

Orienting Attention Within Visual Short-Term Memory: Development and Mechanisms

Andria Shimi
*University of Oxford and
Medical Research Council*

Anna C. Nobre
University of Oxford

Duncan Astle
Medical Research Council

Gaia Scerif
University of Oxford

How does developing attentional control operate within visual short-term memory (VSTM)? Seven-year-olds, 11-year-olds, and adults (total $n = 205$) were asked to report whether probe items were part of preceding visual arrays. In Experiment 1, central or peripheral cues oriented attention to the location of to-be-probed items either prior to encoding or during maintenance. Cues improved memory regardless of their position, but younger children benefited less from cues presented during maintenance, and these benefits related to VSTM span over and above basic memory in uncued trials. In Experiment 2, cues of low validity eliminated benefits, suggesting that even the youngest children use cues voluntarily, rather than automatically. These findings elucidate the close coupling between developing visuospatial attentional control and VSTM.

Attentional biases prioritize information at multiple processing stages to enhance representations of stimuli that are relevant to current task goals (Desimone & Duncan, 1995; Gazzaley & Nobre, 2011; Kastner & Ungerleider, 2000). These biases have been investigated extensively using the Posner paradigm, in which spatial cues direct attention to the location of subsequent target stimuli (Posner, 1980; Posner & Cohen, 1984). This paradigm has been pivotal in showing that attentional orienting improves adults' processing of upcoming stimuli at cued locations (e.g., Corbetta, Miezin, Shulman, & Petersen, 1993; Luck, Hillyard, Mouloua, & Hawkins, 1996; Luck, Woodman, & Vogel, 2000; Prinzmetal, McCool, & Park, 2005).

Our everyday activities, nonetheless, rely as much on how we orient attention to externally presented stimuli as to representations in memory. A direct comparison of externally and internally

focused attentional processes provides novel perspectives on how attention affects visual short-term memory (VSTM) and on how information in VSTM guides attention (Chun, Golomb, & Turk-Browne, 2011). For example, Griffin and Nobre (2003) modified the Posner cueing paradigm to orient participants' attention in advance of encoding (with "pre-cues") and retrospectively during VSTM maintenance (with "retro-cues"). This and other studies (e.g., Kuo, Stokes, & Nobre, 2011; Landman, Spekreijse, & Lamme, 2003; Lepsien, Griffin, Devlin, & Nobre, 2005; Makovski & Jiang, 2007; Ruff, Kristjánsson, & Driver, 2007; Sligte, Scholte, & Lamme, 2008) suggest that visuospatial attentional orienting optimizes encoding and maintenance in VSTM in adults. Attentionally refreshing a just-presented item enhances its representation during maintenance (Raye, Johnson, Mitchell, Greene, & Johnson, 2007; Raye, Johnson, Mitchell, Reeder, & Greene, 2002) and attentional efficiency constrains how adults maximize VSTM capacity (Fukuda & Vogel, 2009; Matsukura, Luck, & Vecera, 2007; Vogel, McCollough, & Machizawa, 2005; Woodman, Vecera, & Luck, 2003).

In a parallel and equally vast literature, adult models of VSTM and visual working memory

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Correspondence concerning this article should be addressed to Gaia Scerif, Department of Experimental Psychology, University of Oxford, South Parks Road, Oxford OX1 3UD, UK. Electronic mail may be sent to gaia.scerif@psy.ox.ac.uk.

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(VWM) stipulate that both spatial and nonspatial attentional processes play an important role in prioritizing information for encoding, updating and monitoring information during VSTM maintenance (e.g., Awh & Jonides, 1998, 2001; Baddeley & Hitch, 1974; Cowan, 2001; Engle, Tuholski, Laughlin, & Conway, 1999). For example, memory for spatial sequences in the Corsi Block span task requires attentional resources (e.g., Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009; Rudkin, Pearson, & Logie, 2007; Vandierendonck, Kemps, Fastame, & Szmalec, 2004) and imposing concurrent attentionally demanding tasks during maintenance has established that, in adults, attention is involved in avoiding interference and/or protecting representations in VSTM (Ueno, Allen, Baddeley, Hitch, & Saito, 2011).

Despite these advances at the interface between attention and VSTM and VWM in adults, it remains unclear whether changes in attentional control play a similar role in the earlier development of VSTM and VWM. Children's STM capacity increases dramatically between 3 and 10 years (e.g., Gathercole, 1999; Gathercole, Pickering, Ambridge, & Wearing, 2004), although these changes are better understood for verbal than for visual material (Pickering, 2001). Models of childhood memory development include a domain-general attentional controller (e.g., Baddeley & Hitch, 2000), but exactly how this operates in spatial and nonspatial terms remains unclear. While the ability to "refresh" items in visual memory distinguishes older and young adults (Johnson, Reeder, Raye, & Mitchell, 2002; Raye, Mitchell, Reeder, Greene, & Johnson, 2008; Raye et al., 2002), these processes have rarely been investigated in childhood. Furthermore, children's VSTM capacity measured with tasks such as the Corsi Blocks increases with age (Kemps, De Rammelaere, & Desmet, 2000; Logie & Pearson, 1997). Examining precisely how attentional orienting contributes to these commonly used tasks across development can elucidate further the contribution of attentional control to developing VSTM and VWM.

Investigating attentional contributions to changes in VSTM, 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 by focusing on items of particular upcoming shapes. With large arrays, 7-year-olds differed from 12-year-olds and adults at attending to changes for items in the cued shape. In contrast, when they allocated attention to small arrays, they did not differ in how they dealt with changes, suggesting that both attentional

abilities and basic limitations in storage capacity influence developmental differences in VSTM. Age-related differences in VSTM persisted even when slow encoding was possible (Cowan, AuBuchon, Gilchrist, Ricker, & Saults, 2011), indicating that changes in storage capacity, rather than encoding differences or attentional filtering, underpinned developmental changes in VSTM and VWM capacity in these two studies.

Yet, the distinct contributions of visuospatial biases to encoding and maintenance in VSTM could not be assessed in the paradigms used by Cowan and colleagues because attention was always oriented to a nonspatial target dimension (shape) prior to encoding. Complementary insights into the role of developing visuospatial attention for VSTM and VWM over childhood are needed (Astle & Scerif, 2011; Scerif, 2010). Pioneering work in infants by Oakes and colleagues points in this direction. For example, Ross-Sheehy, Oakes, and Luck (2011) elegantly demonstrated that salient visuospatial attention cues facilitate detection of a change in VSTM in infants as young as 5 and 10 months of age. The mechanisms by which spatial cues orient attention in function of memory later in childhood are less well understood. A recent study examined 7-year-olds', 10-year-olds', and adults' memory when visuospatial cues oriented attention to items in memory (Astle, Nobre, & Scerif, 2012). Despite poorer overall memory in children, all groups benefited from the attention cues. Children benefited from cues in advance of encoding just as much as adults, but this was not the case for cues orienting attention during maintenance, highlighting developmental similarities and differences in how visuospatial attention operates in VSTM. Furthermore, children's cueing benefits during maintenance predicted VSTM and VWM span, and the authors concluded that individual differences in visuospatial attention contribute to differences in visual memory capacity.

The precise reasons why young children and adults should differ in how their visuospatial attentional biases operate in VSTM remain to be investigated. We aimed to assess whether the differential developmental time course of visuospatial orienting in service of encoding versus maintenance depends on specific characteristics of the orienting cues, that is, their symbolic nature, abrupt onset or position (Experiment 1), or on the validity of cues and therefore, in turn, on voluntary as opposed to reflexive orienting (Experiment 2). To understand the nature of orienting benefits, we also examined the extent to which individual differences in visuospatial cueing

benefits and traditional measures of VSTM and VWM span are closely coupled (Experiment 1).

Experiment 1

The role of attention in VSTM and VWM tasks has been demonstrated in adults (e.g., Rudkin et al., 2007; Salway & Logie, 1995; Ueno et al., 2011) and in infants (e.g., Ross-Sheehy et al., 2011). However, developmental trajectories through childhood and their cognitive underpinnings are not clear. When tested in the context of simple target detection or discrimination, attentional orienting varies in its rate of change over development depending on whether central or peripheral cues are used (Akhtar & Enns, 1989; Brodeur & Boden, 2000; Enns & Brodeur, 1989; Iarocci, Enns, Randolph, & Burack, 2009; Ristic & Kingstone, 2009; Wainwright & Bryson, 2002). Although central and peripheral cues are often interpreted as engendering, respectively, voluntary and automatic orienting, they differ along simpler dimensions (Ristic & Kingstone, 2009): Their locus of presentation and the symbolic nature of central cues also distinguish them. In departure from Astle et al. (2012), whose cues conflated central and peripheral elements, we contrasted cues at distinct positions to study whether participants' encoding in VSTM and maintenance would benefit from cues despite their differences. This experimental manipulation is critical for distinguishing alternative factors underpinning developmental changes in the ability to orient attention in VSTM: either an increasing ability to control and direct attention in service of memory or a greater ability to interpret and follow central symbolic arrow cues.

First, we hypothesized that attention cues would benefit VSTM for all age groups, but we expected smaller benefits with attention cues presented during maintenance in children than in adults and compared to cues presented prior to encoding, consistent with Astle et al. (2012). Second, we hypothesized that if these developmental differences in cueing benefits truly reflect children's improving attentional control rather than difficulties in interpreting or using central symbolic cues, then we should observe similar performance in central and peripheral cues within each age group. Finally, attentional cueing benefits during maintenance should relate to individual differences on measures of VSTM and VWM capacity that are commonly used to study these in childhood, elucidating shared mechanisms for visuospatial attention and memory.

Method

Participants

Forty children (15 boys) between 6 and 8 years old ($M = 6.9$ years old, $SD = .62$; "7-year-olds" henceforth), 40 children (17 boys) between 10 and 12 years old ($M = 10.8$ years old, $SD = .63$; "11-year-olds" henceforth), and 36 adults (15 males) between 18 and 34 ($M = 23.7$ years old, $SD = 3.91$, "adults" henceforth) participated in the study. Twenty children in each child group and 15 adults completed the central-cue task ("central-cue group"); the remaining children and 21 adults completed the peripheral-cue task ("peripheral-cue group"). Children were recruited from local primary schools via an opt-in procedure. Adults were recruited among university undergraduates and postgraduates. Due to time constraints in testing, additional data on individual differences in VSTM and VWM capacity could only be collected from participants in the central-cue groups ($n = 55$, 40 children). Children with neurological/psychiatric disorders were excluded from the study and no hearing problems were reported by the parents or teachers of the participants. All participants had normal or corrected-to-normal vision. 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 children participants signed informed consent forms.

Apparatus

Attentional orienting task. The experimental task (see Figure 1 for examples of conditions) was programmed in E-prime v.1.2 (Psychological Software Tools, Pittsburgh, PA) and presented on a PC screen. Participants viewed an array of four items comprising identical line drawings of familiar objects and animals (each subtending $1.64^\circ \times 2.05^\circ$ and centered at 2.87° lateral and 2.87° azimuthal eccentricity from a central fixation point). The array was followed by a single memory item ("probe") and participants responded whether the probe had been present in the preceding array. Array items were presented in different colors (drawn from a set of seven colors: blue, green, yellow, orange, pink, red, and white) on a black background. Attention cues appeared briefly before encoding of the array or while the array was being maintained in VSTM and guided participants' attention to the location of the item to be probed. Cues directing attention to an array item were always valid (i.e., they cued the location of the item to be probed with 100% validity).

Three trial types (Figure 1b) were included in the experiment: pre-cue, retro-cue, and neutral trials. In pre-cue trials, an attention cue was presented before the array and it guided participant's attention to one of the upcoming items of the array. In retro-cue trials, an attention cue was shown after the array and guided participants' attention to one of the already encoded items. In neutral trials, white squares (that provided no spatial information as to a specific location) were presented before and after the array, to control for the nonspatial alerting benefits that pre- and retro-cues may have engendered. To also equate pre-cue and retro-cue trials in the amount of nonspatially informative alerting, we included neutral squares at the uncued time-point within each trial type. For example, in pre-cue trials, a white square ("neutral square") appeared after the memory array, at the time point at which the retro-cue would appear in the other trial type. This controlled for generic alerting effects by our attention cues.

Two experimental groups were tested. In the central-cue groups, the attention cue was a white arrow presented centrally ($0.82^\circ \times 0.82^\circ$). In the peripheral-cue groups, the attention cue was a white square outline ($1.64^\circ \times 2.05^\circ$) presented at the location subsequently or previously occupied by one of the array items. Neutral squares ($0.82^\circ \times 0.82^\circ$) were centrally presented.

The task consisted of two practice blocks of six trials each, followed by four test blocks of 48 trials each, totalling 192 experimental trials. The first practice block was a slower version of the real experiment to ensure that the participants really understood the task; the second adopted the timing parameters of test trials. To prevent children from being confused by continually changing cue types across trials, each test block contained neutral trials and either pre-cues (two "pre-cue blocks") or retro-cues (two "retro-cue blocks"). Block order was counterbalanced across participants. Two thirds of trials were probe-present trials and one third was probe-absent trials. Half of all trials were cued (equally likely to point to one of the four possible spatial locations) and half were neutral. Central and peripheral cues always predicted target location in probe-present trials (100% valid). Half of "probe-absent" trials also contained attention cues to ensure that these did not simply come to signal a "present" response (in probe-absent trials, the cue pointed to an item in the array, but the probe was not part of the array). Participants received visual feedback (i.e., correct, incorrect, no response) after each practice trial. On test blocks, feedback about the number of correct responses was given on the

screen after every 16 experimental trials and at the end of the block.

Automated Working Memory Assessment (AWMA; Alloway, 2007). We employed the *Dot Matrix* task and the *Spatial Recall* task and followed the nomenclature employed by the test designer in labeling the first a spatial STM task and the second a spatial WM task although both load on attentional processes. Both tasks are derivatives of the Corsi block task, allowing us to link our experimental measures with traditional span measures (see Introduction). In *Dot Matrix*, participants view a 4×4 matrix and sequentially presented red dots. They recall where dots appeared in exactly the same order by pointing to the computer screen. In *Spatial Recall*, participants view two identical shapes, one of which is the mirror image of the other on half of all trials. They report whether the two shapes are a mirror image of each other, thus performing a mental rotation on the second shape. At the same time, the second shape is paired with a red dot whose serial positions participants recall at the end of the sequence. The task therefore requires the child to retain the ordered locations of a dot while rotating objects in mind. For both scales, the number of to-be-remembered items increases until below 2/3 criterion. Raw scores and standardized scores can be computed for both subscales.

Procedure

Participants were tested individually in a quiet room within their school or at the university. Participants sat at a comfortable distance from the screen. The examiner explained the characteristics of trial types on the orienting 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 item was present in the previous array. Participants were also asked to respond as quickly and accurately as possible while focusing their gaze on the fixation point throughout the trial. Children placed the index finger of each hand on each mouse button while adults held the mouse in one hand. Participants received feedback from the experimenter while performing the practice trials, to ensure that they understood the task. After completing the orienting task, participants in the central-cue groups also completed the two subscales of the AWMA.

Design

Separate mixed-design analyses of variance (ANOVAs) were performed for each dependent

variable to test the effect of the between-subject factors of age group (7-year-olds, 11-year-olds, adults) and cue position (central, peripheral), and the within-subject factors of cue timing (attention cues presented prior to encoding, “pre-cues” henceforth; attention cues presented during maintenance, “retro-cues” henceforth) and trial type (cued, neutral). Accuracy-based d' -prime and median reaction times (RTs) were both computed, as these may index distinct effects on how well stimuli are represented in memory and information is accessed, respectively (Prinzmetal et al., 2005). To aid comparisons with previous findings (e.g., Cowan et al., 2005; Cowan et al., 2010; Cowan et al., 2011), Cowan’s K was computed as a measure of VSTM capacity (see formula, Figure 2). A further analysis on response criterion c' investigated age-group differences in response bias. RTs were computed for correct probe-present trials only (e.g., Griffin & Nobre, 2003). Greenhouse-Geisser and Bonferroni corrections were employed when necessary.

To understand the cognitive processes underpinning visuospatial orienting benefits, preliminary correlational analyses with well-understood measures of VSTM/VWM span were followed by hierarchical regression models in which age in months, performance on neutral trials, and performance on cued trials were assessed as predictors of raw scores on the Dot Matrix and Spatial Recall tasks. An accuracy-based measure (K) was chosen as predictor here because traditional span measures

are unspedded, and because RT is thought to index less well the precision of cued representations (Prinzmetal et al., 2005).

Results

Accuracy-Based Improvements: Cowan’s K

Analyses were consistent across distinct accuracy-based measures (d' -prime and Cowan’s K). Thus, for brevity, only statistics for K are reported. The analysis revealed two significant three-way interactions of Age Group \times Cue Timing \times Trial Type, $F(2, 110) = 11.89, p < .001, \eta^2 = .18$, and Cue Position \times Cue Timing \times Trial Type, $F(1, 110) = 4.75, p = .03, \eta^2 = .04$. Analyses of simple main effects for the interaction of Age Group \times Cue Timing \times Trial Type revealed that all age groups performed better in cued than neutral trials in both blocks ($p < .05$, for all comparisons), and that pre-cue benefits were larger than retro-cue benefits for all groups ($p < .05$). What, then, drove the interaction? As there were age-related baseline differences in memory for neutral trials ($p < .05$ for all comparisons), difference scores were calculated as the difference between cued and neutral trials (see Figure 2). These revealed a main effect of cue timing, $F(1, 110) = 109.84, p < .001, \eta^2 = .500$, and a Cue Timing \times Age Group interaction, $F(2, 110) = 11.89, p < .001, \eta^2 = .178$. The interaction was driven by the fact that, when the cue was presented in

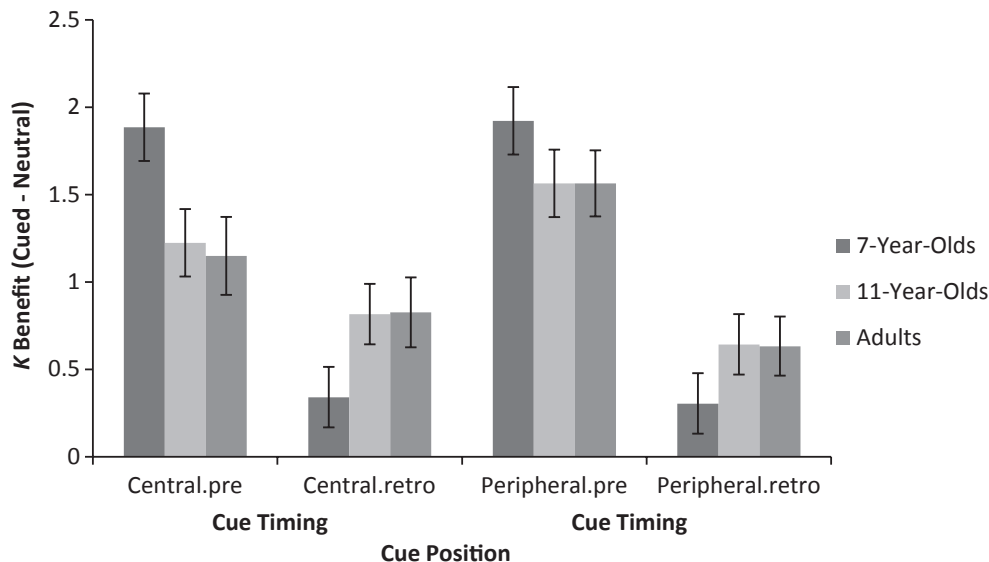


Figure 2. Cowan’s K difference scores from neutral baseline, comparing the central with the peripheral cue across pre-cue and retro-cue trials, for all three age groups in Experiment 1. Cowan’s K scores were computed by subtracting the false alarm rate (proportion of trials that participants incorrectly reported as present) from the hit rate (proportion of trials that participants correctly reported as present) and multiplying the residual with the set size of the memory array. Error bars represent standard errors of the means.

advance of encoding, all three age groups benefited to the same degree ($p > .05$ for all comparisons), but when the cue was presented during maintenance, adults and 11-year-olds benefited to a similar degree to each other ($p > .05$) and significantly more than the 7-year-olds ($p < .05$). These age-related group differences in cueing benefits held even when a proportional difference score taking baseline memory into account [(cued-neutral)/neutral] was computed, Age Group \times Cue-Timing Benefit, $F(2, 108) = 9.27$, $p < .001$, $\eta^2 = .15$.

To return to the question of whether the characteristics of cues drive attentional orienting effects, the Cue Position \times Cue Timing \times Trial Type interaction was driven by better performance for central cues compared to peripheral cues in the retro-cue block ($M = 2.50$ and 2.17 , respectively, $p = .02$). Difference scores confirmed that there were greater benefits stemming from the pre-cues than from the retro-cues regardless of the position of the cue ($M_s = 1.42$ and $.66$, respectively, for central cues and $M_s = 1.68$ and $.53$, respectively, for peripheral cues, $p < .001$). Crucially, there was no interaction between age group and cue position on K benefit having controlled for differences in neutral trials by computing difference scores. This in turn suggested that benefits across age groups were not affected by the physical characteristics of the cue, and were not poorer in children than adults for symbolic central cues, with both encoding and maintenance cues ($p > .05$ for all comparisons).

There were no significant main effects of age group or interactions with age group ($p > .05$) on criterion c , suggesting that there were no differences among the three age groups in their tendency to respond yes or no. These findings suggest that the K (and d -prime) results reflect participants' ability to make use of the cue and not responding biases.

Median RTs

The ANOVA on median RT showed that main effects were moderated by a highly significant three-way interaction of Age Group \times Cue Timing \times Trial Type, $F(2, 110) = 12.34$, $p < .001$, $\eta^2 = .18$, bolstering the similar effect for K (and d -prime). As there were again age-related differences in baseline neutral trials, cueing benefits were again calculated as the difference in median RT on neutral minus cued trials. Difference scores showed a significant main effect of age group, $F(2, 110) = 5.05$, $p = .008$, $\eta^2 = .08$, and a significant interaction of Age Group \times Cue Timing, $F(2, 110) = 12.34$, $p < .001$,

$\eta^2 = .18$, driven by the 7-year-olds benefiting more in speed when presented with pre-cues ($M_s = 421.70$) than with retro-cues ($M_s = 253.26$, $p < .001$). Adults and 11-year-olds benefited equally from pre-cues and retro-cues (adults: $M_s = 231.16$ and 256.23 , 11-year-olds: $M_s = 229.79$ and 262.89 , respectively, $p > .05$). When overall slower responses in children were taken into account by scaling RT differences by neutral RTs, that is, (neutral-cued)/neutral, the Age Group \times Cue Timing interaction remained significant ($p < .001$).

Attentional Cueing Benefits and VSTM and VWM Capacity

To understand further the cognitive processes underpinning visuospatial orienting benefits, we assessed whether individual differences in attentional orienting related to performance on validated VSTM and VWM span tasks for the sample of children and adults in the central-cue groups. Preliminary partial correlations controlling for chronological age in months across measures of attentional orienting (d -prime and K ; again, the two measures revealed similar results, and thus for brevity, statistics for K only are reported) and memory span performance (raw scores from the two AWMA subscales) are presented in Table 1. In addition to examining relations across all measures (as seen above the top diagonal in Table 1), we tested whether performance in cued trials correlated with VSTM and VWM span subscales having controlled for K on neutral trials at an earlier step (see two bottom rows in Table 1). This is a conservative approach because it excludes variability in attentional processes that are also required by maintaining information in VSTM when no spatially informative cues are provided. In essence, it focuses solely on attentional processes explicitly related to visuospatial orienting.

In summary, when individual differences in age and baseline memory on uncued trials were taken into account, performance following retro-cues related significantly to both visuospatial STM span (as indexed by the Dot Matrix task) and to visuospatial WM span (as indexed by the Spatial Recall task). Although performance on neutral and cued trials were significantly correlated, having controlled for basic memory on neutral trials and age-related differences, K on retro-cued trials significantly predicted additional unique variance in Spatial Recall scores, smallest $F(1, 51) = 4.73$, $p = .03$, and in Dot Matrix scores, smallest $F(1, 51) = 4.82$, $p = .03$ (see online Appendix S1, for regression

Table 1

Experiment 1 Relations Between Chronological Age (Age in Months), Attentional Control Measure (K), and Raw Scores for Visual Short-Term (Dot Matrix) and Working Memory Span (Spatial Recall, Automated Working Memory Assessment [AWMA]).

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

Note. Values above the diagonal indicate partial correlations across measures controlling for chronological age in months, whereas values below the diagonal indicate partial correlations between performance on cued trials and AWMA subscales, controlling for both chronological age and performance on neutral trials.

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

statistics). As these relations may have been driven by the adults in the sample, we conducted the same analyses on children alone, obtaining converging results.

Discussion

In Experiment 1, attention cues resulted in benefits both prior to encoding and during maintenance, suggesting that deploying attentional control can facilitate accurate and fast retrieval of information from VSTM. For the first time, we assessed whether, like in the case of orienting in service of target detection or discrimination (e.g., Iarocci et al., 2009), age-related differences in benefits for VSTM depended on cue's physical characteristics, that is, cue position, even in the context of identical cue validity. The effects of cue position were driven by better performance with central compared to peripheral retro-cues for all, rather than just for adults. This is may be because peripheral retro-cues could act themselves as masks during the maintenance period and partly interfere with probe recognition, in a way that central cues could not (see Ueno et al., 2011, for interference during maintenance). Similar effects of cue position across age groups argue against *developmental differences* in attentional orienting in VSTM being driven by the physical or symbolic characteristics of cues, at least down to 7 years of age.

Benefits in d-prime and K were bolstered by similar effects on RT, suggesting improvements in both the precision and access of VSTM representations (Prinzmetal et al., 2005). These overall benefits show that despite poor basic memory for 7-year-olds (similar to estimates obtained with a different paradigm, e.g., Cowan et al., 2010), visuospatial attention cues improved memory significantly in all groups. This

was the case especially when cues preceded encoding. Developmental differences emerged in the extent to which cues during maintenance helped participants, even when we accounted for basic memory performance. The youngest children did not benefit from these cues as much as older children and adults pointing to the differential developmental trajectories by which spatial attention facilitates encoding and maintenance in VSTM. Unlike the findings by Astle et al. (2012), 11-year-olds here aligned themselves with adults. Their performance may have been superior in the current experiment because cues were fully predictive a point to which we return later.

Furthermore, the ability to use visuospatial attention cues during the maintenance period was closely coupled with individual differences in spatial VSTM and VWM span, over and above differences in basic unaided visual memory. What cognitive processes could underpin these relations? These VSTM and VWM measures share spatial requirements and attentional demands (Rudkin et al., 2007; Salway & Logie, 1995; Vandierendonck et al., 2004), but Spatial Recall requires additional attentional resources to protect memory from the interfering concurrent mental rotation task. Relations were strongest between visuospatial cueing benefits and Spatial Recall, suggesting common visuospatial mechanisms protecting representations from interference. However, significant albeit weaker relations with simpler span (Dot Matrix) also emerged. Maximizing VSTM and VWM capacity in both cases may require actively biasing stimuli in space to maintain information, and retro-cued trials capture individual differences in the ability to engage this active process best.

We return to the theoretical significance of the findings and their relation to models of VSTM and VWM development in the General Discussion. First, we tackled alternative explanations for the findings.

Could it be that the benefits derived from the attentional orienting in service of memory observed in Experiment 1 are automatic, rather than voluntary, in nature? Even more critically, could reflexive mechanisms underpin attentional orienting benefits in young children, whereas similar effects are driven by voluntary processes in adults?

Experiment 2

Results from Experiment 1 showed no substantial differences in the way central and peripheral cues modulate VSTM retrieval in children and adults when they reliably predict the target's location, whereas developmental differences were particularly evident when cues oriented attention during the maintenance period. We therefore tested the extent to which these developmental differences in orienting benefits depended on voluntary processes by reducing the predictive validity of cues. Many attention orienting studies to date indicate that central cues can allocate attention automatically, as shown by facilitatory effects of centrally presented eye direction (e.g., Friesen & Kingstone, 1998) or arrow direction (e.g., Ristic & Kingstone, 2012; Tipples, 2002) cues that do not predict upcoming target location. The attention effects of nonpredictive eyes and arrows have been measured in infants (e.g., Hood, Willen, & Driver, 1998), preschool children (e.g., Ristic, Friesen, & Kingstone, 2002), and aging adults (e.g., Olk, Hildebrandt, & Kingstone, 2010). Furthermore, central and peripheral cues can engage both voluntary and reflexive orienting when they are spatially predictive (Olk, Cameron, & Kingstone, 2008) both in adults and in 3- to 4-year-old children (Ristic & Kingstone, 2009), as well as across the life span (Iarocci et al., 2009). As a whole, although peripheral cues have often been characterized as resulting in "automatic" and central arrow cues as resulting in "voluntary" orienting, this substantial body of work in adults and over development warns against drawing such implications, because it is rarer for studies to manipulate cue location and cue validity orthogonally, for example, using fully valid and invalid central cues and fully valid and invalid peripheral cues. In line with this argument, in Experiment 1 we examined whether cue position alone modulates VSTM differentially across development, in the context of an explicit and equivalent motivation to follow fully valid cues, whereas in Experiment 2 we introduced invalid cues.

Manipulations of cue validity can also be extremely useful in understanding mechanisms of

attentional control in VSTM, be they spatial or non-spatial. For example, Cowan et al. (2010) asked participants to attend to a target shape within an array to be encoded, but changes occasionally occurred in the unattended shape. Children and adults were highly sensitive to this nonspatial attentional manipulation, with K dropping significantly when shape validity dropped from 100% to 50%. Berryhill, Richmond, Shay, and Olson (2012) employed a similar logic by contrasting fully valid retro-cues, retro-cues that were only valid in 25% of trials, and fully uninformative retro-cues. Results showed no cue benefits for fully uninformative cues and a nonsignificant trend for cues of low validity, prompting Berryhill et al. to suggest that, at least in adults, voluntary control drives orienting effects during maintenance.

We hypothesized that if the cueing benefits demonstrated by all participants in Experiment 1, and especially by children, depend on automatic orienting effects rather than controlled voluntary orienting, benefits should survive even when cues have very low validity, and this may be the case especially for peripheral cues. If, on the contrary, voluntary allocation of attention drives the effects, cueing benefits and their developmental differences should be drastically reduced compared to Experiment 1 and for all cue positions. All attention cues were retro-cues, since these carried the age-related differences in Experiment 1 and because individual differences in retro-cueing benefits uniquely related to VSTM/VWM span.

Method

Participants

Thirty-four typically developing children (15 boys) aged 6–7 years old ($M = 6.47$ years old, $SD = .51$; 7-year-olds henceforth), 36 children (16 boys) aged 10–12 years old ($M = 10.92$ years old, $SD = .77$; 11-year-olds henceforth) and 19 adults (4 men) aged 19–30 years old ($M = 24.95$, $SD = 3.37$) took part. Recruitment and informed consent operated as in Experiment 1.

Apparatus

Attentional orienting task. All parameters were the same with Experiment 1 except in three respects. First, there were only two trial types, retro-cue and neutral trials. Second, retro-cues could be valid or invalid (see Figure 1c). Third, instead of manipulating cue position across participants, all participants completed two blocks using centrally presented cues ("central

blocks”) and two blocks with peripherally presented cues (“peripheral blocks”), whose order was counter-balanced across participants. As with Experiment 1, each test block contained 48 trials, totalling 192 trials, of which two thirds were probe-present trials and one third probe-absent trials. Of the probe-present trials, three fourths were cued (equally likely to point to one of the four possible spatial locations) and one fourth were neutral. Probe-absent trials contained an equal split of cued and neutral trials to avoid cues indexing “present” trials. In probe-present trials, if a cue was presented, it indicated the location of the probe in the memory array 50% of the time; thus, on target present trials, cues were 50% likely to indicate the location of the probe in the memory array, a significant decrease in their validity compared to Experiment 1 (100%). Time parameters were identical to those used in Experiment 1.

Procedure

The only difference was the nature of the task-specific instructions participants received. They were informed that occasionally the cue would be helpful, but other times it would trick them by pointing to a spatial location other than the one the probe occupied in the memory array. Following Berryhill et al. (2012), participants were recommended to ignore the cue.

Design

A mixed-design ANOVA was performed on K and median RT scores testing the between-subjects factor of age group (7-year-olds, 11-year-olds, adults) and the within-subjects factors of cue position (central, peripheral) and trial type (validly cued, invalidly

cued, neutral). In addition, to contrast effects in Experiments 1 and 2, we conducted ANOVAs on valid central retro-cue and neutral trials and on peripheral retro-cue and neutral trials across experiments, treating experiment as a between-subject variable.

Results

Accuracy-Based Measures: Cowan’s K

As in Experiment 1, statistics for d -prime and K yielded similar results, hence only K is reported for brevity (see online Appendix S1 for all condition means). Critically, cueing benefits compared to neutral trials were much reduced compared to Experiment 1 and no cueing costs were observed for all groups (see Figure 3): There were no significant differences between validly cued ($M = 1.88$) and neutral ($M = 1.75$, $p > .05$) trials, or between invalidly cued ($M = 1.73$) and neutral ($p > .05$) trials, with a residual benefit in trials with valid retro-cue compared to invalid retro-cue ($p = .02$). We also contrasted directly K scores for Experiments 1 and 2. The analyses on difference scores (retro-cue—neutral trials) for both ANOVAs showed a significant reduction in cue benefits in Experiment 2 compared to 1 for all groups (central cue benefit Experiment 1: $M = .66$ and central cue benefit Experiment 2: $M = .23$, $p = .002$; peripheral cue benefit Experiment 1: $M = .53$ and peripheral cue benefit Experiment 2: $M = .04$, $p < .001$; see online Appendix S1 for full statistics).

Median RTs

A similar pattern of results was obtained for median RTs. Cueing benefits and costs were not

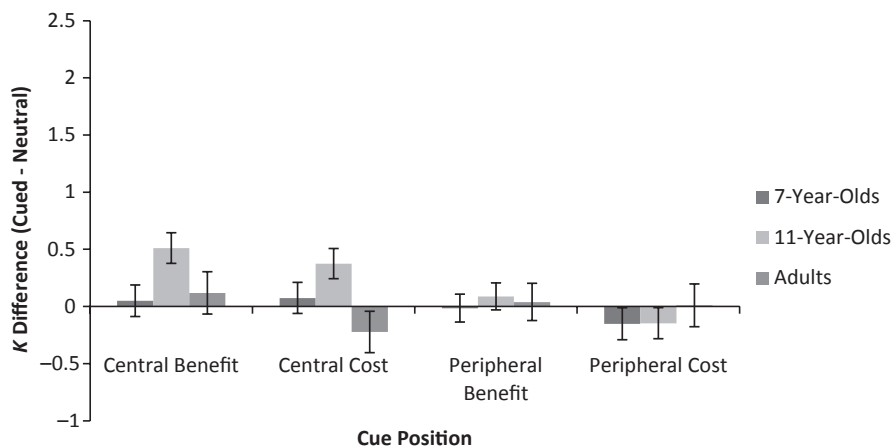


Figure 3. Cowan’s K difference scores from neutral baseline, comparing valid and invalid central and peripheral cues, for all three age groups in Experiment 2.

significant ($ps > .05$), with residual faster performance in valid cued trials ($M = 920.83$) compared to invalid cued trials ($M = 960.71$, $p < .05$) across age groups. As above, we also contrasted the benefits conferred by central and peripheral cues (retro-cue—neutral trials) between Experiment 1 and 2. Again, there was a significant reduction in cue benefits in Experiment 2 compared to 1 for all age groups (central cue benefit Experiment 1: $M = 258.89$ and central cue benefit Experiment 2: $M = 24.15$, $p < .001$; peripheral cue benefit Experiment 1: $M = 256.12$ and peripheral cue benefit Experiment 2: $M = 32.11$, $p < .001$; see online Appendix S1).

Discussion

We reduced the validity of the cues by introducing trials with invalid cues. Improvements in accuracy and response times for probes at validly cued locations compared to neutral trials were consequently eliminated, leaving only a residual advantage compared to invalid cues, consistent with Berryhill et al. (2012). A key finding of Experiment 2 is therefore that even children as young as 7 years of age can voluntarily allocate attention to refresh items in VSTM as well as largely resist automatic effects of cues when they are less informative, regardless of their physical characteristics. Furthermore, there were no age-related differences in cueing effects, in contrast to the marked differences found in Experiment 1, suggesting that differences in the ability to orient attention voluntarily drove the earlier age effects.

The voluntary or automatic nature of attentional refreshment mechanisms is a topical question for recent developmental studies of memory maintenance in the verbal domain (e.g., Barrouillet et al., 2009; Tam, Jarrold, Baddeley, & Sabatos-DeVito, 2010). The present findings suggest that the reliability with which cues predict target location plays a strong role in attentional orienting mechanisms engendered by spatial cues over and above their physical features, both in adults and in children (consistent with Iarocci et al., 2009; Ristic & Kingstone, 2009). To the best of our knowledge, this is the first study that has assessed these developmentally and in service of VSTM.

General Discussion

The aim of this study was to understand the contribution of visuospatial attentional control to VSTM and VWM across development. As we had

predicted, Experiment 1 demonstrated robust attentional cueing benefits for both the accuracy and speed with which information was retrieved from VSTM, both when cues were presented prior to encoding and during maintenance of visual information, suggesting cueing improvements in both precision of and access to these representations. Benefits during maintenance were smaller for younger children even when we controlled for their poorer memory through difference scores. Importantly, the developmental differences were consistent across central and peripheral cues, indicating that children's poorer ability to enhance maintenance and/or retrieval depends on the changing ability to deploy visuospatial attentional control during the maintenance period rather than on the physical or symbolic characteristics of the attentional orienting cues. These conclusions were corroborated by Experiment 2: Benefits of cues during maintenance were greatly decreased by decreasing cue validity and similarly so for peripheral and central cues. Furthermore, the age-related differences in retro-cueing effects obtained in Experiment 1 were eliminated in Experiment 2. This finding demonstrates that participants were able to ignore the cues (indexed by an absence of costs). It also suggests that in Experiment 1 participants in all groups understood the value of the cue and followed instructions to optimize VSTM performance; that is, they used cues to facilitate encoding and maintenance of to-be-probed items.

Taken together, these new findings strongly suggest that developmental differences during maintenance depend on changes in controlled voluntary visuospatial orienting rather than being automatic. Developmental changes are consistent with the vast literature documenting changes in children's ability to orient attention in service of detection and discrimination (Akhtar & Enns, 1989; Brodeur & Boden, 2000; Brodeur & Enns, 1997; Brodeur et al., 1997; Enns & Brodeur, 1989; Goldberg, Maurer, & Lewis, 2001; Iarocci et al., 2009; Ristic & Kingstone, 2009; Wainwright & Bryson, 2002), but add to the more limited investigation of these visuospatial attentional processes in service of VSTM in childhood (Astle et al., 2012) by demonstrating for the first time the voluntary nature of these effects and their independence from cue characteristics.

Cueing benefits for all participants, independent of cue characteristics and influenced by cue validity, suggest that actively deploying visuospatial attention can facilitate retrieval of information from VSTM. Visuospatial attentional biases can influence

representations held in VSTM and be influenced by them, certainly in adults (Chun et al., 2011; Gazzaley & Nobre, 2011; Stokes, 2011; Stokes & Nobre, 2011) and in infancy (see Ross-Sheehy et al., 2011), but the current data provide the necessary bridge in childhood. Beyond attention models, these benefits of visuospatial attention cues are consistent with cognitive models and data on VWM as these include attentional constraints on the encoding and maintenance of stimuli in memory (e.g., Salway & Logie, 1995; Ueno et al., 2011; Vandierendonck et al., 2004).

Recent theories stipulate that a taxonomy of attentional processes operating on externally versus internally focused representations can inform how attention facilitates adults' VSTM and vice versa (Chun et al., 2011). Here, applying this taxonomy developmentally demonstrates that controlled attentional processes operating on VSTM representations at different processing stages fractionate over development: Externally focused orienting in service of encoding seems efficient from relatively early in childhood, whereas internally focused biases during maintenance continue to improve later, a developmental dissociation that could not be studied as easily with change detection paradigms that have been used in children and infants (e.g., Cowan et al., 2010; Ross-Sheehy et al., 2011).

What precise cognitive mechanisms drive developmental differences in the efficiency of visuospatial biases during maintenance? Let us begin by ruling out accounts based on simple differences in the amount of information children can remember, because differences persist when we take these basic differences into account. We do not doubt that increasing storage capacity is an important factor for developmental improvements in VSTM and VWM capacity, especially in change detection paradigms (e.g., Cowan et al., 2010; Cowan et al., 2011), but we suggest that differences in the ability to deploy voluntary visuospatial biases can also contribute to them. A number of non-mutually exclusive visuospatial mechanisms may be involved. In the adult literature, it has been proposed that cues enhance the active maintenance of relevant items and/or suppress the activation of irrelevant items (Lepsien & Nobre, 2006), protect the representation of the selected item from decay or interference during the retention interval (Makovski & Jiang, 2007; Matsukura et al., 2007), and provide direct retrieval routes to items in memory by prioritizing the comparison process of the selected item with the probe (Astle, Summerfield, Griffin, & Nobre, 2011). Findings here suggest that prioritization per se is not

the key to developmental differences. This is because cues prior to encoding offered the opportunity to select and prioritize a single item among the four in the memory array for encoding and retention until test. Young children benefited from these cues as much as older individuals. We suggest that instead, older individuals are better able to use visual attentional control to refresh and protect selected representations during maintenance, and the ability to deploy such biases seems to be a critical distinguishing factor across age groups in influencing VSTM. The smaller attentional benefits for younger compared to older children are also consistent with the suggestion by Barrouillet et al. (2009) that attentional refreshment mechanisms may influence WM span differentially from 5 to 14 years of age, but unlike adults and the elderly (Johnson et al., 2002; Raye et al., 2002, 2008), in children these had thus far only been investigated for the verbal modality.

Can our use of more traditional VSTM and VWM measures elucidate further the nature of visuospatial attentional orienting mechanisms in VSTM? Over and above differences in age and basic memory, individual differences in attentional benefits during the maintenance period related to VSTM and VWM capacity, consistent with prior research in adults (e.g., Fukuda & Vogel, 2009; Vogel et al., 2005). All these findings are ultimately correlational in nature and do not imply causality. However, our data point to the fact that attentional orienting and VSTM and VWM capacity measures share variance even when simple retention is taken into account. This close coupling depends, we believe, on multiple mechanisms of attentional control. Both measures of VSTM and VWM span employed here make attentional demands in the visuospatial domain (e.g., Rudkin et al., 2007; Salway & Logie, 1995), although they differ in their concurrent demands. The Spatial Recall task required participants to maintain spatial sequences while also performing a secondary task that introduced interference during retention. Our findings suggest that voluntary attentional orienting and VSTM capacity are coupled whether there is a concurrent processing task or not, but the strongest relations emerged between our experimental measures of attentional orienting and the Spatial Recall task, indicating shared control mechanisms when protecting representations from interference during maintenance.

Cognitive processes other than visuospatial attentional control could also contribute to developmental and individual differences in the ability to

exploit attention cues to optimize memory during the maintenance period, and therefore deserve further investigation. For example, for younger children, information encoded in VSTM may be decaying at a faster rate (e.g., Cowan, Nugent, Elliott, & Sauls, 2000) and/or the memoranda may be interfering with each other to a greater degree (e.g., see Lewandowsky, Geiger, Morrell, & Oberauer, 2010, for an overview of interference-based accounts in adults), so that when a beneficial cue eventually appears in the maintenance period, the quality of the representations on which it can operate is degraded to a greater extent, even when no concurrent secondary processing task is required. Existing data suggest that, at least for 10-year-olds, imposing longer delays between the presentation of the memory array and attention cues does result in smaller cueing benefits than those attained at shorter delays, although the rate of decay of the attentional benefit is similar to that measured in adults (Astle et al., 2012, Experiment 2). Follow-up experiments with variable intervals between arrays and cues with younger children are required to investigate this point further. With regard to interference, adults' VSTM capacity does seem to depend on the ability to filter relevant information (e.g., Fukuda & Vogel, 2009) and work on VWM also suggests that, even for adults, there is an attentional cost to protecting representations from interfering irrelevant stimuli presented in the maintenance period (Ueno et al., 2011).

In conclusion, the current studies are the first to explore precise parameters through which developmental attentional control influences encoding and maintenance in VSTM during childhood. They define how children develop the ability to voluntarily deploy attentional control within VSTM. The study of developmental changes in attentional control and of visual memory are clearly ripe for further integration, and the current data motivate cognitive psychologists and developmental neuroscientists alike to converge on this exciting task.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Appendix S1. Supplementary Tables and Detailed Statistics for d-Prime, Cowan's *K*, and Reaction Time for Both Experiment 1 and Experiment 2; Regression Statistics for Experiment 1.