) ANOVA revealed a statistically significant main effect of trial type, $F(1, 50) = 127.14$, $MSE = 21,123$, $p < .001$, $\eta_p^2 = .718$, moderated by an interaction effect between trial type and group, $F(1, 50) = 6.68$, $MSE = 21,123$, $p = .013$, $\eta_p^2 = .118$. This was driven by

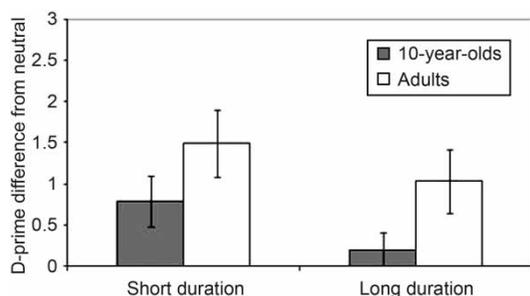


Figure 4. Experiment 2: Mean d' benefits following retrocues by 10-year-olds and adults when cues followed the array by a short or long delay. Benefits were calculated as the difference in d' scores between cued trials and neutral trials.

a simple main effect of age group for valid retrocue trials, $F(1, 50) = 4.30$, $MSE = 63,740$, $p = .043$, $\eta_p^2 = .079$, with 10-year-olds being significantly slower ($M = 925.36$ ms) than adults ($M = 646$ ms), whereas the two groups did not differ on neutral trials ($M = 966.3$ and 791.14 , respectively, $p = .638$). Both groups were significantly faster on retrocue than on neutral trials, $p < .001$ ($\eta_p^2 = .430$ and $.658$ for children and adults, respectively). In addition, there was a statistically significant interaction between delay and age group, $F(1, 50) = 12.52$, $MSE = 8,320$, $p = .001$, $\eta_p^2 = .200$, driven by significantly faster responses for short ($M = 757.6$ ms) than for long trials ($M = 813.77$ ms) for adults, $F(1, 50) = 9.86$, $p = .003$, $\eta_p^2 = .165$, but not significantly so for 10-year-olds (short $M = 895.4$ ms, long $M = 862.1$ ms), $F(1, 50) = 3.48$, $p = .068$, $\eta_p^2 = .065$. Reaction time cueing benefits were calculated for the two age groups in short and long trials. A 2 (age group) \times 2 (trial duration) ANOVA revealed a significant main effect of age group, $F(1, 50) = 6.68$, $MSE = 42,247$, $p = .013$, $\eta_p^2 = .118$, due to adults benefiting from retrocues ($M = 279.36$ ms) to a greater degree than 10-year-olds ($M = 175.16$ ms), but no significant main effect of trial duration or its interaction with age group on reaction time benefits following cues (lowest $p = .662$).

Discussion

Consistent with Lepsien et al. (2005), Lepsien and Nobre (2007), and Sligte et al. (2008), the current

findings indicate that effects of orienting attention to representations held in memory survive prolonged delays, placing them in the realm of short-term and durable, rather than iconic and transient, representations (unlike those measured by Gegenfurtner & Sperling, 1993; Sperling, 1960). Notably, although both accuracy and speed of response were poorer after longer delays, cueing benefits persisted for both adults and 10-year-olds. This in turn suggests that decay of information related to the memory array affects performance (in keeping with Hitch et al., 2001; Towse et al., 1998), but it does so similarly across the age groups tested here.

The current findings nonetheless leave a number of open questions. First, future experiments will also need to assess whether the effects of retrocues on memory can operate over long delays with children younger than 10 years of age. Indeed, 7-year-olds in Experiment 1 showed reliable retrocuing benefits for both *d*'-prime and reaction time, but these could be driven by iconic traces. In addition, recent evidence implies that preschoolers and young children can use centrally presented cues to orient attention voluntarily, but seem to be less capable of sustaining attention at cued locations than adults (Iarocci et al., 2009; Ristic & Kingstone, 2009). Secondly, relationships of retrospective attentional orienting with traditional measures of short-term and working memory may be stronger at long array-to-cue delays, but we could not test this hypothesis here because we did not collect traditional capacity measures for Experiment 2.

GENERAL DISCUSSION

All together, the current findings indicate that visual attentional biases flexibly enhance individuals' capacity to remember information from VSTM (consistent with a growing literature in adults, Landman et al., 2003; Nobre et al., 2004; Sligte et al., 2008). However, taking into consideration developmental and individual differences generated a number of novel findings. First, Experiment 1 revealed that developmental

differences in the effects of attentional orienting extend from effects on stimulus detection and discrimination (e.g., Akhtar & Enns, 1989; Brodeur & Boden, 2000; Brodeur & Enns, 1997; Enns & Brodeur, 1989; Iarocci et al., 2009; Ristic & Kingstone, 2009; Wainwright & Bryson, 2002, 2005) to how attentional control aids memory. We demonstrated that attentional biases on perceptual input and on information held in memory share similarities in how they support memory, but they are also characterized by distinct developmental trajectories: Younger children are better able to remember what they select from incoming perceptual information than from information they hold in memory. These developmental differences may depend on the level of processing at which these different attentional biases operate: For example, even with perceptually identical memory arrays, precues may operate on simple features such as spatial locations, whereas retrocues select objects amongst competitors, all of whom have already been processed (Astle et al., 2009).

Secondly, as well as by developmental differences, attentional control to memory across age groups also displayed informative similarities. In Experiment 1, precues and retrocues resulted in improved memory compared to neutral across age groups. Moreover, Experiment 2 provided evidence that, both in 10-year-olds and in adults, benefits of orienting attention retrospectively to information held in memory effects can operate on durable representations in short-term memory rather than simply transient iconic traces, consistent with a growing body of evidence on attentional cueing in adulthood (Lepsien et al., 2005; Lepsien & Nobre, 2007; Sligte et al., 2008). Thirdly, from an individual differences perspective, the efficiency of basic spatial attentional biases on past information predicted individual differences in complex visual short-term and working memory span (Alloway, 2007) over and above baseline memory performance. These relationships were specific to the visual domain, as they did not extend to verbal memory measures and were not influenced by general intelligence.

The findings as a whole indicate close ties between attentional selection and different

aspects of visual short-term memory, as indexed by both short-term and working memory span. We are of the opinion that they suggest a key role for attentional constraints on memory, because our attentional measures are much more basic than the complex memory tasks with which they correlate. However, our design is correlational in nature, and the directionality of the relationship needs to be investigated further. A productive route to doing so may be to test whether, in individuals of different ages, basic attentional markers from tasks devoid of memory demands underpin differences between individuals with high and low visual short-term memory capacity, as indexed by both behavioural and neural markers in adults (Fukuda & Vogel, 2009; Vogel & Machizawa, 2004; Vogel et al., 2005).

A number of further broad questions remain open. First, what are the precise mechanisms through which such simple attentional biases operate on memory? Attentional orienting may support the active maintenance of relevant items, support the suppression of irrelevant items, or protect the maintenance of specific items from decay and proactive interference. In addition, involuntary processes such as attentional capture may aid later memory performance. In turn, any of these controlled or reflexive attentional mechanisms could operate to constrain changes in visual short-term memory over developmental time. Within this context, it would be of interest to pit against each other centrally presented attentional cues and peripheral ones, as these cue types are thought to recruit voluntary and reflexive attentional effects to different degrees and variably so over developmental time (e.g., Iarocci et al., 2009).

Secondly, what are the relationships between attentional biases on short-term memory and developing stimulus representations held in long-term memory? Here we employed memory arrays of highly familiar objects. However, using stimuli of varying familiarity with participants of different ages may reveal the role of established long-term memory representations in influencing short-term memory and potential interactions with spatial attentional biases, as they have been investigated in adults (Summerfield, Lepsien, Gitelman,

Mesulam, & Nobre, 2006). Again, a developmental approach could inform relationships between attention, VSTM, and long-term memory.

In conclusion, the current findings indicate that gradually developing attentional control biases representations held in memory to facilitate recall and that in turn changes in attentional control over development and differences across individuals constrain the efficiency of VSTM. Further research is now necessary to pinpoint the precise mechanisms through which attentional selection biases memory over time.

REFERENCES

- Akhtar, N., & Enns, J. T. (1989). Relations between covert orienting and filtering in the development of visual-attention. *Journal of Experimental Child Psychology*, *48*(2), 315–334.
- Alloway, T. P. (2007). *Automated Working Memory Assessment (AWMA)*. London: Pearson Assessment.
- Alloway, T. P., Gathercole, S. E., Kirkwood, H., & Elliott, J. (2009). The cognitive and behavioral characteristics of children with low working memory. *Child Development*, *80*(2), 606–621.
- Alloway, T. P., Gathercole, S. E., & Pickering, S. J. (2006). Verbal and visuospatial short-term and working memory in children: Are they separable? *Child Development*, *77*(6), 1698–1716.
- Alloway, T. P., Gathercole, S. E., Willis, C., & Adams, A. M. (2004). A structural analysis of working memory and related cognitive skills in young children. *Journal of Experimental Child Psychology*, *87*(2), 85–106.
- Astle, D. E., Scerif, G., Kuo, B. C., & Nobre, A. C. (2009). Spatial selection of features within perceived and remembered objects. *Frontiers in Human Neuroscience*, *6*(3), 1–9.
- Baddeley, A. D. (1996). Exploring the central executive. *Quarterly Journal of Experimental Psychology*, *49A*, 5–28.
- Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. Bower (Ed.), *The psychology of learning and motivation* (pp. 47–89). New York: Academic Press.
- Brodeur, D. A., & Boden, C. (2000). The effects of spatial uncertainty and cue predictability on visual

- orienting in children. *Cognitive Development*, 15(3), 367–382.
- Brodeur, D. A., & Enns, J. T. (1997). Covert visual orienting across the lifespan. *Canadian Journal of Experimental Psychology—Revue Canadienne de Psychologie Experimentale*, 51(1), 20–35.
- Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, 24(1), 87–114.
- Cowan, N., Elliott, E. M., Saults, J. S., Morey, C. C., Mattox, S., Hismjatullina, A., et al. (2005). On the capacity of attention: Its estimation and its role in working memory and cognitive aptitudes. *Cognitive Psychology*, 51, 42–100.
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual-attention. *Annual Review of Neuroscience*, 18, 193–222.
- Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. *Journal of Experimental Psychology—General*, 128(3), 309–331.
- Enns, J. T., & Brodeur, D. A. (1989). A developmental-study of covert orienting to peripheral visual cues. *Journal of Experimental Child Psychology*, 48(2), 171–189.
- Fukuda, K., & Vogel, E. K. (2009). Human variation in overriding attentional capture. *Journal of Neuroscience*, 29(27), 8726–8733.
- Gathercole, S. E., Alloway, T. P., Kirkwood, H. J., Elliott, J. G., Holmes, J., & Hilton, K. A. (2008a). Attentional and executive function behaviours in children with poor working memory. *Learning and Individual Differences*, 18(2), 214–223.
- Gathercole, S. E., Durling, E., Evans, M., Jeffcock, S., & Stone, S. (2008b). Working memory abilities and children's performance in laboratory analogues of classroom activities. *Applied Cognitive Psychology*, 22(8), 1019–1037.
- Gegenfurtner, K. R., & Sperling, G. (1993). Information-transfer in iconic memory experiments. *Journal of Experimental Psychology—Human Perception and Performance*, 19(4), 845–866.
- Goldberg, M. C., Maurer, D., & Lewis, T. L. (2001). Developmental changes in attention: The effects of endogenous cueing and of distractors. *Developmental Science*, 4(2), 209–219.
- Griffin, I. C., & Nobre, A. C. (2003). Orienting attention to locations in internal representations. *Journal of Cognitive Neuroscience*, 15(8), 1176–1194.
- Hitch, G. J., & Halliday, M. S. (1983). Working memory in children. *Philosophical Transactions of the Royal Society of London Series B—Biological Sciences*, 302(1110), 325–340.
- 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(2), 184–198.
- Iarocci, G., Enns, J. T., Randolph, B., & Burack, J. A. (2009). The modulation of visual orienting reflexes across the lifespan. *Developmental Science*, 12(5), 715–724.
- 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., 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.
- Kuo, B. C., Rao, A., Lepsien, J., & Nobre, A. C. (2009). Searching for targets within the spatial layout of visual short-term memory. *Journal of Neuroscience*, 29(25), 8032–8038.
- Landman, R., Spekreijse, H., & Lamme, V. A. F. (2003). Large capacity storage of integrated objects before change blindness. *Vision Research*, 43(2), 149–164.
- 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.
- 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.
- Lepsien, J., & Nobre, A. C. (2007). Attentional modulation of object representations in working memory. *Cerebral Cortex*, 17(9), 2072–2083.
- 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.
- Mesulam, M. M. (1999). Spatial attention and neglect: Parietal, frontal and cingulate contributions to the mental representation and attentional targeting of salient extrapersonal events. *Philosophical Transactions*

- of the Royal Society of London Series B—Biological Sciences, 354(1387), 1325–1346.
- Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, 24, 167–202.
- Miyake, A., Friedman, N., Rettinger, D. A., Shah, P., & Hegarty, M. (2001). How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *Journal of Experimental Psychology: General*, 130, 621–640.
- Nobre, A. C. (2001). The attentive homunculus: Now you see it, now you don't. *Neuroscience and Biobehavioral Reviews*, 25(6), 477–496.
- Nobre, A. C., Coull, J. T., Maquet, P., Frith, C. D., Vandenberghe, R., & Mesulam, M. M. (2004). Orienting attention to locations in perceptual versus mental representations. *Journal of Cognitive Neuroscience*, 16(3), 363–373.
- 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.
- Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, 32(1), 3–25.
- Posner, M. I., & Cohen, Y. (1984). Component of visual orienting. In H. Bouma & D. Bouwhuis (Eds.), *Attention: X. control of language processes* (pp. 551–556). Hove, UK: Lawrence Erlbaum Associates Ltd.
- Reeves, A., & Sperling, G. (1986). Attention gating in short-term visual memory. *Psychological Review*, 93(2), 180–206.
- Ristic, J., & Kingstone, A. (2009). Rethinking attentional development: Reflexive and volitional orienting in children and adults. *Developmental Science*, 12(2), 289–296.
- Robert, C., Borella, E., Fagot, D., Lecerf, T., & de Ribaupierre, A. (2009). Working memory and inhibitory control across the life span: Intrusion errors in the Reading Span Test. *Memory and Cognition*, 37(3), 336–345.
- Rossion, B., & Pourtois, G. (2004). Revisiting Snodgrass and Vanderwart's object pictorial set: The role of surface detail in basic-level object recognition. *Perception*, 33(2), 217–236.
- Ruff, C. C., Kristjansson, A., & Driver, J. (2007). Readout from iconic memory and selective spatial attention involve similar neural processes. *Psychological Science*, 18(10), 901–909.
- Schul, R., Townsend, J., & Stiles, J. (2003). The development of attentional orienting during the school-age years. *Developmental Science*, 6(3), 262–272.
- Sligte, I. G., Scholte, H. S., & Lamme, V. A. F. (2008). Are there multiple visual short-term memory stores? *PLoS One*, 3(2), e1699.
- Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs*, 74(11), 1–29.
- Summerfield, J. J., Lepsien, J., Gitelman, D. R., Mesulam, M. M., & Nobre, A. C. (2006). Orienting attention based on long-term memory experience. *Neuron*, 49(6), 905–916.
- 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.
- Vogel, E. K., & Awh, E. (2008). How to exploit diversity for scientific gain: Using individual differences to constrain cognitive theory. *Current Directions in Psychological Science*, 17(2), 171–176.
- Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature*, 428(6984), 748–751.
- Vogel, E. K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature*, 438(7067), 500–503.
- Wainwright, A., & Bryson, S. E. (2002). The development of exogenous orienting: Mechanisms of control. *Journal of Experimental Child Psychology*, 82(2), 141–155.
- Wainwright, A., & Bryson, S. E. (2005). The development of endogenous orienting: Control over the scope of attention and lateral asymmetries. *Developmental Neuropsychology*, 27(2), 237–255.
- Wechsler, D. (1999). *Wechsler Abbreviated Scale of Intelligence (WASI)*. San Antonio, TX: Pearson Assessment.