# Interactions between memory and attention orienting across development

Kate Nussenbaum

New College

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# Abstract

The influence of our past experiences in shaping our expectations and preparing us for future perceptual processing is now well documented, but many questions regarding how our long-term memories influence where we direct our attention remain unanswered. This thesis explores three of them. First, how do memories *interact* with other sources of attention orienting? In Chapter 2, we examine how memories influence attention when novel, transient visual events occur within scenes with learned associations. In Chapter 3, we extend this work by investigating how changing the time-course at which the transient visual event occurs affects the degree to which people use memories to orient attention. Second, when multiple sources of orienting are present, how does the degree to which each influences attention change across development? In Chapter 2, we examine how the degree to which concurrently presented memory cues and transient visual events influence attention differs between school-aged children and adults. In Chapter 4, we describe the results of a key control experiment in which we examine memory-guided attention in isolation across these two age groups. Finally, we address the question of how memory-guided attention influences subsequent recognition memory. Chapter 5 details three experiments exploring how previous experiences influence encoding of novel information.

With regards to the first two questions, we found that the onset of transient visual events interferes with memory-guided attention to a greater degree in adults than in children. However, with longer durations between the onset of a salient visual event and a target stimulus, adults also demonstrate an influence of memory on attention. Our follow-up control experiment suggests the developmental differences we observed may be due to children's greater use of memories to guide attention at short time-courses in

the absence of other competing sources of orienting. With respect to the third question, we did not find any evidence for an effect of memory-guided orienting on subsequent encoding. Together, these largely unexpected findings suggest that memories may be a particularly important influence on attention early in life, though their influence on future memory formation remains uncertain. Future experiments should a) further probe the development of memory-guided attention, with a focus on how its time-course may shift from childhood to adulthood, and b) continue to examine whether the spatial attention biases that emerge from experience interfere with or support subsequent recognition memory.

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# 1. Introduction

Over the past 15 years, researchers have revealed a robust influence of past experiences on shaping where people orient their attention (Chun, 2000; Chun & Jiang, 1998; Chun & Turk-Browne, 2007; Goldfarb, Chun, & Phelps, 2016; Patai, Doallo, & Nobre, 2012; Rosen, Stern, Michalka, Devaney, & Somers, 2016; Rosen, Stern, & Somers, 2014; Rosenbaum & Jiang, 2013; Salvato, Patai, & Nobre, 2016; Stokes, Atherton, Patai, & Nobre, 2012; Summerfield, Lepsien, Gitelman, Mesulam, & Nobre, 2006; Summerfield, Rao, Garside, & Nobre, 2011). Through these years of work, many of the behavioural effects and the underlying neural substrates of memory-guided attention have been illuminated. But relative to its ancestors — the largely separate but massive literatures on long-term memory and visual selective attention — the field of memory-guided attention is still quite young. Though both implicit learning (e.g. Chun & Jiang, 1998) and explicit scene-based memory traces (e.g. Summerfield et al., 2006) have been repeatedly shown to shape the anticipatory biases that underlie spatial attention, many important questions regarding the influence of past experiences in guiding adaptive behaviour remain unanswered. The aim of this thesis is to delineate and begin to answer some key questions that have emerged as the field of memory-guided attention enters its adolescence.

**Behavioural findings.** Contextual cuing experiments provided the first laboratory demonstrations of the effects of memories on visual attention. In these experiments, individuals search through visual arrays to find a particular target shape or letter (Chun, 2000). Unbeknownst to them, over the course of the task, some of these arrays begin to repeat. When these repeated arrays are interspersed with novel ones, participants are faster to identify targets among the repeated arrays, *despite* lacking awareness of the repetitions

and *without* forming explicit memories for the layout of the repeated arrays and their associated target locations (Chun & Jiang, 1998). The effects of contextual cuing are robust: they persist when the location of the target is cued by the layout of the distractors, when the identity of the target is cued by the identity of the co-occurring distractors, and even when the target's motion trajectory is cued by the trajectories of a dynamic array of distractors (Chun, 2000).

Beyond the implicit learning that guides contextual cuing, a separate body of literature has demonstrated that explicit spatial memories also influence attention orienting. In these tasks, participants learn to associate naturalistic scenes with specific spatial locations, either through repeatedly searching through the same scenes for objects hidden in a target location (Patai et al., 2012; Salvato et al., 2016; Stokes et al., 2012; Summerfield et al., 2006, 2011), or through identifying a subtle, localized change in the scene over several repetitions (Rosen, Stern, Michalka, Devaney, & Somers, 2015; Rosen et al., 2016, 2014). When people are cued by these scenes in a later task, they demonstrate enhanced detection sensitivity (Patai et al., 2012; Rosen et al., 2016, 2014) and faster reaction times (Salvato et al., 2016; Stokes et al., 2012; Summerfield et al., 2006, 2011) to targets appearing at the location associated with the scene relative to un-cued locations.

**Neural substrates.** Given that memory-guided orienting relies on encoding contextual information that then biases spatial attention, it is not surprising that the neural systems that have been shown separately to underlie these two processes are both recruited in memory-based orienting tasks. Specifically, prior work has revealed that the presentation of a familiar context or a scene with an associated memory triggers engagement of the hippocampus (Goldfarb et al., 2016; Stokes et al., 2012; Summerfield et al., 2006), which has been extensively linked to the formation and retrieval of

contextual memories (Bird, 2017; Davachi, 2006; Diana, Yonelinas, & Ranganath, 2007; Eichenbaum, Otto, & Cohen, 1992; Olsen, Moses, Riggs, & Ryan, 2012). Stokes et al. (2012) proposed that this hippocampal-based memory signal communicates with the fronto-parietal cortex, which in turn modulates preparatory activity in the visual cortex. These visual cortical modulations are reflected in increased BOLD activity and decreased alpha power contralateral to the location cued by the scene (Stokes et al., 2012).

**Developmental changes.** Despite the complex network of brain regions implicated in memory-guided attention, recent work has suggested that experiences may dynamically guide perception even in early childhood. Some research suggests that children as young as five years old begin to demonstrate effects of memory-guided attention (Dixon, Zelazo, & De Rosa, 2010), but other evidence is mixed (Vaidya, Huger, Howard, & Howard, 2007). Many factors, such as the number and nature of the distractors (Couperus, Hunt, Nelson, & Thomas, 2011), and the overall length of the task (Darby, Burling, & Yoshida, 2014), may contribute to whether children demonstrate contextual cueing effects.

Neurodevelopmental data further explain why children's use of memories to guide attention may not be as robust as that of adults'. Previous work has implicated the involvement and coordination of brain networks involved in memory recall and in attention orienting (Giesbrecht, Sy, & Guerin, 2013; Goldfarb et al., 2016; Rosen et al., 2016) in memory-based orienting tasks. The flexible engagement of these two networks has been shown to be mediated by the engagement of cognitive control mechanisms in the prefrontal cortex (Rosen et al., 2016) — mechanisms that continue to develop throughout the school-aged years (Johnson, Munro, & Bunge, 2014).

Furthermore, the circuits that support the formation of explicit, episodic memories also undergo changes during the school-aged years (Ghetti & Bunge, 2012). The hippocampus, which has been implicated in the formation and retrieval of novel memory associations (Davachi, 2006), continues to develop throughout adolescence (Ghetti & Bunge, 2012). Specifically, throughout childhood and adolescence, the anterior hippocampus shrinks while the posterior hippocampus grows (Gogtay et al., 2006; M. Johnson et al., 1996). Ghetti and Bunge (2012) proposed that these developmental differences in hippocampal structure may reflect increasing functional specialization of different hippocampal regions throughout middle childhood. Specifically, the development of the posterior hippocampus and parahippocampal gyrus may be particularly important for forming memories for contextual information (DeMaster & Ghetti, 2013; Golarai et al., 2007), like the scenes used in tasks involving memory-guided attention. Indeed, previous work has found that adults demonstrate more accurate contextual memory than school-aged children, and that neural correlates of these differences can be found in hippocampal regions (DeMaster & Ghetti, 2013; DeMaster, Pathman, & Ghetti, 2013).

**Open questions.** Despite extensive work delineating the neural and behavioural effects of memory on attention, several key questions relevant to how memory and attention operate together in real-world settings remain unanswered.

First, as we explore our cluttered world throughout childhood and adulthood, multiple sources of influence shape how we orient attention at each moment in time. Beyond orienting attention based on our experiences and memories, we frequently engage orienting mechanisms to shift our attention in response to salient external events (Posner, 1980; Posner & Peterson, 1990). Like memories, the sudden onset of salient visual events

also facilitates detection and identification of information subsequently presented in the same locations (Müller & Rabbitt, 1989). Despite extensive research examining these two sources of orienting, it remains unclear whether and how salient visual events and memories presented *concurrently* influence where children and adults orient their attention. In other words, when novel salient events occur in familiar contexts, how does each drive orienting? Additionally, given the protracted development of cognitive control (Johnson et al., 2014) and episodic memory circuits (Ghetti & Bunge, 2012) how does the relative influence of salient visual events and memories differ across children and adults?

Third, in addition to facilitating enhanced perception, spatial attention has been shown to promote encoding of information presented in cued locations, particularly when it involves the engagement of more top-down, fronto-parietal-based processes (Ballesteros, Reales, García, & Carrasco, 2006; Hauer & MacLeod, 2006; MacDonald & MacLeod, 1998; Markant, Worden, & Amso, 2015). Like orienting in response to other types of attentional cues, orienting in response to memories has been shown to enhance perception of stimuli presented in cued locations (Patai et al., 2012; Rosen et al., 2015; Stokes et al., 2012). However, it is unclear if the effects of memory-guided orienting extend beyond perception to enhance *encoding* of novel information. On the one hand, we would expect the enhanced activity of the visual cortex in response to memory cues to similarly benefit encoding. On the other hand, it is also possible that the reactivation of previous memories may proactively *interfere* with encoding of novel information (Bjork, 1978; Jonides & Nee, 2006).

**The present studies.** The studies included in this thesis begin to answer these three questions, examining both how memories interact with salient stimuli to influence

attention orienting in both children and adults (Chapters 1 - 4), and how memory-guided attention may influence encoding of novel information (Ch. 5).

To address these questions, we adapted a naturalistic, scene-based orienting task that has been previously used (Patai et al., 2012; Salvato et al., 2016; Stokes et al., 2012; Summerfield et al., 2006, 2011). All versions of this task we employed included: a) a learning phase, in which participants learned to associate individual scenes with specific target locations, b) a location memory test, in which participants' explicit memories for the locations associated with each scene were probed, and c) an orienting phase, in which participants saw the scenes again, and had to discriminate items presented in locations that were either cued or not cued by the associated memories.

# 2. The effects of concurrent memories and salient events on attention orienting in children and adults

*An edited version of this chapter is in revision at Child Development*: Nussenbaum, K., Scerif, G.* & Nobre, A.C.* (in revision). Salient visual events disrupt memory-guided attention in adults but not children.

Laboratory studies examining orienting responses to sudden visual events typically present those events on neutral or novel backgrounds (e.g. Posner, 1980). However, as we explore and learn from the world around us, we frequently encounter the same environments over and over again — children spend the majority of days in a year within a single classroom; adults pass countless hours within their homes or workplaces. In the real world, the transient visual events that have been shown to influence attention orienting in the lab are often present in environments with which we have previous experiences and associated memories. It may be the case that we use memories to orient attention only when no novel items appear in our environments. Alternatively, robust memories may cause us to ignore salient events that we would otherwise orient toward. Critically, the extent to which sudden visual events or memories orient our attention may change over time as the cognitive and neural systems supporting both memory encoding and spatial orienting develop. Understanding how novel visual events *that occur in familiar contexts* influence attention is key to understanding how memory and salience operate together in real-world settings.

**The effects of salient visual events on attention orienting over development**

Posner's spatial cueing paradigm (Posner, 1980) has been central to investigating the effects of salient visual events on the orienting of visuospatial attention. In one version of this paradigm, participants fixate centrally but are presented with a brief peripheral stimulus. After a short delay period, they must detect or discriminate a target presented in either the same, cued, location or a different, un-cued, location (Posner, 1980; Posner & Cohen, 1984). Beginning at about 4 months of age, infants look toward cued targets more often and with greater speed relative to targets presented at un-cued locations, demonstrating facilitated attention in response to external, salient events (Johnson, Posner, & Rothbart, 1991). The initial peripheral stimuli are said to trigger *exogenous* orienting, in that an external stimulus evokes a reflexive orienting response, such that subsequent stimuli presented at the cued location are briefly prioritized for sensory processing (Posner, 1980).

Exogenous orienting responses to peripheral events emerge during infancy and remain robust through childhood (Iarocci, Enns, Randolph, & Burack, 2009; Johnson, 1994; Schul, Townsend, & Stiles, 2003). Both infants and children demonstrate facilitated detection of targets that are presented at cued relative to un-cued locations (Akhtar & Enns, 1989; Enns & Brodeur, 1989; Iarocci et al., 2009; Pozuelos, Paz-Alonso, Castillo, Fuentes, & Rueda, 2014; Wainwright & Bryson, 2002). As they develop throughout early and middle childhood, children demonstrate a general increase in the speed of their attentional responses (Iarocci et al., 2009; Schul et al., 2003) and an enhanced ability to reorient to new locations (Schul et al., 2003). Despite these changes in orienting behavior, children continue to demonstrate robust exogenous cuing effects as they develop (Schul et al., 2003).

**The effects of memories on attention orienting: Developmental hypotheses**

As is the case for the mechanisms underlying exogenous cuing effects by transient visual events, those that enable memories to guide attention may also emerge as early as infancy. Infants between the ages of 8 and 12 months were able to learn to associate specific contexts with the location of a hidden target (Bertels, San Anton, Gebuis, & Destrebecqz, 2016). By adulthood, these associations enable individuals to deploy their attention more efficiently in familiar compared to unfamiliar contexts, as observed in contextual cueing paradigms (Chun & Jiang, 1998). As discussed in the introduction, however, unlike the robust and replicable effects of salient visual events on orienting (e.g., Schul et al., 2003), memory-guided benefits from contextual cueing are more heavily debated (Barnes et al., 2008; Barnes, Howard, Howard, Kenealy, & Vaidya, 2010; Couperus et al., 2011; Dixon et al., 2010; Merrill, Conners, Roskos, Klinger, & Klinger, 2013).

Additionally, and perhaps more substantially, unlike the naturalistic scene experiments described previously (e.g. Summerfield et al., 2006), contextual cuing experiments do not segregate participants' learning of target locations and their orienting toward remembered locations into two distinct tasks. Thus, any differences between children and adults that are observed in these studies could be due *either* to differences in participants' ability to implicitly learn the target locations, *or* their ability to use what they have learned to guide their attention. Though contextual cuing tasks cannot isolate the locus of potential differences in memory-guided attention between children and adults, findings from contextual cuing suggest that children *can* use memories to guide attention, but mixed results also highlight how their ability to do so may be particularly susceptible to interference, emerging only under optimal task conditions. The relative immaturity of children's cognitive control abilities this age group (Johnson et al., 2014) further suggests

that the interactions between memory systems and orienting systems necessary to enable past experiences to guide attention (Rosen et al., 2016) may be more prone to disruption in children.

**The current study**

We designed an experiment to address two main questions: first, though the bodies of literature examining the effects of salient visual events and memory on attention orienting have remained largely separate, people frequently encounter salient visual stimuli within familiar environments. When salient visual events occur in known environments, do children and adults shift their attention more in response to what they have learned from previous experiences, or in response to salient visual events? In other words, do memory-guided and exogenously driven orienting interact, or act in parallel? Second, younger and older observers might differ in what guides their attention: does the relative strength of each source of orienting differ in childhood, as memory, attention orienting, and cognitive control mechanisms continue to mature?

To address these questions, we adapted the naturalistic scene task used in previous studies of memory-guided attention (e.g. Summerfield et al., 2006). Unlike contextual cueing tasks, this design enabled us to tease apart age-related differences in memory formation from differences in the use of memories to orient attention.

We hypothesized that children and adults would show comparable learning and memory of the locations of the target stars, given past findings on the development of episodic encoding of spatial locations (Schumann-Hengsteler, 1992). Though we expected both age groups to demonstrate evidence of both memory-guided and exogenously cued attention, we expected that in the presence of salient visual events, given their more mature cognitive control networks (Johnson et al., 2014), adults would

weight past experiences more heavily than children in shaping their attentional deployment.

## EXPERIMENT 1

## Methods

**Participants.** This study was approved by the University of Oxford Central University Research Ethics Committee (CUREC). Thirty adults (Mean age = 23.2 years, STD = 3.3 years; Range: 18.7 – 31.5 years; 24 females) and 27 children (Mean age = 9.2 years, STD = 1.5 years; Range: 7.0 – 12.9 years; 10 females), with normal or corrected-to-normal vision and no known history of psychiatric or learning disorders, participated in the study. An additional child was tested but excluded from analyses due to failure to complete all of the tasks.

Adult participants were recruited from the University of Oxford's undergraduate subject pool and from the surrounding community. They gave informed consent prior to participation in the study and were compensated at a rate of either £8 per hour or with research participation credit. Children were recruited via email advertisements sent to local schools. They gave informed assent and their parents gave informed consent prior to their participation, and they received a certificate at the end of the testing session.

**Stimuli.** Stimuli for the task comprised 154 photographs of indoor and outdoor natural scenes acquired from Google images (1920 x 1080 pixels). Eighty-eight of these scenes were used during the learning phase, memory phase, and first orienting phase of the task. Sixty-six of these scenes were only used during the second orienting phase of the task. The learning target was a small gold star prepared in Adobe Photoshop (15 x 15 pixels for adults; 25 x 25 pixels for children). The orienting targets included a small grey

square (50 x 50 pixels) and a small grey circle (with a 50-pixel diameter) prepared in Adobe Photoshop. The exogenous cue at orienting comprised a 200 x 200-pixel square, red outline.

**Procedure.** ***Learning phase.*** Adult participants sat 100 cm away from a 60 x 34-cm computer monitor. They were directed to search through each scene to find a small gold star over the course of three blocks. Additionally, they were instructed to memorize the location of the stars that they found. For each trial, participants saw a new scene with an embedded target. The order of the scenes was randomized within each block. Participants were instructed to click once when they saw the target star. After they clicked, a cursor would appear, and participants were instructed to move the cursor to click on the star. Participants had 60 seconds to look through each scene, and five seconds to move the mouse to click on the star. If participants successfully clicked within 50 pixels of the star, they then saw a feedback screen that said "Target Found" for 500 ms. If the scene timed out or if participants clicked on an incorrect location, they saw a feedback screen that said "Target Not Found" for 500 ms. Participants were given short breaks every 22 scenes. At the end of each block, participants saw a screen that told them how many targets they found, and they had another opportunity to take a break.

Children completed the same task, except that it was framed as a game featuring the Nintendo character Mario. Additionally, to cut down the length of the experiment, the stars were made easier to locate by increasing their size slightly (from 15 x 15 pixels to 25 x 25 pixels). Children were told that Mario had lost his stars, and needed help finding and collecting them. When children located the star and clicked the mouse, a small image of Mario served as the cursor. Children could move Mario to collect the star by moving the mouse and clicking. Prior to beginning the task, children completed one trial in which they practiced this entire procedure.

***Location-memory test.*** After a short break (3 – 5 minutes), participants were tested on their explicit memory for the target locations. Participants once again viewed the 88 scenes from the learning phase in a random order, but this time the target stars were absent from the scene. Participants were instructed to click when they remembered where the star was, and then to move the cursor to the remembered location and click again. Participants had 30 seconds to initiate the first mouse click, and an additional 10 seconds to move the cursor.

Children completed the same test of explicit memory, except they were told that they were responsible for informing Mario's friend, Luigi, of the star locations. When children clicked the mouse, Luigi appeared, and they had to move him over to the location of the star and click again. Children completed one practice trial prior to beginning the real task.

***Orienting.*** *Memory and visual event interactions.* After the location memory test, participants completed the first block of the orienting task. Throughout the task, participants were told to respond to a small, grey target that appeared on every trial using a standard keyboard. Participants were instructed to press the up arrow if they saw a grey square and the down arrow if they saw a grey circle. Square and circle stickers were taped over the appropriate keys.

For the first 100 ms of every trial, participants viewed a scene with an associated memory from the learning phase. Then, a transient, visual event, which comprised a red box appeared within the scene (50-ms duration). After the visual event disappeared, the scene remained on the screen for another 100 ms, after which the grey target appeared briefly within the scene (200 ms duration). The scene then remained on the screen for an

additional 1300 ms. Participants could respond to the target any time between its onset and the end of this 1300 ms window (Figure 1).

In summary, then, memory cue (scene) onset preceded target onset by 250 ms, while the visual events preceded target onset by 150 ms. These timings were chosen based on previous experiments in order to optimize effects of both cue types. Previous work using a similar paradigm found that memory cues presented for 100 or 500 ms prior to target onset elicited comparably sized validity effects (Summerfield et al., 2006). For peripheral, visual events, the 150 ms cue-to-target interval has previously resulted in attention orienting benefits at cued vs un-cued locations for both adults (Eimer, 2000) and children (Brodeur & Enns, 1997).

In the first orienting block, as described in Table 1A, targets appeared at memory-cued locations on half of trials (44), meaning the target appeared exactly where the star was hidden in the scene during the learning phase. Targets appeared at locations cued by the visual events on half of trials (44). Cues were orthogonalized such that on one quarter of trials (22), the target appeared in a location: cued by both the memory and the visual event (*MV*), cued by the memory only (*M*), cued by the visual event only (*V*), or in a fully un-cued location (*U*). Un-cued locations were randomly selected locations on the opposite hemifield from the visual or memory cues. For example, on memory-cue-only trials (*M*), if the memory was associated with a location on the left side of the screen, the visual event would occur at a random location on the right side of the screen, and the target would then appear at the memory-cued location on the left. On visual-cue-only trials (*V*), if the visual event occurred on the right side of the screen, the memory would be associated with a location on the left side of the screen, and the target would appear where the visual event occurred on the right. On fully un-cued trials, the visual event always occurred in the same location as the memory association, such that if the memory association was on the left,

the visual event would occur in that same location on the left, and the target would then appear in a random location on the right half of the screen. All trial types were intermixed, and the order of the trial was randomized for each participant. Participants had the chance to take short breaks every 22 trials.

Participants were explicitly told that both the memory and the visual event would sometimes, but not always, indicate the target location. They were also instructed to keep their eyes fixated on the central cross that appeared on top of all orienting stimuli. Participants were told to respond to the target stimuli as quickly and as accurately as possible. Before beginning the real trials, adult participants completed 10 trials to practice the button-press responses in which they saw the grey targets appear on top of a black screen.

Children completed the same task, but they were told that the grey squares and circles were stones that Mario needed to build his castle. After every set of 22 trials, they were shown a picture of a castle in various stages of completion, until the end, in which they saw the whole castle. Additionally, children completed 20 practice trials before beginning the task.

*Visual-events-only block.* The second orienting block was identical to the first except that all scenes used were novel, and thus contained no information about the location of the target. This block therefore served the purpose of establishing whether there were any age-related differences in visual event cueing effects, when cues and targets were embedded in novel natural scenes.

Adult participants completed 66 trials. One third of trials (22) were neutral (*VN*) such that no visual event was included prior to target onset. The target appeared on the scene after a 250 ms delay. The remaining two thirds of trials (44) included the same

visual event as the first orienting block (the red box outline). On half of these trials (22), the target appeared in a location cued by the visual event, and on half of these trials (22), the target appeared in an un-cued location on the opposite side of the screen. We will refer to these as visual-only cued (*VC*) and visual-only uncued (*VU*) trials. As in the first orienting block, participants were given short breaks every 22 trials.

Children completed the same task, but were told they were building a castle for Mario's friends Toad and Toadette. After each set of 22 trials, participants were shown a picture of a different castle in various stages of completion, until the end, when they once again saw the whole castle.

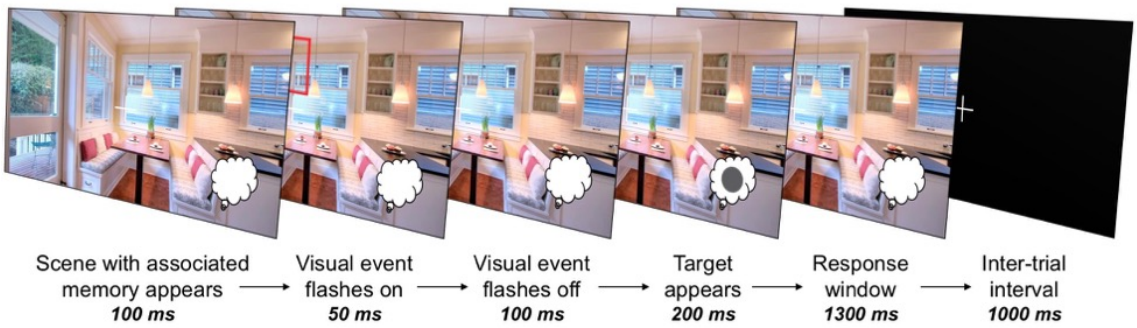



**Figure 1.** Orienting task: memories and visual events. In the first orienting block, participants saw a scene with an associated memory for 100 ms. Then, a red square appeared for 50 ms. After a brief delay (100 ms), a target square or circle appeared, which participants were instructed to discriminate. The cloud in the figure represents participants' memory associations; no cloud image was visible during the task.

**Counterbalancing.** Presentation of the scenes was counterbalanced across participants, such that they appeared with equal chance in the four orienting conditions in the first orienting block (*MV, M, V, U*), and the three orienting conditions in the second orienting block (*VN*, *VC*, *VU*) (Table 1). The location of the learning target was counterbalanced across both participants and scenes, such that each participant saw half

of the learning targets (44) on the right and half (44) on the left, and for each scene the target appeared on the right for half of the participants and the left for half of participants. Within each half of the screen, the specific location of the learning target was randomized. The location of the orienting target and the identity of the orienting target was randomized for each scene but counterbalanced within conditions for each participant.

Table 1:

*Task counterbalancing for first (A) and second (B) orienting blocks*

A.

| *Learning:* Target location | 44 Left (L) | | | | 44 Right (R) | | | |
|---|---|---|---|---|---|---|---|---|
| *Orienting:* Memory association | 44 L | | | | 44 R | | | |
| *Orienting:* Visual event | 22 L | | 22 R | | 22 L | | 22 R | |
| *Orienting:* Target location | 11 L | 11 R | 11 L | 11 R | 11 L | 11 R | 11 L | 11 R |
| Target cued by memory? | Yes | No | Yes | No | No | Yes | No | Yes |
| Target cued by visual event? | Yes | No | No | Yes | Yes | No | No | Yes |
| Condition | *MV* | *U* | *M* | *V* | *V* | *M* | *U* | *MV* |

B.

| *Learning:* Target location | No learning phase | | | | | |
|---|---|---|---|---|---|---|
| *Orienting:* Memory association | None | | | | | |
| *Orienting:* Visual event | None | | Left (L) | | Right (R) | |
| *Orienting:* Target location | 11 L | 11 R | 11 L | 11 R | 11 L | 11 R |
| Target cued by visual event? | No | No | Yes | No | No | Yes |
| Condition | *VN* | *VN* | *VC* | *VU* | *VU* | *VC* |

**Variables of interest.** ***Learning Phase.*** Three variables were extracted as measures of participants' learning of the target locations across the three blocks: missed-targets z-scores, search-time z-scores, and search-time slope. Missed targets were simply the number of targets participants failed to find in each learning block. Search time was calculated as the time from scene onset to first mouse click. Only trials in which the target was found across all three blocks were included in the search-time analysis (*Mean number included*: 75.2 trials; *Range:* 53 - 85 trials). Because children and adults viewed learning targets of slightly different sizes, rather than using raw scores, we z-scored these variables to index the extent to which each participant improved relative to their own baseline throughout the learning phase. To index roughly how performance improved over the course of the three blocks, we also computed slope values for search times for each participant. To compute the search-time slope, we subtracted participants' average search time in the first block from their average search time in the third block and divided the resulting value by their search time across all three blocks.

***Location-memory test.*** Two measures were extracted to determine participants' explicit memories for the target locations: memory precision and memory accuracy.

Memory imprecision was calculated as the distance in pixels between where the participant clicked during the memory test and the true center of the target location during the learning phase. Trials in which participants failed to find the target at least once during the learning phase were excluded from the analysis (*Mean number included*: 84.8 trials; *Range:* 78 - 88 trials).

Trials were considered "accurate" if participants clicked within an imaginary 200 x 200-pixel box centered on top of the target location. With this criterion, participants had a 3.9% chance of accurately selecting the target location by guessing. Using the binomial distribution, we confirmed that even the participant who performed the poorest on the memory test (8 out of 77 correct responses), still performed above chance level, $p = .01$. This indicated that all participants understood the task and complied with the instructions. Given that past work has revealed that memory-guided attention orienting may be influenced by the strength of explicit memories *but also* by implicit learning (Salvato et al., 2016), we did not exclude any trials from subsequent analyses on the basis of participants' memory test performance.

***Orienting.*** The first and second orienting blocks were analyzed separately. For the first block, only trials in which the target was found at least once during the learning phase were included (*Mean number included*: 84.8 trials; *Range:* 78 - 88 trials). Three measures were extracted to determine the effects of cueing condition on attention orienting: accuracy, accuracy with missed trials excluded, and reaction time. Trials were considered accurate if participants made a correct response within the 1500 ms response window. Trials were considered inaccurate if participants failed to respond during the 1500 ms window or if they pressed the wrong button. To calculate accuracy with missed trials excluded, we ignored all trials in which participants failed to respond. Even when missed trials were excluded, the performance of three children was still statistically

indistinguishable from chance level (Chance level: 50%). Thus, they may not have tried to perform the task correctly and instead pressed random buttons. As such, these participants were excluded from the orienting analyses.

Reaction time was calculated as the time from target onset to button-press response. Only accurate trials were included (Block 1 (88 trials) *Mean number included*: 64.4 trials; *Range:* 45 – 78 trials; Block 2 (66 trials): *Mean number included*: 52.5 trials; *Range:* 37 – 62 trials).

## Results

**Successful learning of target locations.** Converging evidence from our targets-missed and search-time analyses suggest that both children and adults learned the location of the targets across search blocks.

A repeated-measures ANOVA examining targets missed z-scores with learning block as a within-subjects factor and age group as a between-subjects factor revealed that both children and adults found increasing numbers of targets as the task proceeded, $F(2, 110) = 50.9$, $p < .001$, $\eta^2 = .481$. (Figure 2A). There was no learning block x age group interaction, $F(2, 110) = .86$, $p = .201$, $\eta^2 = .029$, indicating that children and adults demonstrated comparable improvement in finding targets across blocks.

Additionally, a repeated-measures ANOVA (with Greenhouse-Geisser correction, applied as necessary in subsequent analyses) examining the effects of learning block and age group on search-time z-scores revealed that both children and adults demonstrated faster search times across learning blocks, $F(1.1, 62.4) = 804.5$, $p < .001$, $\eta^2 = .936$ (Figure

2B). As before, there was no learning block x age group interaction, $F(1.1, 62.4) = 2.1$, $p = .15$, $\eta^2 = .036$.

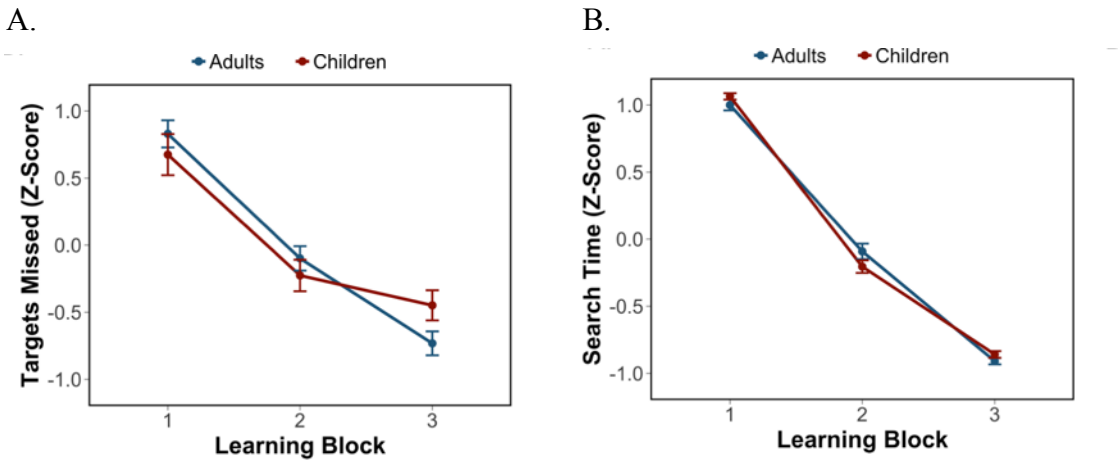



**Figure 2**. Adults and children both found increasing numbers of targets over the course of the three learning blocks (A) with increasing speed (B).

**Explicit memories for target locations.** We next analyzed whether children and adults form explicit memories for the target locations to a similar extent. One-sample t-tests examining memory accuracy revealed that accuracy for both groups was significantly above chance; Adults: $t(29) = 20.8$, $p < .001$; Children: $t(26) = 14.4$, $p < .001$.

There was not a statistically significant difference in memory accuracy between adults ($M = .67$, $SD = .17$) and children ($M = .58$, $SD = .20$), $t(55) = 1.8$, $p = .07$. However, independent-samples t-tests indicated that adults had more precise memories for the target locations ($M = 145.1$ pixels, $SD = 79.1$ pixels) than children ($M = 203.5$ pixels, $SD = 126.9$ pixels), $t(55) = 2.1$, $p = .039$ (Figure 3). Thus while both groups formed memories for the target locations, on average, adults responded with a higher degree of precision on the explicit memory test.

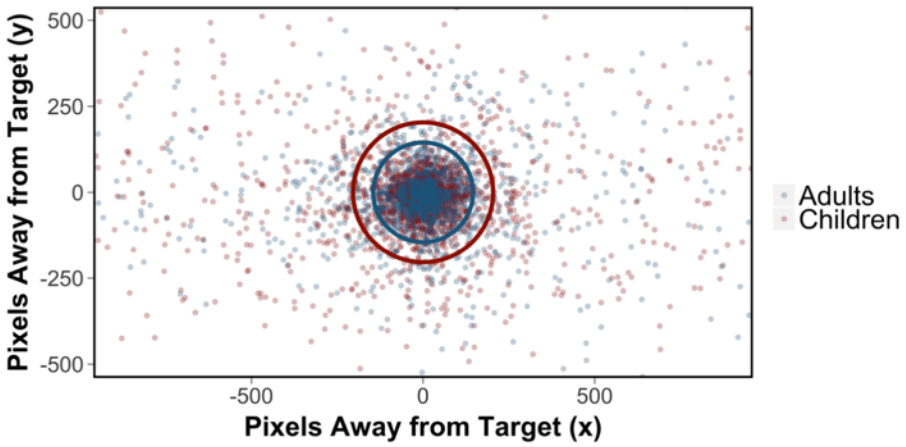



**Figure 3**. Adults responded with greater precision on the explicit test of recognition memory for target locations. The dots in the figure represent individual responses on the explicit memory test, with all target locations centered at (0,0) on the graph. The solid circles indicate the average distance between the actual target location and the memory response for adults and children.

Additionally, we examined whether participants' search-times slopes — a measure of their ability to learn the location of the targets throughout the learning phase — correlated with their memory imprecision on the explicit location memory test. For both adults and children, there were significant correlations between participants' search-time slopes and memory imprecision; *Adults:* $r(30) = -.60$, $p < .001$, *Children:* $r(27) = -.48$, $p = .012$. This analysis indicates that participants who showed evidence of the steepest learning curves during the first part of the experiment also demonstrated the greatest memory precision (higher values indicate higher *im*precision while lower values indicate greater precision) in the second part. These data suggest that the decreasing search speeds we observed across learning blocks at least partially index learning of the target locations, and not just improvement in performing the search task with practice.

**Effects of visual events on attention orienting.** We next wanted to ensure that our visual events were salient enough to engage exogenous attention-orienting

mechanisms when they appeared on top of our scene stimuli. To address this question, we analyzed the data from our second orienting block, in which a salient, visual event occurred soon after a novel scene was presented.

To account for subject-level differences in orienting effects, we analyzed participants' orienting accuracy and reaction times with multilevel models using the lme4 package in R (Bates, Mächler, Bolker, & Walker, 2015; R Core Team, 2014). This approach enabled us to include all trials for each participant, rather than just the means of aggregated data (Baayen, Davidson, & Bates, 2008; Jaeger, 2008; Judd, Westfall, & Kenny, 2012). To determine the random-effects structure for our models that would both minimize Type I error and maximize power, we followed the "forward-stepping-best-path" approach recommended in Barr et al. 2013 (Barr, Levy, Scheepers, & Tily, 2013). Using this approach, we began with a baseline model that included our fixed effects of interest and random intercepts for subject and scene. Since we did not want to assume that the effects of our orienting manipulations would be identical across subjects and stimuli, we iteratively added each random slope to the model, only keeping in those that significantly improved model fit, as indexed by AIC values. If adding a random slope significantly improved model fit, we updated our baseline model to include that slope and repeated the process. We did not consider models that failed to converge.

To determine how visual events influenced orienting accuracy across age groups we constructed a logistic mixed-effects model. Our final model included our fixed effects of interest (visual event condition with three levels: neutral (*VN*), cued (*VC*), un-cued (*VU*); and age group with two levels: adults, children), and random intercepts for subject and scene. A likelihood ratio test implemented through the Analysis of Factorial Experiments (afex) package for R (Singmann, Bolker, & Westfall, 2015) indicated that including the visual event condition significantly improved model fit, $\chi^2 = 96.3$, $p <$

.0001. To determine whether these accuracy effects were driven by a performance advantage in the cued (*VC*) condition vs. a performance impairment in the un-cued (*VU*) condition, we used the Simultaneous Inference in General Parametric Models (multcomp) package for R (Torsten Hothorn, Bretz, & Westfall, 2008) to conduct paired comparisons of accuracy across the cue conditions using Tukey contrasts. Results indicated that participants were more accurate in the cued and neutral conditions relative to the un-cued condition, *ps* <.0001. There was not a statistically significant difference in accuracy between the cued and neutral conditions, $p = .533$.

Additionally, including age group also improved model fit, $\chi^2 = 13.5$, $p = .0002$. Across conditions, children performed less accurately than adults (Table 2). There was no effect of including the visual event condition x age group interaction term in the model, $\chi^2 = 1.0$, $p = .60$, meaning that we observed no evidence that children and adults demonstrated different patterns of attentional costs on un-cued trials.

We followed the same process to analyze our reaction-time data, but we tested the significance of our effects using F tests with Kenward-Roger approximations for degrees of freedom. Similarly to our accuracy data, we observed a main effect of visual event condition on orienting reaction times, $F(2, 2607.4) = 24.1$, $p < .0001$. Tukey contrasts revealed that participants performed more slowly on un-cued (*VU*) trials relative to both cued (*VC*) trials ($p$ <.001) and neutral (*VN*) trials ($p < .001$) (Figure 4). There was not a statistically significant difference in reaction times across cued and neutral trials, $p = .096$. As with our accuracy analysis, there was also a main effect of age group on reaction times, $F(2, 56.8) = 50.13$, $p < .0001$, with children demonstrating overall slower reaction times than adults (Table 2). The cue condition x age group interaction effect was not significant, $F(2, 2586.0) = .52$, $p = .59$. These results indicate that both children and adults showed a

comparable effect of visual events on orienting performance, with the onset of a visual event impairing performance when it did not cue the target location.

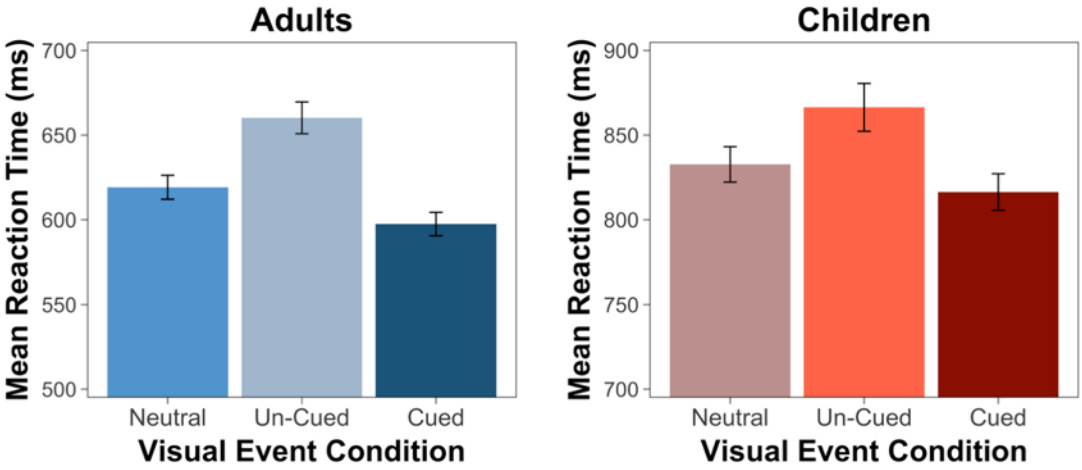



**Figure 4.** Adults and children both demonstrated the fastest orienting reaction times in response to cued targets and the slowest reaction times in response to un-cued targets, Error bars indicate standard errors.

Table 2

*Means (and standard deviations) of accuracy and reaction times as a function of age group and visual event condition for the visual-cue-only orienting block*

| Age Group | Visual Event | Accuracy | Reaction Time (ms) |
|---|---|---|---|
| Adults | Neutral | .86 (.35) | 619.2 (168.6) |
| | Cued | .88 (.33) | 597.5 (166.7) |
| | Un-Cued | .76 (.43) | 660.3 (210.2) |
| Children | Neutral | .78 (.42) | 832.7 (202.8) |
| | Cued | .83 (.38) | 816.4 (215.7) |
| | Un-Cued | .63 (.48) | 866.5 (246.4) |

**Interactions between memory cues and visual events on attention orienting.** Finally, after verifying that children and adults a) learned to associate target locations with specific scenes, and b) demonstrated differences in orienting accuracy and reaction time depending on whether the visual event cued the target location, we examined our results

from the first orienting block to address our main question of interest: how memories and visual events *interact* to influence attention orienting.

As before, we constructed two mixed-effects models: a logistic model to examine orienting accuracy and a linear model to examine orienting reaction times. Both models included memory condition (cued, un-cued), visual-event condition (cued, un-cued) and age group (children, adults) as fixed effects, and subject and scene as random intercepts. Very few models that included slopes converged successfully; those that converged did not fit the data significantly better than the models with random intercepts only.

As indicated in Table 3, the only reliable predictors of orienting accuracy were visual-event condition and age. Visual events that cued the target location led to increased accuracy, and adults performed better than children (Table 5). These results indicated that our visual events effectively facilitated attention toward the cued location. We observed no effects of memory condition on orienting accuracy, nor a memory condition x age group interaction.

Table 3

*Orienting accuracy mixed effects model: coefficients and $\chi^2$ values*

| **Effect** | **Coefficient (std. error)** | $\chi^2$ | ***p*** |
|---|---|---|---|
| Intercept | .97 (.13) | | |
| Visual- Event Condition*** | 1.01 (.15) | 216.4 | <.0001 |
| Memory Condition | .11 (.13) | 2.83 | .09 |
| Age Group** | - .56 (.18) | 0.33 | .001 |
| Visual-Event x Memory Condition | .05 (.22) | 0.01 | .91 |
| Visual-Event Condition x Age Group | .15 (.21) | 0.53 | .47 |
| Memory Condition x Age Group | .03 (.19) | 0.00 | .95 |
| Visual-Event Condition x Memory Condition x Age Group | -.07 (.30) | 0.05 | .82 |
| ** $p < .01$, *** $p < .001$ | | | |

As with our accuracy model, our reaction-time model indicated that the visual-event condition was a reliable predictor of orienting reaction times (Table 4), with participants responding more quickly on trials in which the visual event cued the target location (Table 5). Additionally, we observed a significant effect of memory condition on participant reaction times, which was qualified by a significant memory cue validity x age group interaction effect.

Table 4

*Orienting reaction time mixed-effects model: F test with Kenward-Rogers approximations for degrees of freedom*

| **Effect** | ***df*** | ***F*** | ***p*** |
|---|---|---|---|
| Visual-Event Condition*** | 3352.9 | 4.0 | <.0001 |
| Memory Condition* | 3363.5 | .74 | .05 |
| Age Group*** | 52.09 | 8.7 | <.0001 |
| Visual-Event Condition x Memory Condition | 3367.9 | .36 | .55 |
| Visual-Event Condition x Age Group | 3334.9 | .16 | .14 |
| Memory Condition x Age Group** | 3339.1 | .91 | .009 |
| Visual-Event Condition x Memory Condition x Age Group | 3322.8 | .24 | .63 |
| * $p < .05$, ** $p < .01$, *** $p < .001$ | | | |

Table 5

*Means (and standard deviations) of accuracy and reaction times as a function of age group, visual-event condition, and memory condition*

| Age Group | Visual-Event Condition | Memory Condition | Accuracy | Reaction Time (ms) |
|---|---|---|---|---|
| Adults | Cued | Cued | .88 (.32) | 704.9 (210.6) |
| | | Un-Cued | .86 (.34) | 690.2 (200.0) |
| | Un-Cued | Cued | .73 (.44) | 727.6 (233.8) |
| | | Un-Cued | .71 (.45) | 731.2 (226.8) |
| Children | Cued | Cued | .82 (.38) | 872.5 (211.2) |
| | | Un-Cued | .81 (.39) | 898.0 (214.7) |
| | Un-Cued | Cued | .62 (.48) | 932.7 (230.2) |
| | | Un-Cued | .60 (.49) | 962.3 (254.7) |

We further investigated this interaction with separate mixed-effects models for each age group. Including memory-cue condition had a significant effect on model fit only for our child model, in which memories that cued the target location facilitated faster orienting reaction times, $F(1, 1409.4) = 7.3$, $p = .007$. Adults did not demonstrate any effects of memory cue condition on orienting reaction times, $F(1, 1891.6) = .30$, $p = .58$ (Figure 5). These analyses indicate that when visual events occurred within familiar contexts, children's attention orienting was influenced by *both* sources, whereas adults were only influenced by the visual events. These differences emerged *despite* adults demonstrating greater precision in their memories for target locations.

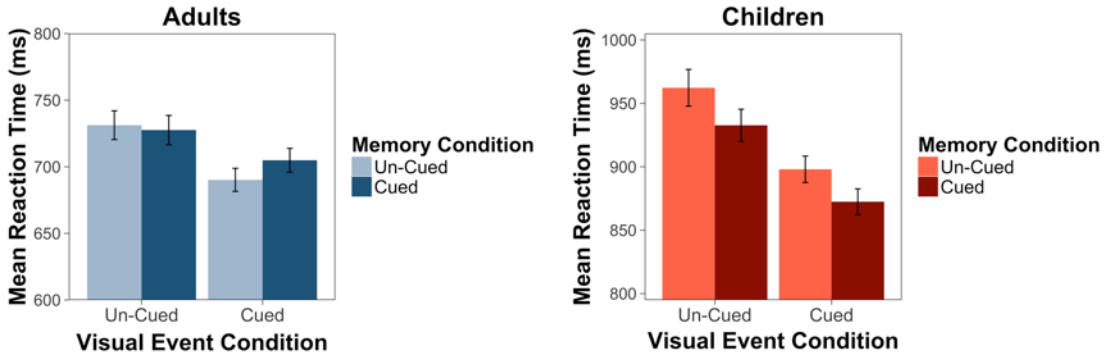



**Figure 5.** Adults and children both demonstrated faster reaction times when the visual event cued the target location. However only children demonstrated similar cuing effects in response to memories, demonstrating faster reaction times when the memory cued the target location. Error bars indicate standard errors.

To examine further the effects of memory on orienting reaction times, we re-ran our model, but replaced the categorical predictor memory condition with a continuous measure of memory distance (Table 6).[1] This variable was computed for each trial by calculating the distance between where the participant indicated they remembered the target being located during the location memory test and where the target actually appeared during orienting. Thus it accounts for trial-by-trial differences in memory imprecision as well as the random placement of the un-cued targets (i.e., un-cued could appear anywhere on the opposite side of the screen, so sometimes by chance they appeared closer to the learned target location).

[1] We additionally tried to re-run our accuracy model with memory distance instead of memory condition, but the more-complex logistic model would not converge, even when we removed random intercepts.

Table 6

*Orienting reaction time mixed-effects model with memory distance: F and p values*

| **Effect** | ***df*** | ***F*** | ***p*** |
|---|---|---|---|
| Visual-Event Condition*** | 3396.3 | 7.6 | <.0001 |
| Memory Distance** | 3406.4 | 9.5 | .002 |
| Age Group*** | 58.8 | 28.9 | <.0001 |
| Visual-Event Condition x Memory Distance | 3406.0 | 3.2 | .07 |
| Visual-Event Condition x Age Group | 3336.0 | .17 | .70 |
| Memory Distance x Age Group** | 3367.7 | 7.2 | .007 |
| Visual-Event Condition x Memory Distance x Age Group | 3344.7 | .56 | .43 |
| * $p < .05$, ** $p < .01$, *** $p < .001$ | | | |

As Table 6 indicates, changing the memory predictor from a categorical variable (cued vs. un-cued) to a more sensitive, continuous measure of memory distance yielded similar results. As with our previous analysis with memory condition, here we also observed a main effect of memory distance on orienting reaction times, as well as a memory distance x age group interaction. To interpret this interaction, we ran separate linear mixed-effects models for each age group independently. These models revealed that memory distance influenced children's orienting reaction times, $F(1, 1457.0) = 12.0$, $p = .0005$, but not adults', $F(1, 1929.8) = .16$, $p = .69$ (Figure 6). In other words, when the novel orienting target appeared close to where participants remembered a target being located during the learning phase, children, but not adults, responded to it more quickly.

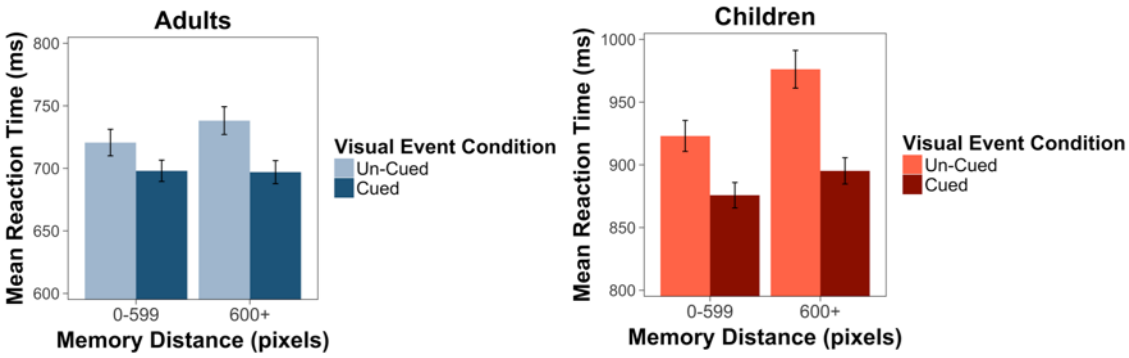



**Figure 6.** Adults' reaction times did not significantly differ as a function of the distance between the location memory associated with the scene and the location of the target at orienting. Children were faster to orient to targets that appeared closer to the remembered location. Error bars indicate standard error.

## Experiment 1 Discussion

The results of Experiment 1 demonstrated that though both children and adults were able to learn to associate specific target locations with scenes, only children used these memories to orient their attention when novel visual events also occurred. These data stand in stark contrast to our initial hypothesis that adults would demonstrate stronger effects of memory on attention, particularly in the presence of potential interference, due to their greater ability to flexibly shift between memory recall and attention orienting (Rosen et al., 2016).

Given that many past studies using similar paradigms have found that adults do demonstrate memory-guided attention orienting (Patai et al., 2012; Salvato et al., 2016; Stokes et al., 2012; Summerfield et al., 2006), our results suggest that the salient, visual events *disrupted* or *overwrote* the effects of memory-guided attention in adults but not in children. Interestingly however, the results from our visual-cues-only orienting block indicated that adults and children demonstrated statistically equivalent costs on un-cued trials across both accuracy and reaction time measures. Thus the differences that we

observed in the interaction between memory-guided and visually cued attention across adults and children cannot be attributed to differences in their sensitivity to the visual cues on their own.

There are several possible explanations for why children used memories to orient their attention in the face of competing visual cues but adults did not. First, it is possible that the design specifications of our paradigm were not sensitive enough to elicit or reveal memory-guided attention in adults. Though we based our experimental design on published studies that have shown significant effects of memory cues on attention orienting in adults, several parameters of our task differed from those previously published, including the nature of the target discrimination task. Previously published studies have relied primarily on target detection tasks (e.g. Patai et al., 2012; Stokes et al., 2012; Summerfield et al., 2006). Rather than requiring participants to press separate buttons for different target shapes, many of these tasks require participants to discriminate if a target is present at all, or withhold a response on "catch trials," in which no target is presented, which relies on inhibiting a behavioral response — an ability that continues to develop throughout childhood and adolescence (Best & Miller, 2010). To minimize potential confounds in comparing response distributions across age groups, we used a discrimination rather than a detection task. Though the effects of attention orienting are generally *larger* for discrimination vs. detection tasks, subtle differences in orienting task design can dramatically influence cuing effects (Chica, Martín-Arévalo, Botta, & Lupiáñez, 2014). In order to attribute adults' failure to use memories to orient their attention to the disruptive presence of the visual events, it is important to verify that our task was sensitive enough to elicit memory-guided attention in adults in their absence.

Additionally, it is also possible that adults may have strategically chosen to ignore the memory cues. In our task, memories and visual events each correctly indicated the

target location on half of trials. Since there were more than two possible locations at which the target could appear, paying attention to the cues is an adaptive strategy. However, past work has found that when individuals divide their attention over multiple cued locations, they show smaller facilitated responses at the location of each cue (Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1991; Müller, Malinowski, Gruber, & Hillyard, 2003). Thus, in our task, if individuals divided their attention equally across both the locations associated with the memories and visual events, we would expect them to demonstrate a benefit when both sources cued the target location (1/4 of trials) and a smaller benefit when only one cued the target location (1/2 of trials). However, if individuals chose to ignore the memories completely, we would expect them to demonstrate a large benefit when the visual event cued the target location, regardless of the nature of the memory (1/2 of trials). Adults may have decided that this latter approach would result in equivalent task performance without the need to expend effort on memory recall. Additionally, past work suggests that adults are better than children at strategically modifying their responses to visual events depending on their predictive validity (D. A. Brodeur & Boden, 2000; Enns & Brodeur, 1989; Iarocci et al., 2009); it is possible that the control mechanisms that enable this modulation of *exogenous* orienting responses also enable adults to strategically shift their responses to *memories* to a greater extent than children.

To probe these two possibilities, we conducted a second experiment in adults. In this second experiment, we sought to: a) ensure that the presence of visual events was the reason that we failed to observe memory-guided attention in adults, and b) determine if the presence of visual events prompted adults to strategically ignore the memory cues during orienting. To test these two possibilities, we included orienting trials in which only scenes with associated memories appeared, as well as orienting trials in which the visual events *never* indicated the location of the subsequent target and which we explicitly

instructed participants to ignore. If the presence of visual events disrupted memory-guided attention in adults, we expected that we would see effects of memories on attention orienting when visual events were not present. If the visual events disrupted memory-guided orienting by strategically prompting adults to ignore the memories in favor of the visual events, we expected to mitigate this disruption by replacing the visual cues with non-predictive visual distractors.

## EXPERIMENT 2

## Method

**Participants.** Twenty-seven adults (Mean age = 23 years, STD = 2.6 years; Range: 19.4 – 28.8 years; 19 females) with normal or corrected-to-normal vision and no known history of psychiatric or learning disorders participated in the study. One additional adult was tested but excluded from all analyses due to failure to follow the task instructions (clicked through scenes during learning without attempting to look for stars). Participants were recruited from the University of Oxford's undergraduate subject pool and from the surrounding community. They gave informed consent prior to participation in the study and were compensated at a rate of either £8 per hour or with research participation credits.

**Stimuli.** Stimuli for the task were identical to those used in Experiment 1.

**Procedure.** ***Learning phase and location-memory test.*** Participants completed the same learning phase and location memory test as in Experiment 1.

***Orienting.*** In Experiment 2, the orienting task was broken up into three blocks. The orienting task was the same as that in the first experiment with three key differences.

First, in the first *memories-only* block (44 trials), no visual events were presented. The first block included memory-cued and memory-un-cued trials only.

Second, in the *memory cue and visual distractor* block (44 trials), each trial included a scene with an associated memory as well as a visual distractor. The memory cued the target location on half of trials (22). The visual distractor *never* indicated the subsequent target location, and participants were explicitly instructed to ignore them. The distractor location was counterbalanced such that, within each memory condition, half of trials (11) included a *near distractor* that appeared on the same horizontal side of the screen as the target, and half of trials (11) included a *far distractor*, that appeared on the opposite horizontal side of the screen as the target.

Third, in the *visual-distractor only* block (66 trials), distractors were presented on top of novel scenes. Thirty-three trials included no distractor (neutral trials), 16 or 17 trials included a near distractor, and the remaining 16 or 17 trials included a far distractor. As in the second orienting block, participants were explicitly instructed to try to ignore the distractor.

**Counterbalancing.** As in Experiment 1, presentation of the scenes was counterbalanced across participants, such that they appeared with equal chance in both orienting conditions from the first block (Memory Cued, Memory Un-cued), both orienting conditions from the second block (Memory Cued + Distractor, Memory Un-cued + Distractor), and both orienting conditions in the third block (Neutral, Distractor). Whether scenes appeared with a near or far distractor was randomized for each participant.

The location of the learning target was counterbalanced across both participants and scenes, such that each participant saw 1/2 of the learning targets on the right (44) and

1/2 on the left (44), and for each scene the target appeared on the right for 1/2 of the participants and the left for 1/2 of participants. Within each half of the screen, the specific location of the learning target was randomized. The location of the orienting target and the identity of the orienting target was randomized for each scene but counterbalanced within conditions for each participant.

**Variables of interest.** ***Learning phase and location-memory test.*** As in Experiment 1, we extracted four measures of participants' learning of the target locations across the three blocks: targets missed z-scores, search-time z-scores, search-time slope, and two measures of participants' explicit memory for the target locations: memory imprecision and memory accuracy.

***Orienting.*** We analyzed the first, second, and third orienting blocks separately. For the first and second orienting blocks, only trials in which the target was found at least once during the learning phase were included. As in Experiment 1, we analyzed three measures to determine the effects of cue condition on attention orienting: accuracy, accuracy with missed trials excluded, and reaction time. No subjects performed below-chance level when missed trials were excluded, so all participants were included in our subsequent accuracy and reaction-time analyses.

## Results

**Successful learning of target locations.** As in Experiment 1, repeated-measures ANOVAs examining the effects of learning block on the targets missed z-scores and search-time z-scores indicated that participants found increasing numbers of targets over

the course of the learning phase ($F(2, 52) = 52.9$, $p < .001$, $\eta^2 = .943$) with increasing speed ($F(1.0, 27.1) = 48.9$, $p < .001$, $\eta^2 = .670$) .

**Explicit memory for target locations.** Additionally, participants performed above chance on the explicit test of location memory, $t(26) = 25.4$, $p < .001$, correctly remembering an average of 70.3% ($SD$ = 13.6%) of the target locations. On average, participants clicked 131.4 pixels ($SD$ = 62.0 pixels) away from the correct location. As in Experiment 1, participants' search time slope correlated with their memory imprecision, $r(27) = -.398$, $p = .040$, such that participants whose speed improved the most over the course of the three blocks also demonstrated more precise memories for the target locations.

**Effects of memories on attention orienting**. After verifying that participants were able to learn and remember locations associated with scenes, we examined whether these memories influenced attention orienting in the absence of additional visual events. As in Experiment 1, we constructed a logistic mixed-effects model to examine the effects of memory condition (cued, un-cued) on orienting accuracy, and a linear mixed-effects model to examine the effects of cue condition on orienting reaction time. Our models included memory condition (cued, un-cued) as a fixed effect and subject and scene as random intercepts.

A likelihood-ratio test revealed no effect of memory cuing on orienting accuracy, $\chi^2(1) = .82$, $p = .37$. However, participants responded more quickly when target locations were cued by memories, $F(1, 864.3) = 4.3$ $p = .03$ (Figure 6; Table 7). Additionally, when we replaced the categorical variable of memory cue condition with the more sensitive, continuous measure of memory distance, we observed the same pattern of results, $F(1, 904.2) = 4.5$, $p = .03$. Thus, without the onset of novel visual events, we observed the

expected benefits of memory cuing on attention orienting in adults. These results suggest that our failure to observe memory-guided attention orienting in adults in Experiment 1 was in fact due to the presence of transient visual events at orienting, rather than the specific parameters of our orienting task.

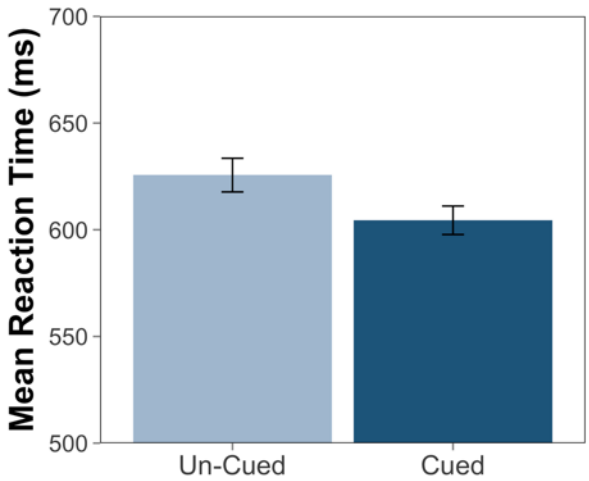



**Figure 7.** In the absence of the sudden onset of novel visual events, adults demonstrated faster orienting reaction times to targets presented in locations cued by memories, relative to un-cued locations. Error bars indicate standard error.

**Effects of distractors on attention orienting**. Next, we examined the results from our third orienting block, to determine how non-predictive, visual distractors influenced attention orienting. We constructed a logistic mixed-effects model to examine the effects of distractor location on orienting accuracy and a linear mixed-effects model to examine the effects of distractor location on orienting reaction times. Our models included orienting condition (neutral, near distractor, far distractor) as a fixed effect and subject as a random intercept. Our reaction time model additionally included scene as a random intercept; we had to remove this term from our accuracy model in order to reach convergence.

Results revealed a significant effect of distractor location on orienting accuracy, $\chi^2(2) = 24.3$, $p < .0001$, with participants responding most accurately when no distractor was present and least accurately when a far distractor appeared (Table 7). Post-hoc Tukey contrasts revealed that participants responded less accurately on far-distractor trials relative to both near-distractor trials ($p = .028$) and no-distractor trials ($p < .001$). There was no significant difference in participants' accuracy across no-distractor and near-distractor trials ($p = .191$).

We observed a slightly different effect of distractor location on orienting reaction times, $F(2, 1194.5) = 19.2$, $p < .0001$ (Figure 8; Table 7). Post-hoc Tukey contrasts revealed that responses were significantly faster on no-distractor trials, relative to trials with either near or far distractors ($p$s $< .0001$). There was no reliable difference in reaction times across near- and far-distractor trials ($p = .839$). Taken together, these results indicate that our visual distractors operated much like the visual events on un-cued trials in Experiment 1: they impaired orienting accuracy and speed, even when participants were explicitly instructed to ignore them.

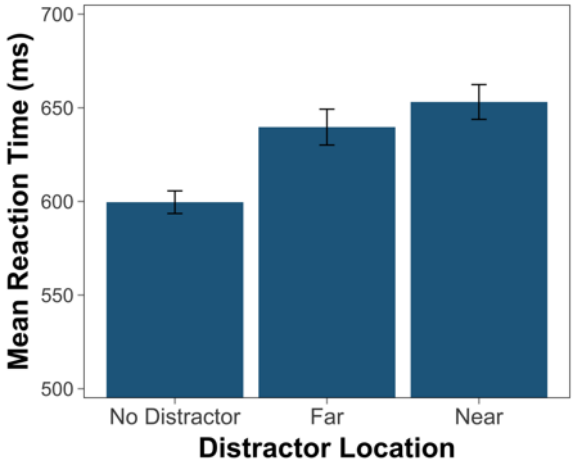



**Figure 8.** Participants' orienting responses were significantly slowed by the presence of a visual distractor. Error bars indicate standard error.

**Interaction between memory cues and distractors on attention orienting.** Finally, we sought to determine whether the addition of distractors would disrupt memory-guided attention orienting in adults, or whether their failure to use memory cues in Experiment 1 was due to strategically ignoring them in favor of the predictive, visual events. Here, the memories were the only source of predictive information, and thus ignoring them would not be an adaptive strategy. Additionally, participants were explicitly instructed to attend to them and ignore the visual distractors

As before, we constructed a logistic mixed-effects model to determine the effects of orienting condition on accuracy and a linear mixed-effects model to determine the effects of orienting condition on reaction times. Our models included the fixed effects of memory condition (cued, un-cued) and distractor location (near, far), and random intercepts for subject and scene.

There was a significant effect of distractor location on orienting accuracy, $\chi^2(1) = 13.7$, $p = .0002$, with participants responding more accurately when distractors were presented near the target location, as they did in the block when no memories were present (Table 7). There was no effect of memory condition on orienting accuracy, $\chi^2(1) = 1.3$, $p = .26$, nor was there a memory cue validity x distractor location interaction effect, $\chi^2(1) = 0.04$, $p = .83$.

Memory condition similarly did not influence orienting reaction times, $F(1, 814.7) < 0.001$, $p = .96$. Additionally, there was no effect of distractor location on orienting reaction times, $F(1, 581.2) = .04$, $p = .85$, nor was there a memory condition x distractor location interaction effect, $F(1, 432.8) = 0.01$, $p = .93$ (Figure 9). Taken together, these results indicate that, like the visual events Experiment 1, the onset of visual distractors disrupted memory-guided attention in adults.

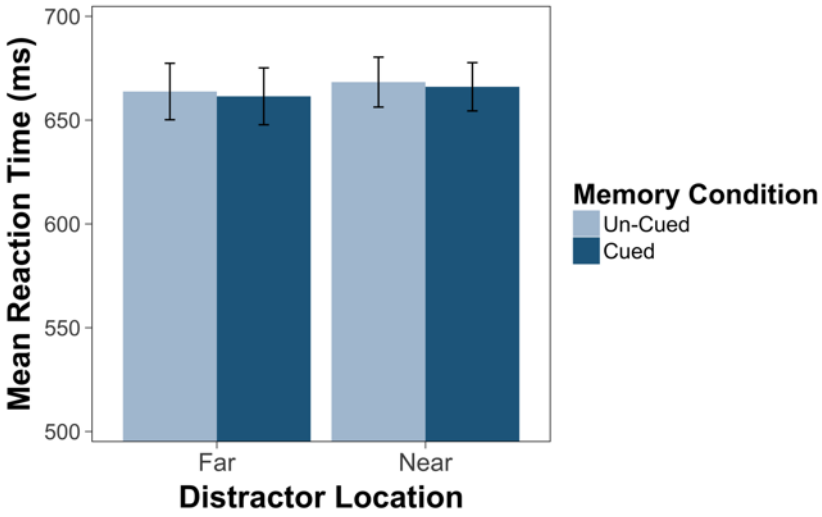



**Figure 9.** When visual distractors flashed during orienting, there was no effect of memory condition on orienting reaction times. Error bars indicate standard error.

Table 7:

*Means (and standard deviations) of accuracy and reaction times as a function of orienting condition across Experiment 2 Blocks*

| Block | Memory Condition | Visual Distractor Location | Accuracy | Reaction Time (ms) |
|---|---|---|---|---|
| Memories only | Cued | N/A | .87 (.34) | 604.4 (144.9) |
| | Un-cued | | .89 (.32) | 625.6 (174.5) |
| Visual distractors only | N/A | No distractor | .90 (.31) | 598.8 (168.8) |
| | | Near | .86 (.35) | 657.9 (178.9) |
| | | Far | .79 (.41) | 643.2 (191.6) |
| Memories and visual distractors | Cued | Near | .85 (.36) | 666.1 (179.0) |
| | | Far | .76 (.43) | 661.5 (195.6) |
| | Un-cued | Near | .87 (.33) | 668.3 (188.7) |
| | | Far | .79 (.41) | 663.8 (198.0) |

## Experiment 2 Discussion

In Experiment 2, we observed intact memory-guided attention in adults when no visual distractors were present, as evidenced by faster reaction times to targets presented

in memory-cued relative to memory-un-cued locations. However, the addition of a non-predictive, visual distractor disrupted this effect, such that we observed no influence of memory condition on attention orienting accuracy or reaction times, even when participants were explicitly instructed to ignore the distractor and only attend to the memory. Additionally, when presented alone, both near and far distractors significantly impaired orienting speed, indicating that even distractors that cued participants' attention to the correct side of the screen negatively impacted orienting performance.

These results help clarify the interpretation of Experiment 1 in two important ways. First, they indicate that in the absence of visual events adults did indeed demonstrate memory-guided attention. This suggests that the parameters of our task were sensitive enough to reveal memory-guided orienting, particularly given the fact that we observed these effects in the first block of Experiment 2, which comprised half the number of trials of the orienting block of interest in Experiment 1.

Additionally, the fact that adults failed to demonstrate any influence of memory on attention even when they were explicitly instructed to ignore the visual distractors and only attend to the memory cues suggests that the developmental differences in attention that we observed in Experiment 1 were unlikely to be due to differences in strategy use across children and adults. Though we did not expect adults to be able to suppress fully the distractors (Theeuwes & Godljn, 2002), we did expect that they would be more likely to use the memory cues if they knew they were the only source of predictive information in the task. Our data from the first orienting block, in which only memory cues were present, support this insight: adults did use memories to orient attention when they correctly predicted the target location on 50 percent of trials. Taken together, our data suggest that adults' failure to use memories to guide attention when exogenous cues were present in the first task was *not* due to them strategically weighting the salient visual cues.

## GENERAL DISCUSSION

In two experiments, we examined how memories interacted with visual stimuli to influence attention orienting across children and adults. We found that when both memory cues and visual events precede a target in an orienting task, children demonstrated additive cuing benefits from both sources while adults only showed exogenous cuing effects. Adults did use memories to guide attention when no visual stimuli were present, but they failed to do so when either predictive visual events or non-predictive distractors appeared, suggesting that the sudden onset of peripheral, salient stimuli disrupted either the processes underlying memory recall or the use of memory to orient attention in adults but not children.

Our findings bolster previous, somewhat controversial claims of children's ability to use learned environmental regularities to shape their behavior (e.g. Dixon et al., 2010). Furthermore, our memory distance analysis revealed that the strength of the orienting effect that children demonstrated depended on the precise location of their explicitly recalled memory, a relationship which has been observed previously in young adults (Salvato et al., 2016). This link suggests that children with stronger or more precise memory representations may more rapidly deploy their attention to relevant locations, bolstering their ability to learn and remember new information (Ballesteros et al., 2006; Markant et al., 2015; Uncapher & Rugg, 2009).

The network of brain regions involved in memory-guided attention may overlap largely with those implicated in spatial orienting in response to peripheral, visual events (Summerfield et al., 2006). Like visual events, memories may trigger preparatory shifts in spatial attention in which fronto-parietal control mechanisms modulate visual cortical

activity, leading to both greater desynchronization of alpha oscillations and enhanced neural activity, indexed by a greater blood oxygenation, contralateral to the cued location (Stokes et al., 2011). These neural changes may underlie enhanced perceptual sensitivity to information presented in the contralateral hemifield. Critically, in memory-guided orienting, these changes may be catalyzed by interactions between memory-triggered hippocampal activity and control regions including dorsal regions of the frontal and parietal cortices (Rosen et al., 2015; Stokes et al., 2011). Assuming the same mechanisms underlie memory-guided orienting in children and adults, our findings suggest that the medial temporal lobe memory systems, fronto-parietal orienting network, and prefrontal cognitive control systems that are implicated in memory-guided attention (Goldfarb et al., 2016; Rosen, Stern, Michalka, Devaney, & Somers, 2015; Stokes et al., 2012; Summerfield et al., 2006) are sufficiently mature in 7- to 12-year-olds to enable the use of past experience to guide attention orienting.

Studies examining interactions between goal-directed and stimulus-driven attention suggest that people can orient attention in response to two sources, even when they share significant overlap in their neural instantiations. When a central stimulus that predicts a target location (like an arrow) is followed by a peripheral, non-predictive, visual event, individuals demonstrate additive cuing effects of both stimuli (Berger, Henik, & Rafal, 2005), much like we observed in children in our task. This led Berger et al. (2005) to conclude that despite some overlap in the neural systems on which they rely, goal-directed attention and exogenous orienting involve separate and independent orienting mechanisms. This separable pathway that underlies goal-directed attention may also partially support memory-guided attention; both involve similar dorsal regions of the frontal cortex, including the intraparietal sulcus and the frontal eye fields (Chica, Bartolomeo, & Lupiáñez, 2013). These mechanisms differ from those involved in

exogenously cued attention, though both forms of attention, like memory-guided attention, ultimately modulate visual cortical responses to cued locations and items (Chica et al., 2013).

Still, if memory guides attention even in the presence of visual events childhood, the obvious question then is why this relationship differs in adults. Though Experiment 2 ruled out differences in strategy use across children and adults, several other possible explanations persist.

One possibility is that children and adults vary in the extent to which they adapt their weighting of different sources of orienting based on the sequence of trials they have experienced. In Experiment 1, participants were presented with sources of orienting that were in conflict on 50% of trials. On these trials, the remembered location associated with the scene differed from the salient visual event. The degree to which participants enhanced attention toward each location may have been influenced by the preceding trial. Though no previous work has examined how these sequential effects may operate in the domain of memory-guided attention, studies in related domains have shown that the nature of the preceding stimulus can influence how cognitive control and selective attention are deployed on the current trial (e.g. Egner, 2007). When a trial that demands high cognitive control follows another trial that demands high cognitive control, participants generally respond faster than when a trial that demands high cognitive control follows a trial with a lower control demand. These data suggest the brain rapidly monitors and adjusts to the demands of its environment.

Similar adaptive mechanisms could influence the pattern of responding we observed in our experiments. For example, if the visual event correctly cued the target on the previous trial, participants may have been more likely to enhance attention to the

location cued by the visual event on the next trial they experienced rather than the location cued by the memory. Furthermore, the degree to which the preceding trial influenced participants' weighting of the competing sources of orienting may have varied by age group. Adults may have been more likely to adjust their orienting response based on the validity of the previous cues — after experiencing a trial in which a memory incorrectly predicted the location of the upcoming target, they may have reduced the extent to which they used memory-guided attention to a greater extent than children on the next trial.

Additionally, though we verified that adults did demonstrate memory-guided attention when no novel, visual events occurred we did not test children on this baseline condition. Thus, it could be the case that contrary to our predictions, children show larger memory-guided orienting effects that are *more* robust to the presence of interference by other stimuli, and still detectable even when weakened. Very few studies have compared directly children's and adults' use of memories to guide spatial attention within the same paradigm. One (Merrill et al., 2013) found that the magnitude of contextual cuing effects was equivalent across young 6-7-year-old children and young adults, whereas other studies have demonstrated that children fail to show contextual cuing effects on paradigms in which adults do (Couperus et al., 2011; Darby et al., 2014; Vaidya et al., 2007). Dixon et al. (2010), however, found a trend toward larger memory benefits for younger children. In the auditory domain, one study did find that when both children and adults were instructed to respond to a specific tone, children demonstrated *greater* reaction time benefits than adults when tones were cued by implicitly learned sequences (Ruhnau, Schröger, & Sussman, 2017). But in the visuospatial domain, to the best of our knowledge, no work has found that children demonstrate significantly greater memory-cuing effects relative to adults. We examine this possibility in Chapter 4.

Another potential explanation for our surprising findings is that the *time course* of the recruitment of the mechanisms underlying attention orienting changes over development. Past work has revealed that children are slower to disengage attention from a cued location and to reorient toward a second location (Schul et al., 2003). For example, Schul et al. (2003) found that when targets were preceded by peripheral stimuli, children demonstrated larger cuing benefits when the time between the presentation of the initial visual event and the target was increased from 100 to 800 ms. This benefit of extending the cue-to-target interval decreased with age. In other words, younger participants needed more time to use the orienting cues, whereas adults were able to process and shift their attention in response to stimuli within 100 ms. In our task then, adults may have been able to modulate their attention in response to the initial presentation of the scene with the associated memory, and then rapidly disengage from it and completely shift their attention to the visual stimulus in the 150 ms before the target onset. Children however, may have lingered on the memory, unable to fully disengage and fully reorient to the visual event, such that when the target was presented, they were more successful in monitoring *both* cued locations relative to the adults. Thus children's inefficiency in orienting attention may actually be advantageous in situations when contextual information or memories compete with the rapid onset of novel stimuli, particularly if those novel stimuli are irrelevant or distracting. Future studies should manipulate cue order and cue timing to better differentiate whether the cuing differences we observed across age groups are due specifically to changes in the use of memories to guide attention or a consequence of greater orienting efficiency with increasing age.

Finally, it is also possible that when faced with competing sources of information, children may simply place more weight on their experiences and memories in guiding their attention than adults. Though the neural systems underlying memory-guided

attention are generally thought to be complex and slow to mature, evidence suggests that the ability to detect environmental regularities (Saffran, Aslin, & Newport, 1996) and integrate those regularities into more complex representations to guide future learning (Werchan, Collins, Frank, & Amso, 2016) may emerge as early as infancy. In fact, many other sources of orienting, including internal (endogenous) goals and social stimuli, may *rely* on associations that children learn through experience over time.

Our findings suggest that memories may play a particularly important role in shaping attention during childhood. Specifically, they guide attention even in the presence of salient, visual events. In this way, familiar contexts may moderate the negative influence of visual distraction in children's environments. For example, children who have learned through experience to orient toward their classroom's chalkboard may be less likely to fully shift their attention toward a disruptive classmate on the other side of the room. One key implication of this finding is that early differences in memory ability may rapidly snowball into larger gaps as memory supports future learning through its role in guiding attention. Given the reciprocal interactions between memory and attention throughout development (Astle, Nobre, & Scerif, 2012; Astle & Scerif, 2011; Markant & Amso, 2014; Doherty, Patai, Duta, Nobre, & Scerif, 2017), early intervention to boost memory encoding in children who lag behind their peers is critical to close these large learning gaps before they appear.

# 3. The temporal dynamics of the effects of concurrent memories and visual events on attention orienting in adults

The studies detailed in Chapter 2 shed light on how novel, transient visual events that occur in familiar contexts with associated spatial memories influence attention in both children and adults. But the experiments examined only one specific time-course over which these two sources of attention may unfold. In reality, the dynamics of our environments are themselves dynamic and often unpredictable — in some cases, we may enter a known environment and immediately encounter a novel event that demands our attention. In other cases, events may occur more slowly, allowing us more time to retrieve spatial memories associated with familiar contexts or more time to reorient our attention after a disrupting distractor. It is unclear how the timing of a transient visual event influences our ability to use memories to guide attention. Beyond deepening our understanding of how different sources of orienting interact in real-world settings, determining whether there are particular time-points at which memory-guided attention is particularly susceptible to disruption will help to illuminate the temporal dynamics of memory-guided attention itself.

The first study to use a scene-based orienting paradigm to examine memory-guided attention found no evidence for differences in the strength of the memory-based cuing effect over 100-, 500- , and 900-ms cue-to-target intervals (Summerfield et al., 2006). Though participants responded more quickly on trials with longer cue-to-target intervals, the duration of the cue period and the memory-cue condition itself (i.e. cued vs.

un-cued) did not interact; participants demonstrated equivalent reaction-time benefits on cued relative to un-cued trials across all three intervals. Most other studies employing a similar paradigm used much longer cue-to-target intervals (500 – 12000 ms) in order to optimize timing for EEG and fMRI data acquisition (Patai et al., 2012; Stokes et al., 2012; Summerfield et al., 2011), so it is difficult to determine whether the effects of memories on attention grow stronger (or weaker) and more (or less) robust to interference with increasing time, particularly at shorter time-scales.

Neural data should be able to provide insight into this question, but an interesting discrepancy arises: the neural changes induced by scenes with associated memories, as measured through EEG, take *longer* to emerge than the cuing effects observed in behavior. Though behavioral research suggests that memories can influence attention within 100 ms (Summerfield et al., 2006), neural changes have been observed only after more than 300 ms post cue-onset (Patai et al., 2012; Stokes et al., 2012; Summerfield et al., 2011). For example, Stokes et al. (2012) observed lateralized changes in alpha synchrony, which reflect anticipatory biases in spatial attention, approximately 400 ms after cue onset. Similarly, Patai et al. (2012) observed neural differentiation of scenes associated with spatial memories and scenes without spatial memories only 400 – 470 ms after scene onset and Summerfield et al. (2011) found differences in neural activity elicited by scenes with memories and scenes without memories after 340 ms. Together, these data suggest that behavioral effects of memory cues emerge *before* changes in cue-related neural activity can be measured with EEG.

If this discrepancy were specific to memory cues, one interpretation might be that the cuing effect observed after 100 ms in Summerfield et al. (2006), as well as the cuing effects we observed in Ch. 2, were spurious findings. But that is not the case. Across many domains, detectable changes in neural activity occur at timescales much slower than their

behavioral correlates. For example, changes in alpha activity elicited by endogenous cues have been shown to occur around 300 – 500 ms after cue presentation (Worden, Foxe, Wang, & Simpson, 2000), but the behavioural effects of endogenous cues emerge at cue-to-target intervals as short as 150 – 200 ms (Eriksen & Collins, 1969; Shulman, 1979). Neural data then, might provide useful insight into the *relative* speed of the effects of different types of cues, but may not provide an *absolute* metric for the time-course of memory-guided attention.

In our previous experiments (Ch. 2), we found that salient visual events disrupt or interfere with adults' use of memories to orient attention. Still, it may be the case that the effects we observed were specific to the timing of the presentation of the two types of attentional cues in our orienting task. In our experiments, the scene with associated memory always cued participants to a remembered location 250 ms prior to target onset. In Experiment 1, a transient visual event with a 50-ms duration always onset 100 ms after the initial scene presentation and offset 100 ms prior to target onset. In the first orienting block of Experiment 2, in which we *did* observe an influence of memories on attention, the scene appeared without interruption for 250 ms prior to target onset. Thus our data from Experiment 2 suggests that within a 250-ms window, adults were able to: a) retrieve the association between the scene and a location, and b) orient their attention to that location.

The transient visual events in our paradigm may have interfered with an early stage of memory retrieval, preventing the formation of a robust representation of the target location. With a longer delay between the presentation of the scene and the visual event, participants may have time to retrieve and reinstate a stronger representation of the learned target location that is less susceptible to interference by a salient visual event. Additionally, it is also possible that the visual events caused participants to reorient their

attention only temporarily. With a longer delay between the visual event and the target, participants may have time to reorient *back* to the location cued by memory.

To address these possibilities, we conducted two additional experiments in adults. In both experiments, we manipulated the length of time between the scene onset and the onset of the transient visual event (delay 1) and the length of time between the offset of the transient visual event and the onset of the target (delay 2). We hypothesized that memory cue condition would interact with both delay periods, such that the effects of memories on attention would be stronger when either (or both) delay periods increased in duration. To determine whether any effects of timing we observed were specific to *memory*-guided attention, we included an additional orienting block in which novel scenes with static visual cues appeared prior to the onset of the transient visual event. Though we expected to see similar patterns of accuracy and reaction time across both orienting blocks, we hypothesized that these static visual cues would be *less* susceptible to interference from the transient visual events, and thus not interact as strongly with our timing manipulations.

# EXPERIMENT 3

## Methods

**Participants.** This study was approved by the University of Oxford Central University Research Ethics Committee (CUREC). Sixteen adults (Mean age = 20.8 years, STD = 2.9 years; Range: 18.3 – 27.9 years; 11 females) with normal or corrected-to-normal vision and no known history of psychiatric or learning disorders, participated in the study.

Adult participants were recruited from the University of Oxford's undergraduate subject pool and from the surrounding community. They gave informed consent prior to participation in the study and were compensated at a rate of either £8 per hour or with research participation credit.

**Stimuli.** Stimuli for the task were identical to those used in Experiments 1 and 2. This experiment comprised two orienting blocks with 88 trials each. As such, we added 22 additional scenes from Google images to accommodate the increased number of trials.

**Procedure.** ***Learning phase & Location-memory test.*** The learning phase and location memory test were identical to those in Experiments 1 and 2.

***Orienting.*** *Memory-guided attention.* After the location-memory test, participants completed the first block of the orienting task. As in Experiments 1 and 2, participants were told to discriminate a small grey square or circle target that appeared on every trial using a standard keyboard.

On every trial, participants first viewed a scene with an associated memory. Then, after a short delay, a transient, visual event (a red, square outline) appeared within the scene (50-ms duration). After the visual event occurred, the scene with the associated memory remained on the screen, and the target appeared for 200 ms. Participants then had an additional 1800 ms to respond to the target, during which time the scene remained on the screen. On half of the orienting trials, the scene with the associated memory cued the target location. As in Experiment 2, the visual event *never* cued the target location, though its location was counterbalanced such that on half of trials, it appeared in the same hemifield as the subsequent target.

In this experiment, our question centered on the *timing* of the transient, visual event. As such, we manipulated the duration of two delay periods: *Delay 1* refers to the time between the initial scene onset and the onset of the visual event. *Delay 2* refers to the time between the offset of the visual event and the onset of the target (Figure 10). Each delay period was either *short* (S; 100 ms) or *long* (L; 500 ms), such that participants experienced four different delay period combinations: short-short (SS), short-long (SL), long-short (LS), long-long (LL). Participants experienced equal numbers of each delay period combinations within each memory-cue condition (cued, un-cued). The order of the trials was randomized.

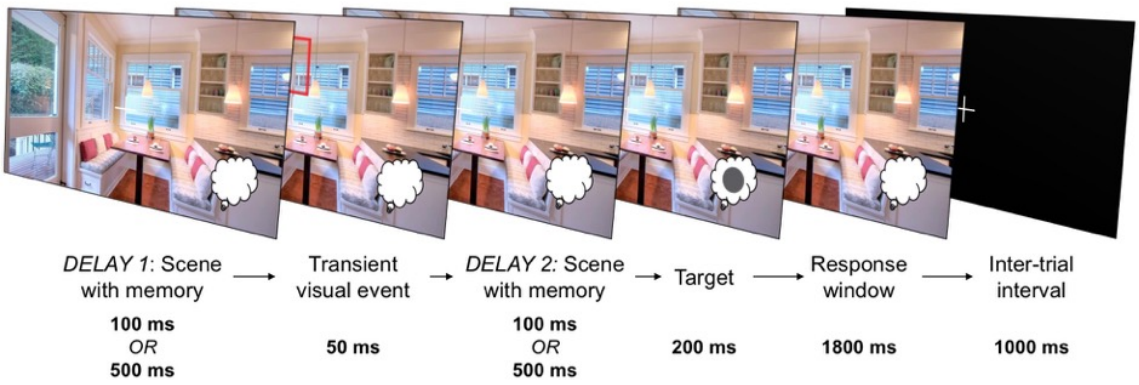



**Figure 10.** Orienting task: memories and visual events. In the first orienting block, participants saw a scene with an associated memory for either 100 or 500 ms (Delay 1). Then, a red square appeared for 50 ms. After a brief delay (100 or 500 ms) (Delay 2), a target square or circle appeared, which participants were instructed to discriminate.

As in Experiment 2, participants were explicitly told that the memory association would sometimes indicate the target location, and that the visual event would never indicate the target location. They were also instructed to keep their eyes fixated on the central cross that appeared on top of all orienting stimuli. Participants were told to respond to the target stimuli as quickly and as accurately as possible. Before beginning the real

trials, adult participants completed 10 trials to practice the button-press responses in which they saw the grey targets appear on top of a black screen.

*Visually guided attention.* The second orienting block was identical to the first except that all scenes used were novel, and thus contained no information about the location of the target. However, when these scenes first appeared, they contained a static red box (identical to the visual event). Like the memory cue, this *static visual cue* correctly indicated the target location on half (88) of the trials in the block. As in the first orienting block, we manipulated delay period 1, between the appearance of the scene with the static visual cue and the onset of the transient visual event (100 or 500 ms), and delay period 2, between the offset of the transient visual event and the onset of the target (100 or 500 ms). Participants were informed that the *static visual cue* sometimes indicated the target location, but that the second, *transient visual event* never did. We included this block in order to determine whether any patterns we observed in our first orienting block were specific to interactions between memory-guided and visually cued attention, or whether we would observe similar effects of manipulating the temporal dynamics of the trial when both cues were visual.

**Counterbalancing.** Presentation of the scenes was counterbalanced across participants, such that they appeared with equal chance in the eight orienting conditions in the first orienting block (memory cued and un-cued; SS, SL, LS, LL) and the eight orienting conditions in the second orienting block (visually cued and un-cued; SS, SL, LS, LL) (Table 8). The location of the learning target was counterbalanced across both participants and scenes, such that each participant saw half of the learning targets (44) on the right and half (44) on the left, and for each scene the target appeared on the right for half of the participants and the left for half of participants. Within each half of the screen, the specific location of the learning target was randomized. The location of the orienting

target and the identity of the orienting target was randomized for each scene but counterbalanced within conditions for each participant. Finally, the transient visual events *never* cued the location of the target, but within each condition, they occurred in the same hemifield as the target on half of trials. Within each hemifield, their location was randomized.

Table 8

*Task counterbalancing: Orienting Block 1*

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Learning:* Target location | 44 Left | | | | | | | | 44 Right | | | | | | | |
| *Orienting:* Memory association | 44 Left | | | | | | | | 44 Right | | | | | | | |
| *Orienting:* Target Location | 22 Left | | | | 22 Right | | | | 22 Left | | | | 22 Right | | | |
| *Orienting:* Delay 1 | 11 S | | 11 L | | 11 S | | 11 L | | 11 S | | 11 L | | 11 S | | 11 L | |
| *Orienting:* Delay 2 | 5 S | 6 L | 6 S | 5 L | 5 S | 6 L | 6 S | 5 L | 6 S | 5 L | 5 S | 6 L | 6 S | 5 L | 5 S | 6 L |
| Memory Condition | Cued | | | | Un-Cued | | | | Un-Cued | | | | Cued | | | |
| Timing Condition | *SS* | *SL* | *LS* | *LL* | *SS* | *SL* | *LS* | *LL* | *SS* | *SL* | *LS* | *LL* | *SS* | *SL* | *LS* | *LL* |

**Variables of interest.** ***Learning phase and location memory test.*** As in Ch. 2, we extracted three measures of participants' learning of the target locations across the three blocks: targets missed, search time, and search time slope. Additionally, we extracted two measures of participants' explicit memory for the target locations: memory precision and memory accuracy.

***Orienting.*** We analyzed the first and second orienting blocks separately. For the first orienting block, only trials in which the target was found at least once during the learning phase were included. As in Ch. 2, we analyzed three measures to determine the effects of cue condition on attention orienting: accuracy, accuracy with missed trials

excluded, and reaction time. No subjects performed below-chance level when missed trials were excluded, so all participants were included in our subsequent accuracy and reaction time analyses. Finally, in our timing experiments, participants were able to respond up to 2 seconds after target onset. Initially, we intended to test children on this task as well, and so lengthened our response window to capture a larger range of their responses. However, to enable comparisons between our initial experiments described in Ch. 2. and our timing experiments described in the current chapter, we have excluded from our orienting accuracy and reaction time analyses all trials with response times greater than the 1500 ms allowed in our first set of experiments (*Block 1:* 32 trials excluded out of 1305 total trials; *Block 2:* 26 trials excluded out of 1410 total trials).

## Results

**Successful learning of target locations.** Converging evidence from our targets-found and search-time analyses suggest that participants learned the location of the targets across search blocks. Two repeated-measures ANOVAs examining the number of targets missed and average search speed with learning block as a within-subjects factor revealed that participants found increasing numbers of targets as the task proceeded, $F(2, 30) = 40.7$, $p < .001$, $\eta^2 = .731$, with increasing speed, $F(2, 30) = 153.1$, $p < .001$, $\eta^2 = .911$.

**Explicit memory for target locations.** Additionally, participants performed above chance on the explicit test of location memory, $t(15) = 38.3$, $p < .001$, correctly remembering an average of 82.9% (*SD* = 7.1%) of the target locations. On average, participants clicked 111.9 pixels (*SD* = 50.7 pixels) away from the correct location. Furthermore, participants' search-time slopes correlated with their memory precision, $r(16) = -.62$, $p = .011$, such that participants whose speed improved the most over the

course of the three blocks also demonstrated more precise memories for the target locations.

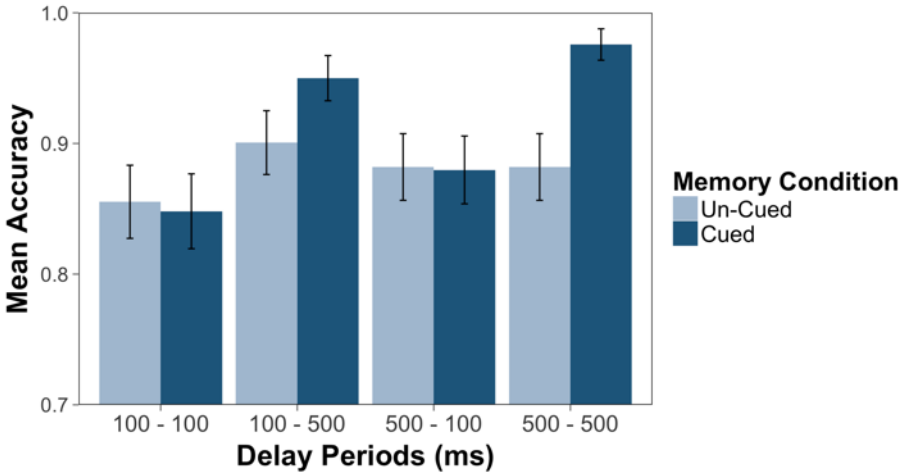
**Effects of visual event timing on attention orienting.** After verifying that participants were able to learn and remember locations associated with scenes, we examined whether these memories influenced attention orienting when novel visual events occurred at different times within the orienting trial. Additionally, we examined whether the effects of memory cues and visual cues on attention orienting differed by combining the data from both of our orienting blocks and analyzing them within a single model.

As in Ch. 2, we used mixed-effects models to examine the effects of orienting block (memory, visual), cue condition (cued, un-cued), delay 1 (S, L), and delay 2 (S, L) on orienting accuracy and reaction times. The random effects structure for each model was selected using the "forward-stepping-best-path approach" (Barr et al., 2013). Both our accuracy and reaction-time models included orienting block, memory condition, delay 1, and delay 2 as fixed effects and subject as a random intercept. Our reaction-time model additionally included scene as a random intercept.

A likelihood-ratio test revealed a main effect of orienting block on orienting accuracy, $\chi^2(1) = 8.6$, $p = .003$, with participants responding with greater accuracy in the memory-cued block ($M = .90$, $SD = .30$) relative to the visually cued block ($M = .85$, $SD = .35$). Additionally, as we predicted, a likelihood-ratio test revealed a main effect of delay 2 on orienting accuracy, $\chi^2(1) = 40.3$, $p < .0001$, with participants responding with greater accuracy when the delay period was long ($M = .91$, $SD = .28$) relative to short ($M = .84$, $SD = .37$; Figure 11). We also observed a main effect of cue condition on orienting accuracy, $\chi^2(1) = 22.0$, $p < .0001$. Across orienting blocks, participants were more

accurate to respond on cued trials ($M$ = .90, $SD$ = .30) relative to un-cued trials ($M$ = .85, $SD$ = .36). However, this main effect was qualified by a condition x delay 2 interaction, $\chi^2(1) = 10.1$, $p = .002$, as well as an orienting block x condition x delay 2 interaction, $\chi^2(1) = 3.9$, $p = .05$ (Figure 11; Table 9). To understand these interactions, we used the R package "multcomp" (Hothorn et al., 2016) to conduct pairwise comparisons of participant accuracy on cued and un-cued trials within each orienting block and delay-2 duration. These contrasts revealed that on visually guided trials, participants performed more accurately on cued relative to un-cued trials across *both* delay 2 durations ($p$s < .04). However, on memory-guided trials, participants demonstrated an effect of cue condition on accuracy when delay 2 was long ($p$ = .0002), but not when delay 2 was short ($p$ = .87). No other effects were significant ($p$s > .11). Thus our accuracy data largely supported our hypothesis: the degree to which transient visual events interfere with memory-guided attention depends on the time-course of the presentation of the two sources of orienting. However, most of the effects we observed were *not* specific to memory cues, and also emerged in our visually cued block.

A.




B.

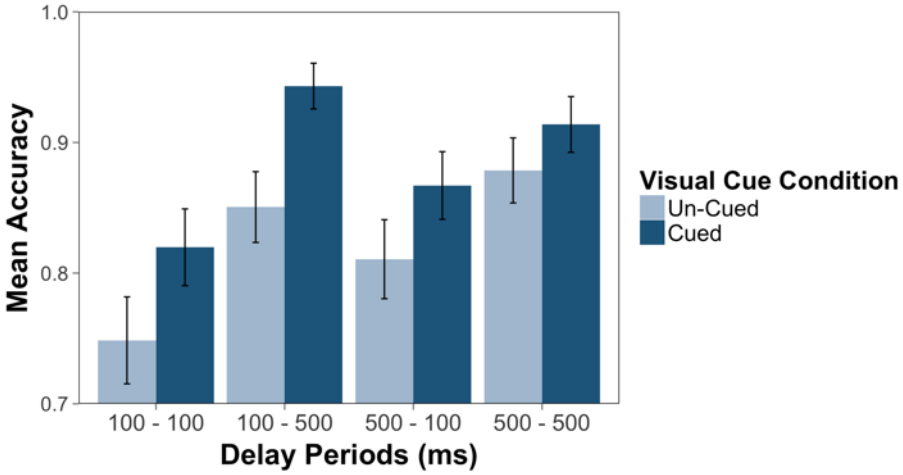
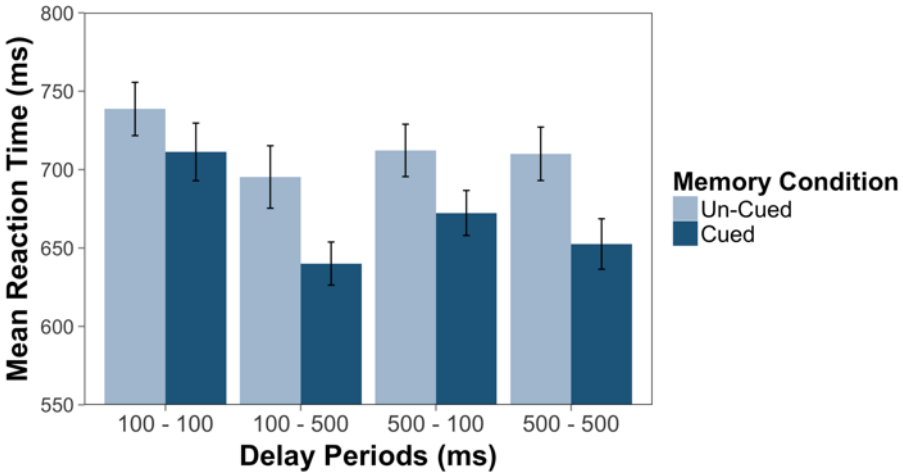



**Figure 11.** In the memory-cued block (A), participants only responded more accurately on cued relative to un-cued trials when the delay 2 duration was long. However, in the visually cued block (B), participants responded more accurately on cued relative to un-cued trials across both long and short delay 2 durations. Error bars indicate standard error.

Our reaction-time data largely aligned with our accuracy data, though we observed some differences. As with our accuracy data, we observed a main effect of orienting block on reaction times, $F(1, 172.0) = 11.5$, $p = .0008$. Here, however, participants responded more quickly on trials within the visually cued block ($M = 677.3$ ms, $SD = 197.0$ ms) relative to trials within the memory-cued block ($M = 690.1$ ms, $SD = 201.1$ ms), perhaps reflecting a speed-accuracy trade-off between the two blocks. Additionally, there was a

main effect of delay 2 on orienting reaction times, $F(1, 2203.1) = 32.1$, $p < .0001$, with participants responding faster when the delay period was long ($M = 663.4$ ms, $SD = 195.8$ ms) relative to short ($M = 705.8$ ms, $SD = 200.5$ ms). There was also a main effect of cue condition on reaction times, $F(1, 2199.5) = 62.9$, $p < .0001$, with participants responding faster on cued trials ($M = 656.8$ ms, $SD = 186.7$ ms) relative to un-cued trials ($M = 712.3$ ms, $SD = 207.9$ ms). As with our accuracy data, this effect was qualified by a cue condition x delay 2 interaction, $F(1, 2208.6) = 5.1$, $p = .02$, such that the effects of cue condition were greater when delay 2 was long relative to short (Figure 12; Table 9). Additionally, we also observed a delay 1 x delay 2 interaction effect, $F(1, 2209.2) = 15.0$. $p = .0001$, such that the difference in reaction times across delay 2 timings was greater when delay 1 was short. No other effects were significant ($ps > .07$).

A.




B.

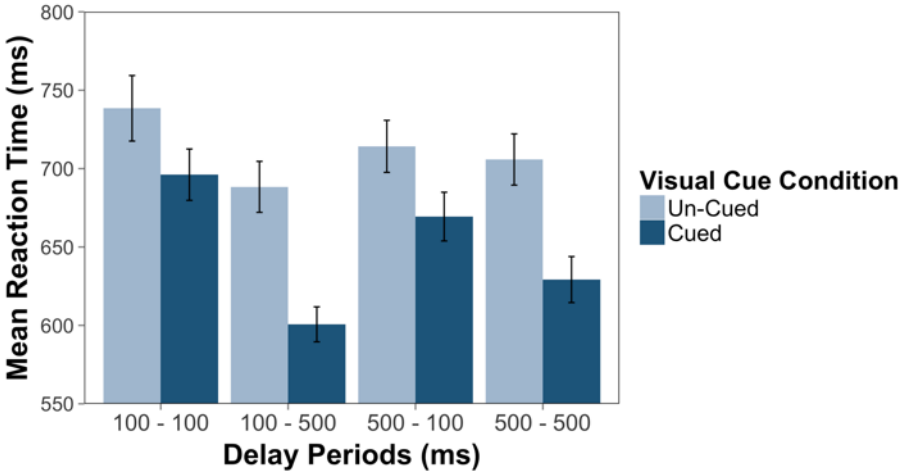



**Figure 12.** In both the memory-cued block (A) and the visually cued block (B), participants responded more quickly on cued relative to un-cued trials. This cuing effect was greater when the delay 2 duration was long relative to short. Error bars indicate standard error.

Table 9

*Orienting accuracy and reaction-time means (and standard deviations) across orienting blocks, cue conditions and delay periods*

| Orienting Block | Cue Condition | Delay 1 | Delay 2 | Accuracy | Reaction Time (ms) |
|---|---|---|---|---|---|
| Block 1: Memory-cued | Cued | Short | Short | .85 (.36) | 711.3 (212.6) |
| | | Short | Long | .95 (.22) | 640.1 (169.3) |
| | | Long | Short | .88 (.33) | 672.3 (169.3) |
| | | Long | Long | .98 (.15) | 652.5 (204.2) |
| | Un-Cued | Short | Short | .86 (.35) | 738.7 (198.2) |
| | | Short | Long | .90 (.30) | 695.3 (232.4) |
| | | Long | Short | .88 (.32) | 712.2 (199.1) |
| | | Long | Long | .88 (.32) | 710.1 (203.2) |
| | | | | | |
| Block 2: Visually cued | Cued | Short | Short | .82 (.39) | 696.1 (194.6) |
| | | Short | Long | .94 (.23) | 600.7 (143.6) |
| | | Long | Short | .87 (.34) | 669.4 (190.2) |
| | | Long | Long | .91 (.28) | 629.2 (185.0) |
| | Un-Cued | Short | Short | .75 (.44) | 738.5 (236.4) |
| | | Short | Long | .85 (.36) | 688.4 (197.8) |
| | | Long | Short | .81 (.39) | 714.2 (194.1) |
| | | Long | Long | .88 (.33) | 705.8 (201.4) |

## Experiment 3 Discussion

In Experiment 3, participants demonstrated facilitated target detection when target locations were cued by memories and when they were cued visually, even when a transient visual event occurred during orienting. The effects of both types of cues on attention were independent of the duration between the initial presentation of the scene and the occurrence of the transient visual event but influenced by the duration between the occurrence of the transient visual event and the target onset: both memories and visual

cues facilitated orienting to a greater degree when the time between the visual event and the target was the longer, 500-ms interval relative to the shorter, 100-ms delay-2 interval.

These results support two novel insights. First, while memory cues and visual cues recruit largely overlapping neural systems (Stokes et al., 2012) and have been shown to influence behavior similarly (Summerfield et al., 2006), our accuracy results suggest that memory cues may take longer to recover after disruption by a transient visual event. Secondly, transient visual events attenuated the effects of memories on attention, but only temporarily; at longer time-courses, accuracy and reaction time benefits for targets cued by memories grew stronger.

One possible explanation for why we observed accuracy benefits of visual cues but not memory cues when the delay 2 duration was short is that visual cues are simply stronger and less susceptible to interference. Though previous work has observed stronger effects of memory cues relative to visual cues (Summerfield et al., 2006), we employed static visual cues that were embedded within scenes, which may have elicited voluntary, endogenous orienting (Chica et al., 2013) rather than the transient visual cues used in prior work. *Endogenous* cues, which engage the voluntary orienting of attention (like our static visual cues), can inhibit reflexive orienting in response to *exogenous* cues (like our transient visual events), particularly during difficult discrimination tasks (Berger, Henik, & Rafal, 2005). Though exogenous cues can also inhibit or compete with endogenous cues, Berger et al. (2005) found that participants still demonstrated endogenous cuing effects when a transient visual event occurred 100-, 200-, 300-, and 1000-ms prior to target onset. It is unclear whether memory associations can similarly inhibit exogenous cuing effects.

Interestingly, however, the degree to which the transient visual event attenuated accuracy and reaction-time benefits on cued relative to un-cued trials depended on its time course. Though the transient visual erased accuracy benefits and attenuated reaction-time benefits on memory-cued relative to un-cued trials when the delay 2 duration was 100 ms, accuracy benefits re-emerged and we observed stronger reaction-time effects when the delay 2 duration was increased to 500 ms. Originally, we hypothesized that during a trial with a memory cue, participants would first recall the location associated with the scene, and then use that memory representation to orient their attention. Within this sequential framework, lengthening delay 1 would give participants more time to retrieve a robust representation of the location cued by memory, and lengthening delay 2 would give participants more time to reorient *away* from the location cued by the transient visual event and *back* to the memory-cued location. If this were the case, our data support the idea that the transient visual events disrupted the *use* of memories to guide attention, rather than the initial retrieval of the memory associated with the scene. However, data from both short-term memory and long-term memory tasks suggest that memory retrieval and spatial orienting operate in parallel, and likely cannot be neatly segmented into two processes with separate time-courses (Corbetta, Kincade, & Shulman, 2002; Holm & Mäntylä, 2007; Matsukura, Luck, & Vecera, 2007; Nobre et al., 2004). In fact, previous work has found that spatially orienting to a location may enhance retrieval from short-term memory of an item previously presented at that location (Nobre, Griffin, & Rao, 2008). Thus conceptualizing the different delay periods in our task as encompassing two entirely distinct components of memory-guided attention is not realistic, and in fact runs contrary to our broader theoretical framework which treats memory and spatial attention as a functionally integrated, constantly interacting system.

Still, data from our task support the idea that memory-guided attention was not equally susceptible to disruption at every time point during the cue period. Though our trials likely cannot be parsed into entirely distinct and separable "memory retrieval" and "spatial orienting" phases, this result nevertheless suggests lengthening the time for memory-guided attention to *recover* after disruption is more important than lengthening the preparatory time *prior* to disruption. The similarity between the effects of memory cues and static visual cues that we observed support this insight: given the fact that we observed similar results across blocks, it is more likely that the transient visual event disrupted processes related to *orienting*, rather than *retrieval*, which was only relevant in the memory block.

The modulation of the effects of memory on attention that we observed in adults by changing the temporal dynamics of the salient visual event also suggests an interesting re-interpretation of our results from Experiments 1 and 2. Previously, we hypothesized that memory-guided attention in children may be less susceptible to disruption than memory-guided attention in adults. However, the results from this chapter indicate that this pattern may hold true only at short time-courses. With a longer delay-2 period, the effects of memories on attention re-emerge in adults. One question these results raise then is how this longer time-course may affect memory-guided orienting in children. Previously, we noted that prior work has found that children are slower to disengage their attention from one location and reorient to another (Schul et al., 2003). With the short time-course used in Ch. 2, children may not have had time to fully disengage from the location cued by memory and reorient to the location cued exogenously. However, with a longer time-course, children may be able to more fully reorient to the exogenous cue. Thus, we might observe the opposite pattern from that which we observed in adults: up until a point, lengthening the time between the presentation of the exogenous cue and the

presentation of the target may *reduce* children's use of memories to guide attention. Future work should test this hypothesis directly.

Finally, Experiment 3 examined only four possible time-courses of interactions between memory-guided and exogenously cued attention, in a relatively small sample, with a relatively small number of trials in each orienting condition. It is thus unclear how intermediate timings may influence memory-guided attention. For example, it may be the case that with a smaller difference between our long and short delay durations, the duration of the first delay becomes more important. In other words, in Experiment 3, the 500-ms delay 2 duration may have provided enough time for memory to exert its maximal effect attention, regardless of the delay 1 period, while the 100-ms delay 2 duration may not have provided enough time for memory to exert any influence on orienting, regardless of the strength of the memory representation when it was temporarily interrupted. But an intermediate delay-2 duration may render the preparatory time prior to the onset of the transient visual event more relevant. Thus, we decided to conduct a second experiment in order to a) replicate our general pattern of results and b) test the effects of a 300-ms delay-1 and delay-2 duration. To do so, we employed the same task, but reduced our "long" delay durations from 500 to 300 ms.

## EXPERIMENT 4

## Methods

**Participants.** This study was approved by the University of Oxford Central University Research Ethics Committee (CUREC). Sixteen adults (Mean age = 21.6 years, STD = 3.8 years; Range: 18.2 – 30.7 years; 12 females) with normal or corrected-to-

normal vision and no known history of psychiatric or learning disorders, participated in the study.

Adult participants were recruited from the University of Oxford's undergraduate subject pool and from the surrounding community. They gave informed consent prior to participation in the study, and were compensated at a rate of either £8 per hour or with research participation credit.

**Stimuli & Procedure.** The experiment was identical to Experiment 3 with one key difference: the "long" duration for the Delay 1 and Delay 2 periods was shortened from 500 ms to 300 ms.

**Data processing.** As before, to enable comparison across experiments, we excluded trials from our orienting data analysis with reaction times that were greater than 1500 ms. This resulted in excluding 15 out of 1295 trials from the first block, and 22 out of 1408 trials from the second block.

## Results

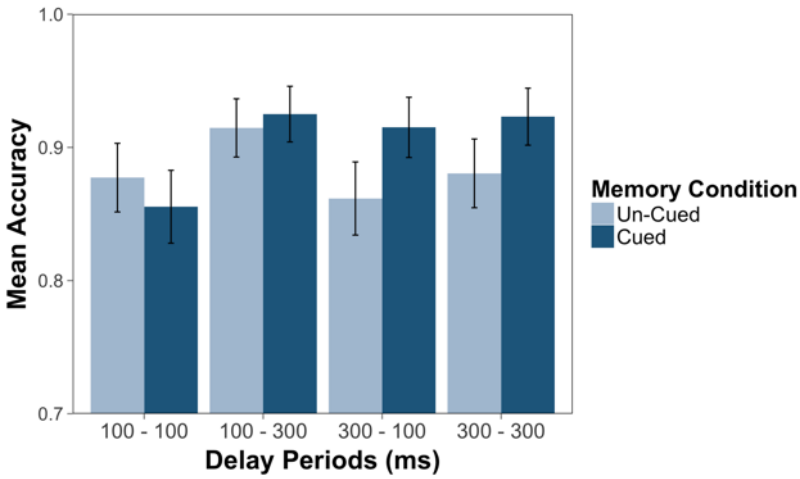
**Successful learning of target locations.** As in our previous experiments, converging evidence from our targets-missed and search-time analyses suggest that participants learned the location of the targets across search blocks. Two repeated-measures ANOVAs examining the number of targets missed and average search speed with learning block as a within-subjects factor revealed that participants found increasing numbers of targets as the task proceeded, $F(2, 30) = 19.1$, $p < .001$, $\eta^2 = .560$, with increasing speed, $F(2, 30) = 153.5$, $p < .001$, $\eta^2 = .911$.

**Explicit memory for target locations.** As in Experiment 3, participants performed above chance on the explicit test of location memory, $t(15) = 29.9$, $p < .001$, correctly remembering an average of 78.9% ($SD$ = 7.9%) of the target locations. On average, participants clicked 132.5 pixels ($SD$ = 63.7 pixels) away from the correct location. Furthermore, participants' search time slopes correlated with their memory imprecision, $r(16) = -.70$, $p = .003$, such that participants whose speed improved the most over the course of the three blocks also demonstrated more precise memories for the target locations.

**Effects of visual event timing on attention orienting.** Next, we examined how memory cues and static visual cues influenced attention orienting when novel visual events occurred at different times within the orienting trial, using the same mixed-effects modeling approach as in Experiment 3. Both our accuracy and reaction-time models included memory condition, delay 1, and delay 2 as fixed effects and subject as a random intercept. Our reaction-time model further included scene as a random intercept.

As in Experiment 3, we observed a main effect of delay 2 on orienting accuracy, $\chi^2(1) = 14.4$, $p = .0001$ (Figure 13). Participants were more accurate to respond on trials in which delay 2 was long ($M$ = .91, $SD$ = .29) relative to trials in which the delay 2 was short ($M$ = .86, $SD$ = .34). Additionally, we observed a main effect of cue condition on orienting accuracy, $\chi^2(1) = 6.3$, $p = .01$, such that participants responded more accurately on cued trials ($M$ = .90, $SD$ = .30) relative to un-cued trials ($M$ = .87, $SD$ = .33). Both these effects were qualified by a delay 2 x cue condition interaction, $\chi^2(1) = 4.7$, $p = .03$, such that the effects of cue condition on orienting accuracy were greater when delay 2 was longer (Figure 13; Table 10). No other effects were significant ($p$s > .10).

A.




B.

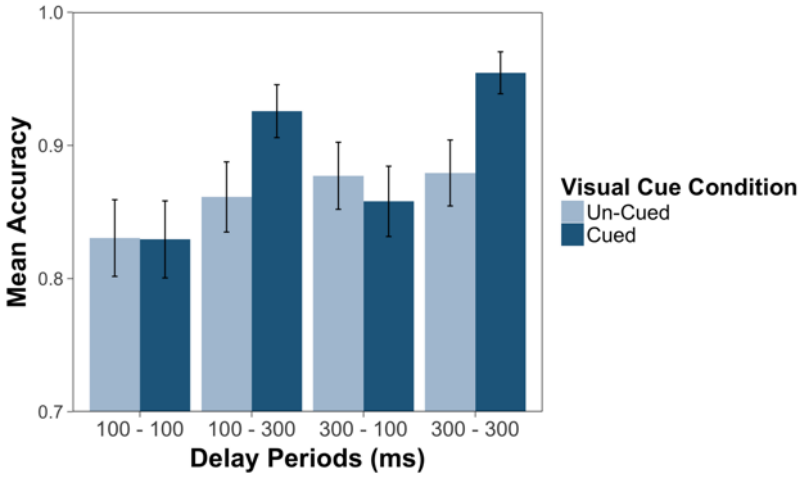
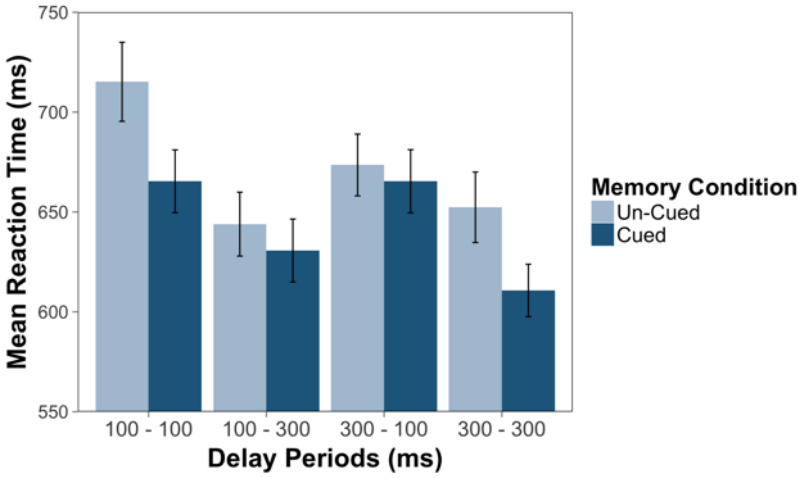



**Figure 13.** Within both the memory-cued block (A) and the visually cued block (B), participants responded more accurately on cued relative to un-cued trials. The effect of cue condition on orienting accuracy was greater when the delay 2 duration was long relative to short. Error bars indicate standard error.

We next analyzed our reaction-time data. As in Experiment 3, there was a main effect of orienting block, $F(1, 172.6) = 6.5$, $p = .01$. Here, however, participants responded more quickly on trials in the memory-cued block ($M = 656.8$ ms, $SD = 196.1$ ms) relative to trials in the visually cued block ($M = 678.0$ ms, $SD = 190.6$ ms). Additionally, participants also were faster to respond on trials in which delay 2 was long ($M = 649.8$ ms, $SD = 191.2$ ms) relative to short ($M = 686.7$ ms, $SD = 194.3$ ms), $F(1, 2213.7) = 25.5$,

$p < .0001$. Across blocks, participants were also faster to respond on cued trials ($M$ = 651.6 ms, $SD$ = 187.1 ms) relative to un-cued trials ($M$ = 684.3 ms, $SD$ = 198.6 ms), $F(1, 2224.4) = 19.8$, $p < .0001$ (Figure 14; Table 10). No other effects reached significance ($p$s > .12).

A.




B.

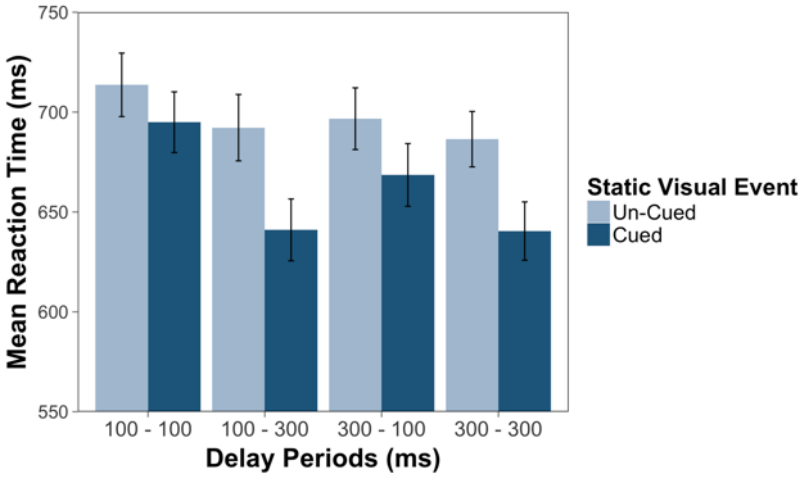



**Figure 14.** Across both the memory-cued block (A) and the visually cued block (B), participants responded more quickly on cued relative to un-cued trials. Error bars indicate standard error.

Table 10

*Orienting accuracy and reaction-time means (and standard deviations) across orienting blocks, cue conditions and delay periods*

| Orienting Block | Cue Condition | Delay 1 | Delay 2 | Accuracy | Reaction Time (ms) |
|---|---|---|---|---|---|
| Block 1: Memories | Cued | Short | Short | .86 (.35) | 665.4 (187.3) |
| | | Short | Long | .93 (.26) | 630.7 (191.7) |
| | | Long | Short | .92 (.28) | 665.4 (187.2) |
| | | Long | Long | .92 (.27) | 610.7 (157.2) |
| | Un-Cued | Short | Short | .88 (.33) | 715.2 (236.5) |
| | | Short | Long | .91 (.28) | 643.9 (196.0) |
| | | Long | Short | .86 (.35) | 673.6 (181.1) |
| | | Long | Long | .88 (.33) | 652.4 (209.0) |
| | | | | | |
| Block 2: Static Visual Cues | Cued | Short | Short | .83 (.38) | 695.0 (180.6) |
| | | Short | Long | .93 (.26) | 641.0 (197.0) |
| | | Long | Short | .86 (.35) | 668.6 (192.8) |
| | | Long | Long | .95 (.21) | 640.5 (189.4) |
| | Un-Cued | Short | Short | .83 (.38) | 713.7 (189.4) |
| | | Short | Long | .86 (.35) | 692.2 (202.9) |
| | | Long | Short | .88 (.33) | 696.7 (189.2) |
| | | Long | Long | .88 (.33) | 686.5 (171.6) |

## Experiment 4 Discussion

In Experiment 4, we reduced the duration of our "long" delay periods from 500 ms to 300 ms. Though this small change resulted in somewhat different statistical effects of both memories and static visual cues on attention across Experiments 3 and 4, the overall pattern of results that we observed support the same general conclusion: longer delay periods *after disruption* strengthen the effect of both memory cues and visual cues on attention.

These data suggest that both memory and visual cuing effects may be susceptible to disruption, at shorter relative to longer time intervals. The disruption of spatial attention by a transient visual event is consistent with past studies. For example, recordings from neurons in monkey extrastriate cortex show that the sudden onset of a transient visual event temporarily disrupts neural activity associated with attending to an endogenously cued location about 120 ms after its onset (Busse, Katzner, & Treue, 2008).

It is also worth noting that we originally hypothesized that in our task, the duration of delay 1 may exert a greater influence on memory-guided attention if delay 2 was shorter. In other words, if participants had more time to form a robust representation of the cued location prior to disruption, we expected that they might be able to reorient to that location more quickly, such that we would observe an effect of cue condition at an intermediate delay 2 duration (300 ms) when delay 1 was long (300 ms) but not when delay 1 was short (100 ms). However, this is not what we observed. Participants demonstrated a statistically equivalent influence of cue condition on accuracy and reaction times across delay 1 durations.

## GENERAL DISCUSSION

Across two experiments, we explored how the *timing* of a salient, distracting visual event influences memory-guided attention. Furthermore, within each experiment, we ran an identical task using visual cues instead of memory cues to determine which of our effects were specific to memory-guided attention. The different pattern of participant accuracy and reaction times that resulted from changes in duration to the first and second part of the cue-to-target interval, broadly, confirmed our hypothesis: memory-guided attention is a dynamic process, with timing differences of milliseconds influencing the

extent to which participants were able to retrieve spatial memories and use them to orient attention.

As discussed previously, it is difficult to tease apart whether the transient visual event interrupted memory retrieval, orienting to the location cued by memory, or a combination of both processes. However, the similar pattern of results we observed across trials that engaged memory-guided attention and trials that engaged visually guided attention suggest that the transient visual event primarily disrupted *orienting* rather than *retrieval* processes. Still, though longer intervals after the onset of a salient distractor strengthened the influence of both memory cues and visual cues, some of our results suggest that the influence of memory on attention recovered more slowly. For example, in Experiment 3, we observed an orienting block x cue condition x delay 2 interaction, such that visual cues enhanced orienting accuracy across *both* delay 2 durations, while memory cues only enhanced accuracy when delay 2 was long.

What accounts for these differences across cue types? One possibility is that while the transient visual event engaged a competing spatial bias on trials with both visual cues and memory cues, on memory-cued trials specifically, it further distracted from or disrupted the retrieval of a robust representation of the relevant location memory (Fernandes & Moscovitch, 2000; Wais & Gazzaley, 2011; Wais, Rubens, Boccanfuso, & Gazzaley, 2010). Interestingly, studies investigating whether visual distraction impairs memory retrieval have found mixed results (Craik, 2014). Though visual distraction may interfere with the fidelity of the representations of retrieved from long-term memory (Wais & Gazzaley, 2014), effects of visual distraction on retrieval are generally small (Craik, 2014). Representations stored in working memory are similarly robust to interference from visual distraction (Bettencourt & Xu, 2015).

A more plausible explanation may be that relative to visually guided attention, memory-guided attention relies more heavily on cognitive control systems that enable the rapid transition between memory retrieval and spatial orienting (Rosen et al., 2016; Stokes et al., 2012). Rather than interfering with memory retrieval per se, the onset of a transient visual event may have placed additional attentional control demands on the system, particularly if participants were attempting to actively suppress interference from the distracting stimulus (Demeter & Woldorff, 2016; Suzuki & Gottlieb, 2012). These demands may have more severely impacted memory-guided attention relative to visually guided attention in our task, particularly because our visual cues were also salient, and as such may have engaged simpler, exogenous orienting processes that do not rely on the top-down engagement of attentional control processes (Chica et al., 2013).

One limitation of our current study is that the visual cues we used likely engaged elements of both endogenous and exogenous orienting, muddling our interpretation of how memory-guided attention orienting from either of these two forms of attention. The cues we used were predictive, and participants were explicitly told to attend to the locations at which they appeared, so they likely engaged *voluntary* or *endogenous* orienting mechanisms (Posner, 1980). But they also appeared peripherally, and comprised highly salient red boxes, so they likely engaged involuntary, reflexive, or exogenous mechanisms as well (Chica et al., 2013; Posner, 1980). That said, we chose to use these cues because like memories, they involve placing a salient trace at a specific location in a scene. Memories themselves may rely on behavioral tags that also engage both involuntary and voluntary orienting.

Furthermore, in our task, the visually cued orienting block always came *after* the memory-guided orienting block. This was done so as not to interfere with participants' memory representations by presenting them with novel scenes prior to the memory-cued

block. However, this means that cue type and block order were perfectly confounded in our task. Though unlikely, it is possible that the differences we observed between visual cues and memory cues were due to block order, rather than cue type. For example, participants may have become better at using cues throughout the orienting tasks, such that they were able to benefit from the visual cues at shorter intervals in the second orienting block. Future studies should de-confound these two variables by interspersing different types of cues throughout the orienting task.

# 4. Baseline differences in memory-guided attention in adults and children at short time scales

*An edited version of this chapter is in revision at Child Development*: Nussenbaum, K., Scerif, G.* & Nobre, A.C.* (in revision). Salient visual events disrupt memory-guided attention in adults but not children.

Thus far, our experiments in Chapters 2 and 3 have revealed several novel insights. First, in the experiments in Chapter 2 we observed that the onset of a transient visual event disrupted memory-guided attention in adults but not children. Second, in the experiments detailed in Chapter 3 we found that this disruption was temporary — with a long enough time between the onset of the transient visual event and the target, adults demonstrated an influence of memory on attention, as measured by greater accuracy and faster reaction times on cued relative to un-cued trials. One key question that remains, then, is why children but not adults are able to use memories to guide attention even when transient visual events occur at short intervals prior to target onset.

One possibility is that the transient visual event interfered with memory-guided attention to a greater extent in adults than children. School-aged children demonstrate a gradual increase in the speed at which they are able to orient attention over development (Schul et al., 2003). As such, at fast time-scales, they may not have had time to fully disengage from the location cued by memory and reorient to the transient visual event. If that were the case, when the target appeared, their attention may have continued to linger

on the location cued by the memory, whereas adults may have fully reoriented to the transient visual event.

Still, before we can reach this conclusion, it is important to determine whether any baseline differences exist in terms of the extent to which memories influence attention *in the absence of transient visual events* across children and adults. Previous literature has described memory-guided attention in children as less robust than memory-guided attention in adults (Couperus et al., 2011; Vaidya et al., 2007). In large part, this description has arisen from the mixed findings for memory-guided attention in children across different studies (Couperus et al., 2011; Dixon et al., 2010; Vaidya et al., 2007; Yang & Merrill, 2015). However, very few studies have directly compared memory-guided attention in children and adults using the same tasks across age groups. Furthermore, as previously mentioned, all published work on memory-guided attention in children has used contextual cuing paradigms; as such, it is impossible to determine whether any developmental differences observed in these tasks are due to differences in learning rate, memory fidelity, or the *use* of memory to guide attention.

Thus we conducted an experiment in which a group of school-aged children and a group of healthy young adults completed identical tasks, modeled after those used in Chapter 2. Here, adults also completed the "gamified" version of the tasks with Mario characters, to mitigate the influence of stimuli which may have been more rewarding (Doallo, Patai, & Nobre, 2013). Additionally, no transient visual events occurred at orienting. Instead, all participants simply saw a scene with an associated memory for 250 ms prior to target onset. We hypothesized that participants in both age groups would demonstrate an influence of memory on attention-orienting, but that, consistent with Experiment 1, adults would demonstrate both more precise memories for target locations

in the location memory test, as well as show a greater difference in performance across cued and un-cued trials during orienting.

## EXPERIMENT 5

## Methods

**Participants.** This study was approved by the University of Oxford Central University Research Ethics Committee (CUREC). Twenty-eight adults (Mean age = 20.0 years, STD = 1.4 years; Range: 18.4 – 25.2 years; 17 females) with normal or corrected-to-normal vision and no known history of psychiatric or learning disorders, participated in the study. Twenty-seven school-aged children (Mean age = 9.0 years, STD = 1.4 years; Range: 7.1 – 11.7 years; 13 females) also participated. Six additional children were tested but excluded from all analyses due to failure to complete all of the tasks.

Adult participants were recruited from the University of Oxford's undergraduate subject pool and from the surrounding community. They gave informed consent prior to participation in the study and were compensated at a rate of either £8 per hour or with research participation credit. Child participants were recruited from advertisements sent to local schools, and from the lab database. They gave informed assent prior to participation in the study, and their parents gave informed consent. Children received a certificate for participation.

**Stimuli.** Stimuli for the task comprised a subset of those used in Experiment 3. This experiment comprised only one orienting block with 88 trials. As such, we selected 88 scene images from the group of stimuli used in the prior experiments.

**Procedure.** ***Learning phase & Location-memory test.*** The learning phase and location memory test were identical to those in Experiments 1 – 4. Stars were 25 x 25 pixels for both children and adults.

***Orienting.*** After the location-memory test, participants completed the orienting task. As in our previous experiments, participants were told to discriminate a small grey square or circle target that appeared on every trial using a standard keyboard.

On every trial, participants first viewed a scene with an associated memory. Then, after a 250-ms delay period, the target appeared for 200 ms. Participants had an additional 1300 ms to respond to the target, during which time the scene remained on the screen. On half (44) of the 88 orienting trials, the scene with the associated memory cued the target location. On the other half (44) of trials, the target appeared at a random location on the opposite hemifield of the screen as the location cued by the memory.

As in our previous experiments, participants were explicitly told that the memory association would sometimes indicate the target location. They were also instructed to keep their eyes fixated on the central cross that appeared on top of all orienting stimuli. Participants were told to respond to the target stimuli as quickly and as accurately as possible. Before beginning the real trials, participants completed 20 trials to practice the button-press responses in which they saw the grey targets appear on top of a black screen.

**Counterbalancing.** Presentation of the scenes was counterbalanced across participants, such that they appeared with equal chance in the two orienting conditions (cued, un-cued) (Table 11). The location of the learning target was counterbalanced across both participants and scenes, such that each participant saw half of the learning targets (44) on the right and half (44) on the left, and for each scene the target appeared on the right for half of the participants and the left for half of participants (Table 11). Within

each half of the screen, the specific location of the learning target was randomized. The location of the orienting target and the identity of the orienting target was randomized for each scene, but counterbalanced within conditions for each participant.

Table 11

*Task counterbalancing*

| | | | | |
|---|---|---|---|---|
| *Learning:* Target location | 44 Left | | 44 Right | |
| *Orienting:* Memory association | 44 Left | | 44 Right | |
| *Orienting:* Target Location | 22 Left | 22 Right | 22 Left | 22 Right |
| Memory Condition | Cued | Un-Cued | Un-Cued | Cued |

**Variables of interest.** ***Learning phase and location-memory test.*** We extracted three measures of participants' learning of the target locations across the three blocks: targets missed, search time, and search time slope. When we compared learning performance across children and adults in Experiment 1 we used z-scores; however, here children and adults searched for targets of an identical size. In order to examine absolute differences in search speeds across age groups, we did not normalize our variables. As before, only trials in which the target was found across all three blocks were included in the search-time analysis (*Mean number included*: 64.6 trials; *Range:* 40 - 80 trials).

Additionally, we extracted two measures of participants' explicit memory for the target locations: memory imprecision and memory accuracy. As before, trials in which participants failed to find the target at least once during the Learning Phase were excluded from the analysis (*Mean number included*: 81.5 trials; *Range:* 66 - 88 trials).

***Orienting.*** For the first orienting block, only trials in which the target was found at least once during the learning phase were included. As in Experiment 1, we analyzed three measures to determine the effects of cue condition on attention orienting: accuracy, accuracy with missed trials excluded, and reaction time. Even when missed trials were excluded, the performance of two children was still statistically indistinguishable from chance level (Chance level: 50%). Thus, they may not have tried to perform the task correctly and instead pressed random buttons. As such, these participants were excluded from the orienting analyses.

Reaction time was calculated as the time from target onset to button-press response. Only accurate trials were included (*Mean number included*: 65.3 trials; *Range:* 36 - 83 trials).

## Results

**Successful learning of target locations.** Converging evidence from our targets-missed and search-time analyses suggest that both children and adults learned the location of the targets across search blocks.

A repeated-measures ANOVA examining the number of targets missed with learning block as a within-subjects factor and age group as a between-subjects factor revealed that both children and adults found increasing numbers of targets as the task proceeded, $F(1.8, 94.3) = 163.0$, $p < .0001$, $\eta^2 = .755$. (Figure 15A). There was also a main effect of age group, with children missing more targets than adults across blocks, $F(1, 53) = 26.7$, $p < .0001$, $\eta^2 = .335$. Finally, there was also a block x age group

interaction, $F(1.8, 94.3) = 7.4$, $p = .001$, $\eta^2 = .123$, with children demonstrating greater improvement across blocks relative to adults (Figure 15A).

Additionally, a repeated-measures ANOVA examining the effects of learning block and age group on search times revealed that both children and adults demonstrated faster search times across learning blocks, $F(1.5, 81.2) = 283.8$, $p < .0001$, $\eta^2 = .843$ (Figure 15B). Additionally, adults demonstrated overall faster search times across blocks, $F(1, 53) = 15.0$, $p = .0003$, $\eta^2 = .221$. Here however, there was no significant learning block x age group interaction, $F(1.5, 81.2) = 2.9$, $p = .076$, $\eta^2 = .051$.

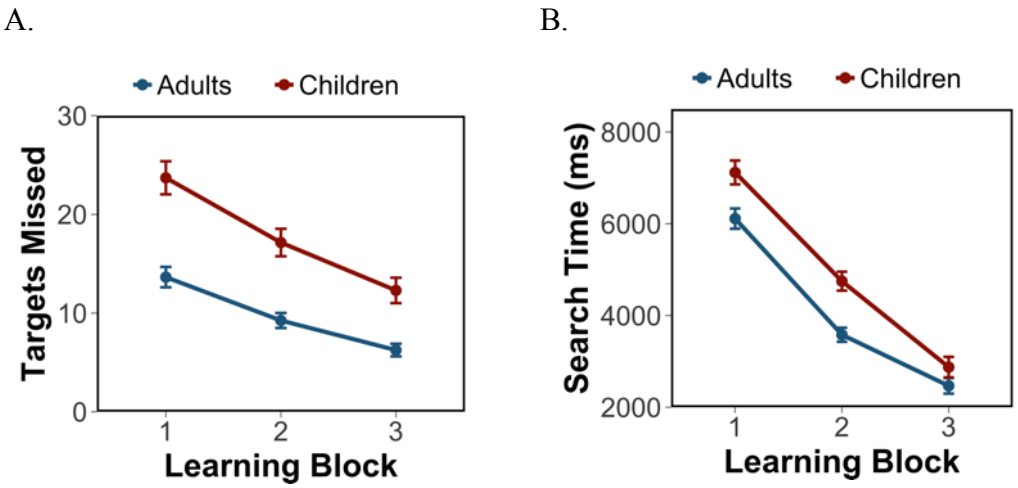



**Figure 15.** Adults and children both found increasing numbers of targets (A) with increasing speed (B) across learning blocks. Error bars indicate standard error.

**Explicit memories for target locations.** We next analyzed whether children and adults formed explicit memories for the target locations to a similar extent. One-sample t-tests examining memory accuracy revealed that accuracy for both groups was significantly above chance level (4%); Adults: $t(27) = 17.5$, $p < .0001$; Children: $t(26) = 16.0$, $p < .0001$.

There was no statistically significant difference in memory accuracy between adults ($M$ = .72, $SD$ = .45) and children ($M$ = .66, $SD$ = .48), $t(53.0) = 1.1$, $p = .29$, nor was there a reliable difference in memory imprecision between adults ($M$ = 132.9 pixels, $SD$ = 224.4 pixels) and children ($M$ = 171.2 pixels, $SD$ = 269.8 pixels ), $t(51.7) = 1.2$, $p = .23$. Thus we observed no evidence to suggest that adults and children formed memories for the target locations that systematically varied in their precision based on age group.

Additionally, we examined whether participants' search-times slopes — measures of their ability to learn the location of the targets throughout the Learning Phase — correlated with their memory imprecision on the explicit location memory test. For both adults and children, there were significant correlations between participants' search-time slopes and memory precision; *Adults:* $r(26) = -.38$, $p = .043$ (Figure 16), *Children:* $r(25) = -.87$, $p < .0001$ (Figure 16).

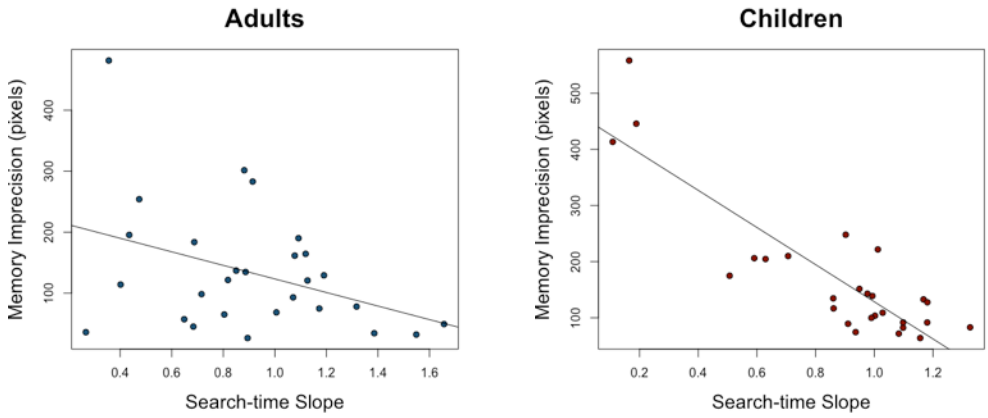



**Figure 16.** Search-time slopes were negatively correlated with memory imprecision across both adults and children, indicating that participants whose speed in finding the targets increased the most across learning blocks also demonstrated the most precise memories for the target locations during the location-memory test.

This analysis indicates that participants who showed evidence of fastest learning during the first part of the experiment also demonstrated the greatest memory precision

(*lower* values indicate higher precision) in the second part. These data suggest that the decreasing numbers of missed targets and increasing search speeds we observed across learning blocks at least partially index learning of the target locations, and not just improvement in performing the search task with practice.

**Effects of memories on attention orienting.** We next turned to our main question of interest: How do memories influence attention across children and adults? To address this question, we analyzed orienting accuracy and reaction times across memory cue conditions and age groups.

As in previous chapters, we analyzed our orienting data with mixed models using the lme4 package and the afex package in R (Bates et al., 2015; Singmann et al., 2015). As before, to determine the random effects structures of our models, we followed the "forward-stepping-best-path" approach recommended in Barr et al. 2013 (Barr et al., 2013). To determine how memory condition influenced orienting accuracy across age groups we constructed a logistic mixed-effects model. Our final model included our fixed effects of interest (memory condition with two levels: cued and un-cued) and age group with two levels: adults and children), random intercepts for subject and scene, and allowed for different slopes for cue condition across scenes. A likelihood-ratio test indicated that including age group improved model fit, $\chi^2(1) = 37.6$, $p < .0001$. Across conditions, children ($M = .72$, $SD = .45$) responded less accurately than adults ($M = .86$, $SD = .34$). There was no effect of memory condition on orienting accuracy, nor was there an age group x memory condition interaction effect, $p$s > .25.

We next analyzed our reaction-time data. Our linear mixed-effects model for reaction time included our fixed effects of interest (memory condition with two levels: cued and un-cued) and age group with two levels: adults and children) and random

intercepts for subject and scene. As with our accuracy data, we observed a main effect of age group, with children ($M$ = 739.5 ms, $SD$ = 201.9 ms) responding more slowly across conditions than adults ($M$ = 588.6 ms, $SD$ = 163.2 ms), $F(1, 50.1) = 32.0$, $p < .0001$. We also observed a main effect of memory condition, such that participants responded more quickly on cued ($M$ = 642.9 ms, $SD$ = 189.9 ms) relative to un-cued trials ($M$ = 655.6 ms, $SD$ = 198.6 ms), $F(1, 3295.1) = 7.5$, $p = .006$. However, this effect was qualified by a memory condition x age group interaction effect, $F(1, 3295.2) = 4.1$, $p = .04$ (Figure 17).

To interpret this interaction, we ran separate models for adults and children. Including memory condition only improved model fit for our child model, such that memories that cued the target location facilitated faster orienting reaction times, $F(1, 1309.3) = 7.8$, $p = .005$. Adults did not demonstrate an effect of memory condition on reaction times during orienting, $F(1, 1942.3) = .39$, $p = .53$. These analyses indicate that, despite forming similarly precise memories for the target locations, children's attention orienting was significantly influenced by these memories while adults' orienting was not.

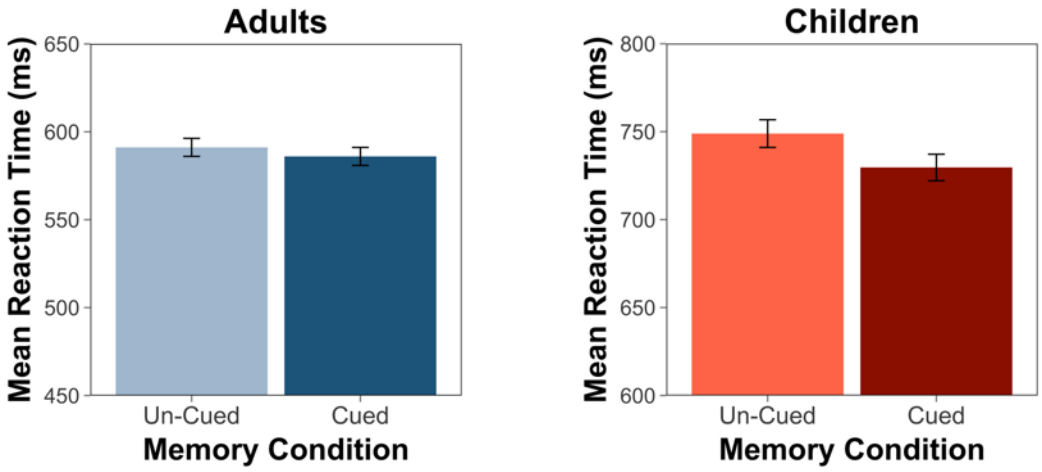



**Figure 17.** While adults demonstrated no effect of memory condition on orienting reaction times, children responded more quickly on cued relative to un-cued trials. Error bars indicate standard error.

To examine further the effects of memory on orienting reaction times, we re-ran our reaction-time model but replaced the categorical predictor memory condition with a continuous measure of memory distance, as in Experiment 1.[2] Our final reaction-time model included our fixed effects of interest: memory distance and age group with two levels (child, adult), as well as random intercepts for subject and scene. As with our categorical model, we observed a main effect of age group, with children responding more slowly than adults, $F(1, 29.7) = 55.5$, $p < .0001$. Additionally, we observed a main effect of memory distance, $F(1, 3313.4) = 10.1$, $p = .002$ (Figure 18). Here, there was no memory distance x age group interaction, $p > .75$. With this more sensitive measure, both children and adults demonstrated an effect of memories on attention: when the orienting target appeared closer to the remembered location, participants across age groups responded to it more rapidly.

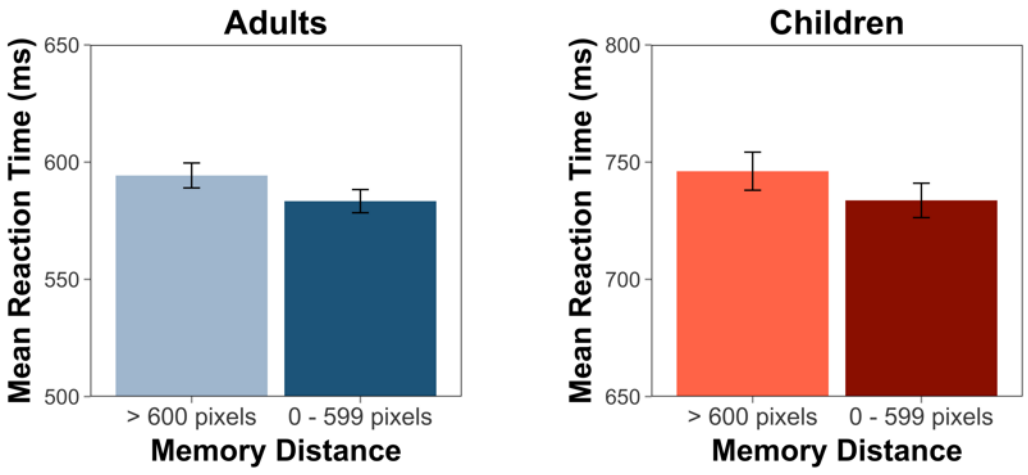



**Figure 18.** At orienting, both adults and children responded more quickly to targets that appeared closer to the memory location they associated with the scene. Error bars indicate standard error.

[2] We similarly tried to re-run our accuracy model with the continuous measure of memory distance, but could not find a model that converged.

# DISCUSSION

The current study aimed to extend our findings from Experiment 1 by comparing memory-guided attention in children and adults in isolation, without other sources of orienting present. Previously, we found that when salient visual events occurred during orienting, children used memories to orient their attention while adults did not. However, in Experiment 2, we observed evidence that adults *did* use memories to orient their attention in the absence of salient visual events. Thus we hypothesized that the developmental differences we observed were primarily due to children and adults responding differently to the presence of the salient events. Without the source of exogenous orienting, we hypothesized that adults would demonstrate a *stronger* influence of memory on attention.

However, in the current experiment, we observed the opposite effect. Children demonstrated a stronger effect of memory condition on orienting reaction times. The effects of memories on attention-orienting in adults did not reliably emerge when we examined the influence of memory condition; they were only unveiled with the more sensitive, continuous measure of memory distance.

Our failure to observe an effect of memory condition on attention-orienting in adults is puzzling because many previous studies using similar tasks have found enhanced target sensitivity and faster target reaction times on memory-cued relative to un-cued trials (Patai et al., 2012; Salvato et al., 2016; Stokes et al., 2012; Summerfield et al., 2006, 2011). First, it is important to note that even true effects in adequately powered (80%)

studies[3], have a 20% chance of not being observed, and so we would expect some samples of participants to not demonstrate reaction time differences between cued and un-cued trials. It may also be the case that aspects of our task design that different from previous studies (i.e. using a discrimination rather than a detection task; using a slightly larger orienting target; incorporating a potentially distracting, child-friendly narrative) prevented adults' from using memories to guide attention. Still, this is unlikely because we used a nearly identical design in Experiment 2, in which we *did* observe the expected effects.

Though further studies should attempt to replicate our findings, our data support the idea that contrary to our initial hypothesis, at short time-scales, the effects of memories on attention-orienting are more robust in children than adults. There are several possible reasons why this may be the case. First, previous studies have found that individuals use both exogenous and endogenous cues to a greater degree when orienting tasks are more difficult (Berger et al., 2005; Snowden, Willey, & Muir, 2001). For example, Berger et al. (2005) found that when a discrimination task was more difficult, participants demonstrated a larger endogenous cuing effect. Our accuracy and reaction-time data suggest that children found our orienting task more difficult than adults. Thus, it may simply be the case that children relied more on orienting cues than adults to perform the task.

This possibility raises one challenge in the design of cross-age-group experiments. Should tasks be identical? Or should task difficulty be normalized across groups? Both

[3] We did not calculate power *a priori* because given our novel task design, we did not have good estimates for the effect size and response variances. Instead, we based our sample size on the higher end of those used in previous studies of memory-guided orienting, which have typically included between 12 – 25 participants per age group (Salvato et al., 2016; Stokes et al., 2012; Summerfield et al., 2006). We aimed for 28 participants per age group in order to cycle through all four counterbalanced designs.

approaches have advantages and disadvantages. To simplify our interpretation of our results, we used identical tasks. But future studies could probe the influence of task difficulty on the use of memory cues by manipulating difficulty within subject or within age group. For example, smaller or more translucent orienting targets could be used on some trials, to see if boosting task difficult in adults made both performance, and the effects of memory condition, more comparable to that of children.

It is also possible that children simply rely on past experiences to orient their attention to a greater degree than adults, particularly in time frames as short as that used in this task. Though past work has suggested that memory-guided attention is less robust in children (Couperus et al., 2011; Vaidya et al., 2007), and that the neural systems supporting cognitive control and episodic memory are still developing throughout middle childhood (Ghetti & Bunge, 2012; Johnson et al., 2014), very little work has directly compared memory-guided attention in these two age groups using the same task. It may even be the case that the relative immaturity of children's memory systems may lead to *greater* use of memories to orient attention. Children demonstrate less flexibility in their retrieval of episodic memories (DeMaster, Coughlin, & Ghetti, 2016; Levy-Gigi & Vakil, 2010; Townsend, Richmond, Vogel-Farley, & Thomas, 2010). For example, DeMaster et al. (2016) had 8-year-olds, 10-year-olds, and young adults complete a task in which they encoded pairs of objects. At retrieval, the positions of some of the old object pairs were flipped, such that the item that was previously above was now presented below the other item. These change in positions did not affect memory performance in 10-year-olds or young adults, but 8-year-olds demonstrated significantly better memory performance when the items were presented in their original positions, suggesting that younger children's memory retrieval may be particularly impaired by contextual changes. In our task then, it may be the case that adults' representations of the initial scene and target star

were more flexible such that the scene and its associated location were less strongly bound. Thus, when the scene later appeared at orienting, adults may not have been as impaired at identifying objects presented in new, un-cued locations. In other words, children's more rigid representations of episodic information *may* lead to stronger effects of contextual information on future behavior, though much more work is needed to determine if this is in fact the case. One simple starting point could be to have the same participants complete a contextual memory task and a memory-guided orienting task to determine if participants most impaired by contextual changes at retrieval also demonstrate the strongest cuing effects of memories on attention.

Finally, our results from Experiment 5 can help clarify our interpretation of Experiment 1. We previously suggested that salient visual events may disrupt memory-guided attention to a greater degree in adults than in children. These data suggest that the reason that may be the case is because the effects of memories on attention are weaker than adults. It is possible that salient visual events *equally* disrupt memory-guided attention in adults and children, but that the greater magnitude of the effect in children means that they emerge even when weakened.

# 5. Effects of memory-guided attention on subsequent recognition memory

Up to this point, the experiments described in this thesis have addressed how different combinations of cues influence where people orient their attention. Implicit in these investigations is the assumption that these orienting behaviors have downstream, functional consequences. When thinking about the development of complex cognition, one particularly relevant aspect of attention is its role in facilitating future encoding. But the role of memory-guided attention in shaping the formation of subsequent memories has never before been examined. The aim of this series of experiments was to investigate how memory-guided attention influences *subsequent* memory for novel information. Specifically, we sought to determine how the enhanced perceptual processing associated with learned target locations influences participants' ability to encode novel information presented in those locations.

As described in the general introduction, previous work has demonstrated that when people learned the location of a target stimulus embedded within a natural scene, their perception of targets subsequently presented in the learned location was enhanced relative to those presented in unlearned locations (Summerfield et al., 2006). The presentation of a scene with an associated memory elicits changes in anticipatory neural activity, reflected in reduced alpha-band power in electrodes contralateral to the expected, target location relative to ipsilateral electrodes (Stokes et al., 2012; Summerfield et al., 2011). Additionally, memory cues have also been shown to elicit increased preparatory activity in frontal, parietal, and visual regions (Stokes et al., 2012, see also Rosen et al., 2015). Critically, these differences in anticipatory activity modulate target processing:

When targets appear in expected relative to neutral locations, early visual potentials (P1) are magnified, indicating that the anticipatory neural activity elicited by the cue leads to differences in the visual processing of expected vs. unexpected stimuli (Summerfield et al., 2011).

Beyond this work examining the effects of memories on attention, a separate body of research has found that attention exerts a strong influence on the degree to which people form memories for visual information (Hauer & MacLeod, 2006; Uncapher & Wagner, 2009). Unsurprisingly, individuals are better at encoding attended relative to unattended information (Ballesteros et al., 2006). Additionally, the degree to which the frontal-parietal attention network modulates activity in the visual cortex during encoding predicts subsequent memory (Hauer & MacLeod, 2006; Markant et al., 2015)

Taken together, these two bodies of work suggest that spatial memories may enhance individuals' ability to encode novel information by facilitating attention toward relevant locations. In other words, if individuals learn to attend to a specific spatial location within a scene, the orienting mechanisms they recruit when they are cued by that scene may not only enhance perception but may also enhance subsequent memory for novel information presented at that learned location. However, prior work has also found that older memories may compete and interfere with processing similar, newer information (Badre & Wagner, 2005; Bjork, 1978; Jonides & Nee, 2006). It may be the case, then, that prior experiences and their associated memories enhance perception *but not* encoding of novel information presented in remembered locations.

Therefore, we designed three experiments to determine whether memory-guided attention enhances or interferes with subsequent encoding of novel information. The basic structure of these experiments mirrored those used in the studies described in previous

chapters. First, participants completed a learning task in which they searched for small targets hidden within naturalistic scenes over three blocks. Then, they completed an explicit memory test that probed their memories for the target locations. Next, participants completed an orienting task, in which they had to discriminate targets presented in either memory-cued or un-cued locations. Critically, in these studies, the targets presented during orienting were all unique objects. Lastly, participants completed another test of recognition memory. In these experiments, their memories for the unique objects presented at orienting was probed. We hypothesized that in addition to discriminating memory-cued items more accurately and quickly relative to un-cued items, participants would also more strongly encode these items, as demonstrated by better performance on our final test of recognition memory.

Furthermore, in Experiment 6, we additionally compared the effects of memories to the effects of visual cues on orienting and encoding. Given that memory-guided attention may involve greater engagement of top-down control processes than visually guided orienting, we further expected that memory benefits for cued relative to un-cued items would be greater for items cued by memories relative to those cued visually.

## EXPERIMENT 6

### Methods

**Participants.** This study was approved by the University of Oxford Central University Research Ethics Committee (CUREC). Twenty adults (Mean age = 20.3 years, STD = 2.3 years; Range: 18.3 – 27.3 years; 16 females) with normal or corrected-to-

normal vision and no known history of psychiatric or learning disorders, participated in the study.

Adult participants were recruited from the University of Oxford's undergraduate subject pool and from the surrounding community. They gave informed consent prior to participation in the study, and were compensated at a rate of either £8 per hour or with research participation credit.

**Stimuli.** ***Scene stimuli.*** Stimuli for the task comprised 60 photographs of indoor and outdoor natural scenes acquired from Google images (1920 x 1080 pixels). All 60 of these scenes were used during the learning phase, location memory test, and orienting phase of the study. An additional 60 images were used during the orienting phase of the study, to serve as the background for the visual cues. These 60 background images comprised the 60 scene images but with all of their pixels scrambled. As before, the visual cue comprised a 200 x 200-pixel red square outline.

***Learning target stimulus.*** The learning target was a small gold star prepared in Adobe Photoshop (25 x 25 pixels).

***Orienting and memory test target stimuli.*** Ninety different images of birds and 90 different images of fish were used in the experiment. Of these, 120 were used as target stimuli during the Orienting Task, and 60 were used as novel stimuli during the target memory test. In each orienting condition (memory cued, memory neutral, memory un-cued, visually cued, visually neutral, visually un-cued), half of the images that appeared were birds, and half were fish (Table 1).

All target stimuli were created with photographs obtained from Google image searches. Images were selected such that no species of birds or fish were duplicated (e.g.

only one hummingbird and one clown fish were part of the stimulus set). The images' backgrounds were removed, and they were then sized to 200 x 200 pixels using Photoshop.

***Orienting distractor stimuli.*** One hundred and twenty different images of flowers were used in the experiment as foil stimuli during the orienting task. We included these foil stimuli to mitigate the exogenous cuing effects of the appearance of the target image on the grey target screen. All foil stimuli were created with photographs obtained from Google image searches. The images' backgrounds were removed, and they were then sized to 200 x 200 pixels using Photoshop.

**Procedure.** ***Learning phase.*** Adult participants sat 100 cm away from a 60 x 34-cm computer monitor. They were directed to search through each scene to find a small gold star over the course of three blocks. Additionally, they were instructed to memorize the location of the stars that they found. Participants were instructed to click once when they saw the target star. After they clicked, a cursor would appear, and participants were instructed to move the cursor to click on the star. Participants had 30 seconds to look through each scene, and five seconds to move the mouse to click on the star. If participants successfully clicked within 50 pixels of the star, they then saw a feedback screen that said "Target Found" for 500 ms. If the scene timed out, or if participants clicked on an incorrect location, they saw a feedback screen that said "Target Not Found" for 500 ms.

On twenty out of 60 learning trials, no target star was present. The presentation time for these trials was yoked to previous trials with target stars, such that the scene would remain on the screen for however long it took the participant to find the target star on one of the five previous trials, randomly selected. After these scenes, participants saw a feedback screen that said "No Target Present" for 500 ms.

Participants were given short breaks every 20 scenes. At the end of each block, participants saw a screen that told them how many targets they found, and they had another opportunity to take a break.

***Location-memory test.*** After a short break (3 – 5 minutes), participants were tested on their explicit memory for the target locations. Participants once again viewed the 60 scenes from the learning phase in a random order, but this time the target stars were absent from the scene. Participants were instructed to click when they remembered where the star was, and then to move the cursor to the remembered location and click again. If participants remembered the scene as not having contained a target, they were instructed to click the center of the screen to initiate the mouse, and then click again without moving the cursor. Participants had 30 seconds to initiate the first mouse click, and an additional 10 seconds to move the cursor.

After participants selected the remembered target location, a second screen appeared that asked participants to rate their confidence in the decision that they just made. They used a keyboard to press "1" if they were "not at all confident" that they selected the right location, "2" if they were "fairly confident" they selected the right location, and "3" if they were "very confident" they selected the right location. Participants had a maximum of five seconds to make this response.

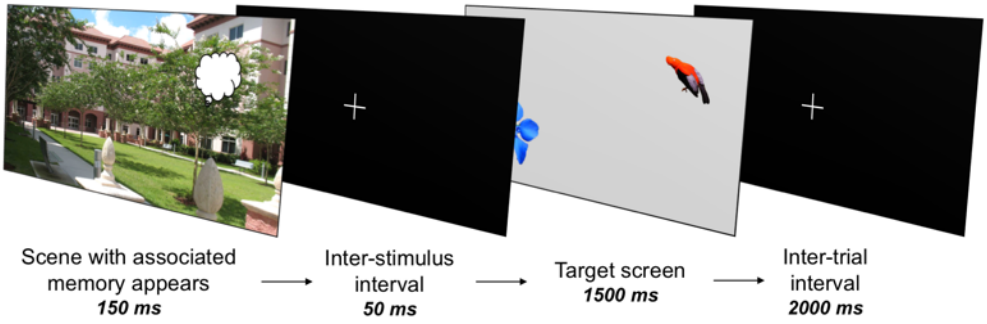
***Orienting.*** After the location memory test, participants completed the orienting task (Figure 19). The task comprised 120 trials. On every trial, participants saw a brief attentional cue (150 ms), followed by a short delay period (100 ms), followed by a target screen, that comprised a grey background with a small picture of either a bird or a fish (1500 ms). During the presentation of the target screen, participants were instructed to press "1" on the keyboard if the image was a fish, and "2" if the image was a bird. They

were instructed to make this response as quickly and as accurately as possible. In addition to the target stimulus, a small picture of a flower, which served as a distractor foil, also appeared on the target screen, located in the opposite vertical and horizontal location from the target. Participants were free to move their eyes and orient overtly. Trials were separated by a black screen with a white fixation cross (2000 ms).

On memory orienting trials, the attentional cue was one of the scene images presented in the learning task (Figure 19A). On visual orienting trials, the attentional cue was a visual event that, after a 50-ms delay, appeared overlaid on a version of a scene image in which all the pixels were randomly scrambled (Figure 19B). Within the memory and visual trials, participants were presented with equal numbers of cued, neutral, and un-cued trials. Cued memory trials were those in which the bird or fish appeared in the same location as the target star in the learning task. Neutral memory trials were those in which the scene that comprised the attentional cue did not contain a star during the learning task. On un-cued memory trials, the bird or fish appeared in a random location on the opposite horizontal side of the screen from where the star was located during learning. On visually cued trials, the bird or fish appeared where the visual event occurred. Neutral visual trials did not contain a visual event. On un-cued visual trials, the bird or fish appeared on the opposite horizontal side of the screen from the visual cue.

Prior to beginning the 120 real trials, participants completed 20 practice trials to ensure that they understood the task and to help them learn the manual button-press responses.

A.




B.

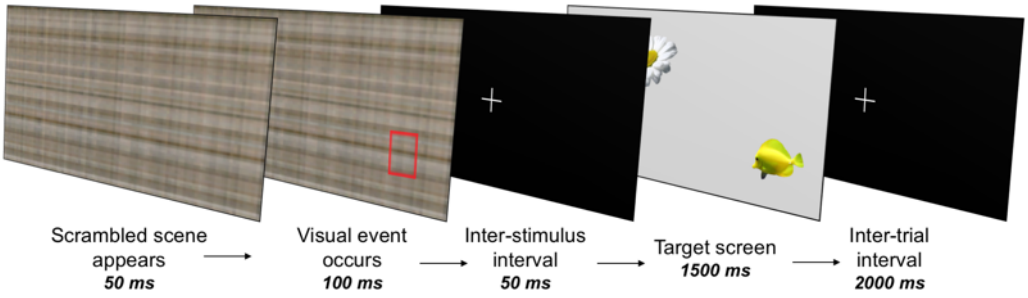



**Figure 19.** In the orienting task, participants experienced both memory-guided (A) and visually guided (B) trials. On memory-guided trials, participants first saw a scene with an associated memory for 150 ms. On visually guided trials, participants first saw a scrambled scene for 50 ms, after which a red square appeared for 100 ms. On both types of trials, after a brief delay (50 ms), a target screen then appeared. The target screen included both a foil stimuli (a flower), and a target bird or fish that participants were instructed to discriminate.

***Target-memory test.*** Participants viewed 180 images of different birds and fish, presented centrally. One hundred and twenty of these images were the birds and fish from the Orienting Task, and 60 of these images were novel birds and fish that the participants had never seen before. On every trial, one image was presented in the center of the screen. Participants' task was to determine if the image presented was new or old, by pressing "1" for new and "2" for old on the keyboard. Participants had 5 seconds to make each response.

The images appeared in a random order at test.

**Counterbalancing.** Presentation of the scenes was counterbalanced across participants, such that they appeared with equal chance in the three memory orienting conditions (memory cued, memory neutral, memory un-cued) (Table 12). The location of the learning target was counterbalanced across both participants and scenes, such that each participant saw half of the learning targets (20) on the right and half (20) on the left, and each scene appeared with a right target for 1/3 of participants, a left target for 1/3 of participants, and no target for 1/3 of participants. Within each half of the screen, the specific location of the learning target was randomized.

In each orienting condition, half of the targets that appeared were birds, and half were fish. The assignment of the target stimuli to the different cueing conditions in the Orienting Task was counterbalanced across participants. The assignment of the distractor stimuli to different trials during the Orienting Task was randomized.

Table 12:

*Task Counterbalancing*

| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Learning:* Target location | 20 Left (L) | | | | 20 Right (R) | | | | 20 No Target | | | | 60 N/A | | | | | | | | | | |
| *Orienting:* Memory association | 20 L | | | | 20 R | | | | 20 None | | | | 60 N/A | | | | | | | | | | |
| *Orienting:* Visual event | 60 N/A | | | | | | | | | | | | 20 L | | | | 20 R | | | | 20 Center | | |
| *Orienting:* Target location | 10 L | | 10 R | | 10 L | | 10 R | | 10 L | | 10 R | | 10 L | | 10 R | | 10 L | | 10 R | | 10 L | | 10 R |
| *Orienting:* Target identity | 5 B | 5 F | 5 B | 5 F | 5 B | 5 F | 5 B | 5 F | 5 B | 5 F | 5 B | 5 F | 5 B | 5 F | 5 B | 5 F | 5 B | 5 F | 5 B | 5 F | 5 B | 5 F | 5 B | 5 F |
| Target cued by memory? | Yes | | No | | No | | Yes | | No | | | | N/A | | | | | | | | | | |
| Target cued by visual event? | N/A | | | | | | | | | | | | Yes | | No | | No | | Yes | | No | | |
| Cue Type | Memory | | | | | | | | | | | | Visual | | | | | | | | | | |
| Cue Condition | Cued | | Un-Cued | | | | Cued | | Neutral | | | | Cued | | Un-cued | | | | Cued | | Neutral | | |

**Variables of interest.** ***Learning task.*** Three variables were extracted as measures of participants' learning of the target locations across the three blocks: missed targets, search time, and search-time slope. Missed targets was simply the number of targets participants failed to find in each learning block. Search time was calculated as the time from scene onset to first mouse click. Only trials in which the target was found across all three blocks were included in the search-time analysis. To index how performance improved over the course of the three blocks, we also computed slope values for search times, as in our prior experiments.

***Location-memory test.*** Three measures were extracted to determine participants' explicit memories for the target locations: memory imprecision, memory accuracy, and memory confidence. Memory imprecision was calculated as the distance in pixels between where the participant clicked during the memory test and the true center of the

target location during the learning phase. Trials with a target in which participants failed to find the target at least once during the learning phase were excluded from the analysis.

Trials were considered "accurate" if participants clicked within an imaginary 200 x 200-pixel box centered on top of the target location.

Memory confidence was simply the response participants gave on the 1 – 3 scale. Trials in which participants failed to provide a rating were excluded from the confidence analysis but not the precision or accuracy analyses.

Location-memory imprecision, accuracy, and confidence were calculated separately for trials in which a target was present during the learning task and for trials in which no target was present during the learning task.

***Orienting.*** Two measures of orienting performance were extracted: accuracy and reaction time. Accurate trials were those in which participants correctly identified whether the orienting target was a bird or fish within the 1500 ms time frame. Reaction time was calculated as the time from target onset to button-press response. Only accurate trials were included. For memory-cue trials, trials with scenes in which participants failed to find the target star at least once during the learning task were excluded from both analyses.

***Target-memory test.*** One measure of performance was extracted: memory accuracy. Trials were considered accurate if participants correctly identified whether the image presented was new or old. As in the orienting accuracy analysis, orienting targets that were presented on memory-cue trials were excluded if participants failed to find the star associated with the scene during the learning task.

## Results

**Learning.** First, we sought to determine whether participants found greater numbers of targets with increasing speed over the course of the learning task. We ran two separate repeated-measures ANOVAs to determine the effect of learning task block on the number of targets participants missed and on their search speed. Over the course of the learning phase, participants found greater numbers of targets, $F(2, 36) = 20.90$, $p < .001$, $\eta^2 = .524$, ($M_1 = 5.0$, $SD_1 = 2.7$, $M_2 = 2.3$, $SD_2 = 1.5$, $M_3 = 2.2$, $SD_3 = 1.8$), with increasing speed, $F(2, 36) = 179.3$, $p < .0001$, $\eta^2 = .904$, ($M_1 = 8855.6$ ms, $SD_1 = 2171.0$ ms, $M_2 = 4555.0$ ms, $SD_2 = 1261.5$ ms, $M_3 = 2281.8$ ms, $SD_3 = 1102.1$ ms).

**Location memory.** Data from our location-memory test indicated that participants were able to learn the target locations. On trials in which no learning target was present, participants responded correctly on 96.0% of trials ($SD$ = 19.6%), with a mean confidence rating of 2.56 ($SD$ = .69). On trials in which a learning target was present, participants responded correctly on 69.3% of trials ($SD$ = 46.1%), with a mean imprecision of 134.4 pixels ($SD$ = 204.5 pixels) and a mean confidence rating of 2.4 ($SD$ = .74).

Additionally, for trials that included a learning target, we used the R package "Hmisc" (Harrell, 2017) to determine if participants' search time slopes were correlated with their location memory imprecision. We found a significant correlation between participants' search-time slopes and memory imprecision, $r(20) = -.68$, $p = .001$, indicating that the decreasing search speeds we observed across learning blocks at least partially index participants' learning of the target locations.

**Orienting.** Next, we analyzed the data from our orienting task. We were interested in how the trial type (memory vs. visual event) and the cue condition (cued, neutral, un-

cued) influenced participants' the accuracy and reaction time with which participants responded to novel orienting targets.

As before, we analyzed participants' orienting accuracy and reaction times with mixed-effects models using the lme4 package in R following the "step-forward-best-path" approach recommended by Barr et al., (Barr et al., 2013) to determine the random-effects structure of our models. Our final orienting accuracy and reaction time models included fixed effects for cue type (memory vs. visual event) and condition (cued, neutral, un-cued), and random intercepts for scenes and subjects.

Likelihood-ratio tests revealed no significant effects of trial type or cue type on orienting accuracy, nor a trial type x cue type interaction effect (all $p$s > .12).

Our reaction-time analysis revealed a different pattern of results. Here, we observed a significant effect of cue condition on reaction times, $F(1, 2251.9) = 7.7$, $p = .0005$ (Figure 3). Follow-up paired comparisons revealed that across cue types, participants were marginally slowed when the target was un-cued, relative to when the target was cued, $z = 1.9$, $p = .052$. There was no statistically significant difference in reaction times between neutral and cued trials, $z = 1.1$, $p = .29$ or between neutral and un-cued trials, $z = 0.9$, $p = .38$.

Additionally, there was also a main effect of cue type on orienting reaction times, $F(1, 117.4) = 8.2$, $p = .005$. Overall, participants were faster to respond on trials with visual cues ($M = 870.0$ ms, $SD = 420.6$ ms) relative to trials with memory cues ($M = 921.3$ ms, $SD = 414.6$ ms). There was no cue type x cue condition interaction effect on orienting reaction times, $F(1, 2251.8) = 1.1$, $p = .35$.

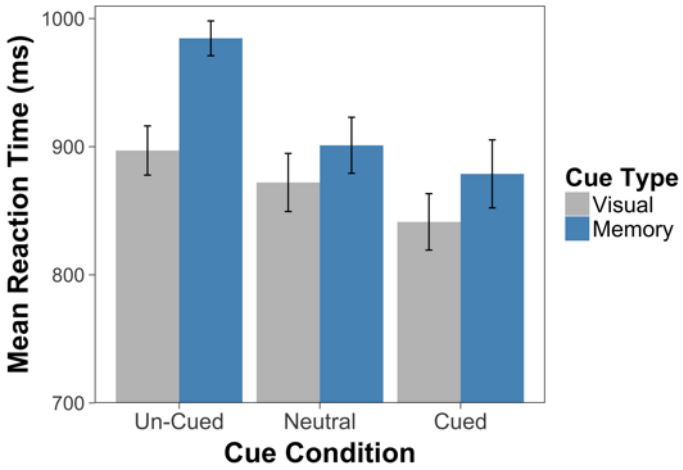



**Figure 20.** At orienting, across cue types, participants were marginally faster to respond on cued trials relative to un-cued trials. Participants were also faster to respond on trials with visual cues relative to trials with memory cues. Error bars indicate standard error.

Our orienting reaction-time data indicate that both types of cues effectively facilitated attention toward cued relative to un-cued locations. Interestingly, the presence of the scenes with associated memories slowed participants across all three cue conditions (cued, neutral, un-cued), potentially indicating that memory retrieval interfered with or impaired processing of novel targets. However, replicating the findings of past studies (Patai et al., 2012; Stokes et al., 2012; Summerfield et al., 2006, 2011), participants still demonstrated an effect of cue conditions within memory-cue trials, indicating enhanced perceptual processing of targets presented at locations cued by memories relative to un-cued locations.

**Target memory.** Finally, we examined the data from our final block to address our main question of interest: In addition to enhancing *perception* for items presented in cued locations, do spatial memories also enhance *encoding* of novel information? To address this question, we constructed a logistic mixed-effects model with target memory

accuracy as our dependent variable, cue type and cue condition as fixed effects, and subject and target as random intercepts.

Our analyses revealed no effect of cue type, no effect of cue condition, and no cue type x cue condition interaction effect on target memory accuracy (all *ps* > .76). However, target-memory accuracy was very poor, with participants correctly identifying between 50% and 52% of previously presented targets as "old" across conditions.

We further investigated target memory by computing memory sensitivity (d') scores for each orienting condition for each participant. This measure enabled us to account for differences in old/new biases across participants. We then compared these values to chance level (d' = 0) using a one-sample t-test. On average, participants memories were slightly above chance, $t(119) = 8.29$, $p < .0001$; $M = .28$, $SD = .37$.

Despite memory being slightly above chance, when we submitted these d' values to a traditional repeated-measures ANOVA, we observed no effect of cue type or cue condition on memory sensitivity (all *p*s > .65).

Thus, while our orienting reaction-time data indicate that both memories and visual events enhanced participants' perception of items presented in cued relative to un-cued locations, we observed no evidence of this enhanced perception benefitting subsequent memory.

## Experiment 6 Discussion

In our first experiment, we asked whether the perceptual benefits conferred by cuing attention either via memories or via exogenous spatial cues would extend into the domain of memory. The results from our orienting task largely replicated the findings

from past studies: participants demonstrated an attentional benefit from both types of cues, as demonstrated by a main effect of cue condition on participant reaction times. However, contrary to our hypothesis, we did not observe any influence of orienting condition on participants' recognition memory for the novel items that were presented at orienting.

Originally, we predicted that participants would more strongly encode the items presented on cued relative to un-cued trials, particularly in our memory-guided attention condition. However, we also noted the possibility that previous memories may interfere with encoding new information. If that were the case, we would expect to see memory impairments in the memory-cued *and* the memory un-cued condition; in both of these conditions, participants likely retrieved a potentially interfering target representation during orienting.

Our two hypotheses make opposing predictions. Thus it is possible that we did not observe memory differences for the orienting targets across conditions because the effects we expected counteracted each other. For example, it is possible that participants experienced the strongest modulation of preparatory activity and visual cortical activity during encoding in the memory-cued condition (Stokes et al., 2012), that enabled participants to form the most robust representations of the novel targets. However, it is also possible that they experienced the most interference from their previous memory of the learning target in this condition, impairing their ability to retrieve the representation of the novel target during the memory test (Jonides & Nee, 2006).

Though the opposing-effects account is possible, it is more likely that our task simply was not sensitive enough to reveal differences in memory encoding across orienting conditions. Our main conditions of interest (memory-cued vs. memory un-cued) included only twenty trials each, limiting our power to detect an effect. Additionally,

though memory sensitivity was, on average, above chance, participants still performed very poorly on the recognition memory test, correctly identifying between 50 – 52% of old items as old. Thus memory performance was not optimal for detecting differences across conditions, since subjects were likely guessing on large numbers of trials.

To increase our chances of detecting an effect of memory-guided attention on subsequent learning, we conducted a second experiment. To boost our power, we increased the number of memory-guided attention trials from 60 to 84. Additionally, to make our memory task easier, we exposed participants to fewer orienting targets by eliminating our visually guided orienting condition. We also replaced our recognition task with a forced-choice memory test, where participants were presented with one old item and one new item.

## EXPERIMENT 7

## Methods

**Participants.** Twenty adults (Mean age = 22.0 years, STD = 3.2 years; Range: 18.7 – 28.6 years; 10 females) with normal or corrected-to-normal vision and no known history of psychiatric or learning disorders, participated in the study.

**Stimuli.** Eighty-four scene stimuli and 84 bird stimuli, 84 fish stimuli, and 84 flower stimuli were used in the experiment. The scenes and flowers comprised subset of those used in Experiment 6. Additional bird and fish stimuli were selected from Google Images, and prepared in the same way as in Experiment 6. The learning target was identical to that used in Experiment 1.

**Procedure**. ***Learning phase and location-memory test.*** The learning phase and location-memory test were the same as those used in Experiment 6, but they included only 84 trials instead of 60. Additionally, the maximum search time was increased to 45 seconds.

***Orienting.*** The orienting task was the same as that used in Experiment 1, but it included memory-guided trials only. Additionally, there were 84 trials instead of 120. Target presentation time was increased from 1500 ms to 2000 ms.

***Target-memory test.*** The target-memory test comprised a forced-choice task. Participants were simultaneously presented with one target stimulus from the orienting task and one novel bird or fish stimulus. They were instructed to press "1" if the image on the left was old and "2" If the image on the right was old. The location of the old image and the order of the trials was randomized.

**Counterbalancing.** The assignment of scenes to orienting conditions, learning target locations, and orienting target locations was done as in Experiment 6.

## Results

**Learning.** As in Experiment 6, we first sought to determine whether participants found greater numbers of targets with increasing speed over the course of the learning task. We ran two separate repeated-measures ANOVAs to determine the effect of learning task block on the number of targets participants missed and on their search speed. As in Experiment 6, over the course of the learning phase, participants found greater numbers of targets, $F(2, 36) = 19.7$, $p < .001$, $\eta^2 = .522$, ($M_1 = 5.3$, $SD_1 = 11.9$, $M_2 = 2.6$, $SD_2 = 13.1$, $M_3 = 2.2$, $SD_3 = 12.9$), with increasing speed, $F(2, 36) = 99.45$, $p < .0001$, $\eta^2$

= .847, ($M_1$ = 8512.6 ms, $SD_1$ = 2240.3 ms, $M_2$ = 4514.0 ms, $SD_2$ = 1422.6 ms, $M_3$ = 2200.2 ms, $SD_3$ = 1283.6 ms).

**Location memory.** Data from our location-memory test indicated that participants were able to learn the target locations. On trials in which no learning target was present, participants responded correctly on 96.1% of trials (*SD* = 19.5%), with a mean confidence rating of 2.7 (*SD* = .64). On trials in which a learning target was present, participants responded correctly on 71.3% of trials (*SD* = 45.3%), with a mean imprecision of 132.1 pixels (*SD* = 204.2 pixels) and a mean confidence rating of 2.5 (*SD* = .70).

Additionally, for trials that included a learning target, we found a significant correlation between participants' search-time slope and memory imprecision, $r(20) = -.58$, $p = .009$, indicating that as in Experiment 6, the decreasing search speeds we observed across learning blocks at least partially index participants' learning of the target locations.

**Orienting.** Next, we analyzed the data from our orienting task. We were interested in how memory cue condition (cued, neutral, un-cued) influenced the accuracy and reaction time with which participants responded to novel orienting targets.

As in Experiment 6, we used mixed-effects models to examine participants' accuracy and reaction times. Our final orienting accuracy and reaction time models included the fixed effect of cue condition (cued, neutral, un-cued), and random intercepts for scenes and subjects.

Likelihood-ratio tests revealed a significant effect of cue condition on orienting accuracy, $\chi^2(3) = 6.6$, $p = .04$, with participants responding most accurately on neutral trials (*M* = .96, *SD* = .19), followed by cued trials (*M* = .94, *SD* = .23), and then un-cued

trials ($M$ = .93, $SD$ = .26). Follow-up paired comparisons indicated that participants' accuracy was impaired on un-cued relative to neutral trials, $z$ = 2.55, $p$ = .011. No other differences between conditions reached significance ($p$s > .13).

Unlike Experiment 6, we observed no effect of cue condition on reaction times, $F(2, 1467.4) = 1.1$, $p$ = .34.

**Target memory.** Finally, we examined data from our target memory test using a logistic mixed-effects model with target memory accuracy as our dependent variable, cue condition as a fixed effect, and subject and target as random intercepts.

Contrary to our hypothesis, we observed no effect of cue condition on target memory, $\chi^2(3) = 1.6$, $p$ = .45. Additionally, as in Experiment 6, memory performance was still poor: Participants correctly identified between 55% and 59% of target images as "old" across conditions.

Average memory sensitivity (d') was above chance, $t(56) = 8.2$, $p < .001$, but only slightly so, $M$ = .38, $SD$ = .33. Despite memory being slightly above chance, when we submitted these d' values to a traditional repeated-measures ANOVA, we observed no effect of cue condition or trial type of memory sensitivity (all $p$s > .65).

## Experiment 7 Discussion

In Experiment 7, we made several changes to our task parameters to increase our chance of observing an effect of memory-guided attention on subsequent recognition memory. Specifically, we increased the number of memory-cued and un-cued trials in our orienting and subsequent recognition memory tasks, and we made our test of recognition memory easier by including fewer targets to encode and changing it to a forced-choice

task. However, these changes were not enough to improve greatly participants' memory performance. Though memory sensitivity was above chance, participants' memory accuracy was still low: they responded correctly on 55 – 59% of trials across conditions.

It is also worth noting that we did not observe any effect of memory cue condition on orienting reaction times. Participants did show attentional facilitation to the location cued by the memory, but this facilitation was reflected only in better accuracy on neutral relative to un-cued trials. It is unclear why this is the case.

Both our orienting data and our memory test data suggest that our task design was still not optimized to detect an effect of memory-guided attention on encoding of novel information. Ideally, we would want to see a robust effect of memory in driving differences in orienting performance between memory cued and un-cued trials. Additionally, performance on the test of recognition memory should be well-above chance in order to mitigate noise from guessing.

Furthermore, the nature of the categorization task may have impaired participants' ability to encode the individual target stimuli. In the categorization task, participants had to determine whether briefly presented targets were birds or fish. To do so, it would be adaptive for participants to enhance their attention to features of the targets that differentiate birds from fish (i.e. wings or gills) (Sigala & Logothetis, 2002; Sowden & Schyns, 2006). However, the features that differentiate birds from fish are also features that are shared among many exemplars within each category. Therefore, while attending to shared features was likely beneficial for the categorization task, doing so may have impaired participants' ability to encode the more specific features of each individual exemplar that would allow them to identify old and new images during the memory test. Instructing participants to categorize them, and therefore actively look for *shared* features

may have exacerbated the difficulty of the already difficult task of encoding many similar items.

With these considerations in mind, we altered our task parameters once again. This time, we changed our target categories from birds and fish to toys and food, with the hope that it would be easier for participants to differentiate and encode the target exemplars. Additionally, we added confidence ratings to our final recognition memory test so that we would have a more sensitive, continuous scale along which to measure memory. Finally, we also included novel scenes at orienting. Though unlikely, it is possible that any prior experience with the scenes was interfering with participant's ability to form new memories at orienting and later retrieve them. As such, we included an encoding condition to enable us to directly test this possibility.

## EXPERIMENT 8

## Methods

**Participants.** Fifteen adults (Mean age = 23.2 years, SD = 2.0 years; Range: 19.5 – 27.8 years; 13 females) with normal or corrected-to-normal vision and no known history of psychiatric or learning disorders, participated in the study.

**Stimuli.** Stimuli for the task comprised 108 scene stimuli, 72 toy stimuli, and 72 food stimuli. The scenes comprised those that were used in Experiment 7, as well as additional scenes selected from Google Images. The toy and food stimuli were photographs selected from the Bank of Standardized Stimuli (Brodeur, Dionne-Dostie,

Montreuil, Lepage, & Rauch, 2010) (Figure 21). They were resized in Photoshop to be 200 x 200 pixels.

A. B.



**Figure 21.** Example toy (A) and food (B) stimuli.

**Procedure.** ***Learning phase.*** The learning phase included 84 scenes repeated over three blocks. Thirty-six scenes included a learning target (the star stimulus) embedded on the left, 36 scenes included a learning target embedded on the right, and 12 scenes did not contain a target.

***Location-memory test.*** The location memory test was identical to that used in Experiments 6 and 7.

***Orienting.*** The task comprised 108 trials split across four orienting conditions: memory-cued (36), memory un-cued (36), neutral scenes (12), and novel scenes (24). Neutral scenes were those that participants saw during learning, but that did not have an embedded target. Participants saw the novel scenes for the first time at orienting. We used both neutral and novel scenes primarily to reduce the number of neutral scenes in the learning phase in order to include more scenes with targets while holding task length constant.

On every trial, participants saw a scene (150 ms), followed by a short delay period (50 ms). They then saw the scene again (2000 ms), but this time, a novel toy or food target was embedded within it that participants were instructed to discriminate (Figure 22).

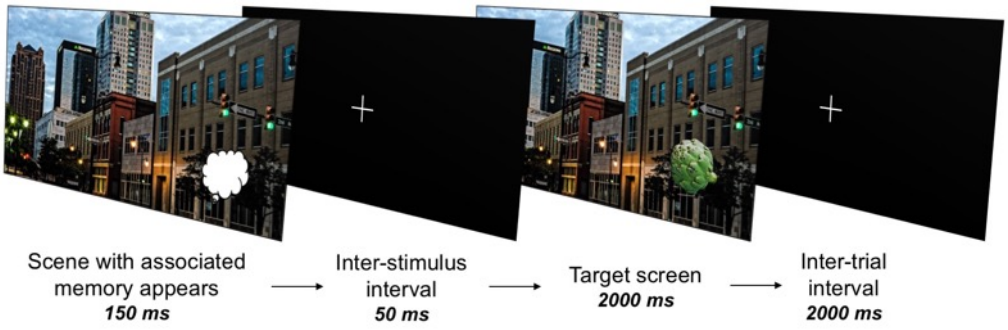



**Figure 22.** In the orienting task, participants first saw a scene with an associated memory for 150 ms. After a brief delay (50 ms), a target then appeared within the scene. Participants had to indicate via button-press if the target item was a food or a toy.

***Target-memory test.*** The target-memory test comprised a recognition task, in which participants were shown either a toy or food stimulus from the orienting task, or a novel toy or food stimulus. Participants were instructed to use four buttons to rate if the image was: definitely old, probably old, probably new, or definitely new. The order of the trials was randomized.

**Counterbalancing.** The assignment of scenes to orienting conditions, learning target locations, and orienting target locations was done as in Experiment 6.

## Results

**Learning.** As in our previous two experiments, we first sought to determine whether participants found greater numbers of targets with increasing speed over the course of the learning task. We ran two separate repeated-measures ANOVAs to

determine the effect of learning task block on the number of targets participants missed and on their search speed. As in Experiments 6 and 7, over the course of the learning phase, participants missed fewer targets, $F(2, 28) = 22.9$, $p < .0001$, $\eta^2 = .62$, ($M_1 = 10.0$, $SD_1 = 4.7$, $M_2 = 7.4$, $SD_2 = 5.1$, $M_3 = 5.6$, $SD_3 = 4.7$), and found targets with increasing speed, $F(2, 28) = 77.5$, $p < .0001$, $\eta^2 = .847$, ($M_1 = 8768.1$ ms, $SD_1 = 2349.9$ ms, $M_2 = 4271.0$ ms, $SD_2 = 1427.4$ ms, $M_3 = 2585.5$ ms, $SD_3 = 1066.1$ ms).

**Location-memory test.** Data from our location-memory test indicated that participants were able to learn the target locations. On trials in which no learning target was present, participants responded correctly on 81.1% of trials ($SD$ = 39.3%), with a mean confidence rating of 2.4 ($SD$ = .80). On trials in which a learning target was present, participants responded correctly on 63.2% of trials ($SD$ = 48.2%), with a mean imprecision of 175.5 pixels ($SD$ = 255.4 pixels) and a mean confidence rating of 2.5 ($SD$ = .75).

Additionally, for trials that included a learning target, we found a significant correlation between participants' search-time slope and memory imprecision, $r(15) = -.80$, $p = .0004$, indicating that as in Experiments 1 - 7, the decreasing search speeds we observed across learning blocks at least partially index participants' learning of the target locations.

**Orienting.** Next, we analyzed the data from our orienting task. We were interested in how memory-cue condition (cued, neutral, novel, un-cued) influenced the accuracy and reaction time with which participants responded to the orienting targets.

As in Experiments 6 and 7, we used mixed-effects models to examine participants' accuracy and reaction times. Our final orienting accuracy and reaction time models included the fixed effect of cue condition (cued, neutral, un-cued), and random intercepts

for scenes and subjects. Our reaction-time model additionally allowed for different slopes for each scene across cue conditions.

Likelihood-ratio tests revealed a significant effect of cue condition on orienting accuracy, $\chi^2(3) = 12.8$, $p = .005$, with participants responding most accurately on cued trials ($M = .93$, $SD = .26$), followed by novel trials ($M = .90$, $SD = .30$), then neutral trials ($M = .89$, $SD = .31$), and finally un-cued trials ($M = .86$, $SD = .35$). Follow-up paired comparisons indicated that participants' accuracy differed significantly only between cued and un-cued trials, $z = 3.5$, $p = .0004$, and between novel and un-cued trials, $z = 2.0$, $p = .048$. This indicates that as in Experiment 2, participants' orienting accuracy was impaired when the memory associated with the scene cued an incorrect location.

We observed only a marginal effect of cue condition on reaction times, $F(3, 1354.08) = 2.5$, $p = .06$. Participants were fastest to respond on cued trials ($M = 944.8$ ms, $SD = 266.9$ ms), followed by neutral trials ($M = 967.7$ ms, $SD = 263.6$ ms), then un-cued trials ($M = 984.7$ ms, $SD = 310.1$ ms), and finally novel trials ($M = 986.2$ ms, $SD = 305.4$ ms). Follow-up paired comparisons revealed that participants were significantly faster to respond on cued relative to un-cued trials, $t(85) = 2.3$, $p = .027$.

**Target-memory test.** Finally, we examined data from our target-memory test. Since our dependent measure (memory confidence ratings) was ordinal, we used the R package "ordinal" (Haubo, Christensen, & Maintainer, 2015) to construct a cumulative link mixed-effects model. Our model included target-memory response as our dependent variable, cue condition as a fixed effect, and subject and target as random intercepts.

As in Experiments 6 and 7, we observed no effect of cue condition on target memory, $\chi^2(3) = 2.96$, $p = .40$. Here, however, participants correctly identified between 71% and 76% of target images as either "definitely old" or "probably old."

We also computed memory sensitivity (*d'*) values for each of our conditions by counting "definitely old" and "probably old" responses as hits for old items at test and false alarms for new items at test, and counting "definitely new" and "probably new" responses as misses for old items at test and correct rejections for new items at test. Unlike in our previous two experiments, here memory performance was well above chance. Memory sensitivity (d') scores for old items were also well above 0, $t(59) = 20.9$, $p < .0001$, $M = 1.68$, $SD = .62$. However, when we submitted these *d'* scores to a traditional repeated-measures ANOVA examining the effect of orienting condition on memory sensitivity, we did not observe any effect, $F(3, 42) = .51$, $p = .67$, $\eta^2 = .035$.

## Experiment 8 Discussion

In Experiment 8, we made additional changes to our task parameters to boost our ability to observe an effect of memory-guided attention on subsequent recognition memory. Specifically, we increased the number of memory-cued and un-cued trials in our orienting task and our subsequent recognition memory task, and we made our test of recognition memory easier by using target images that were more differentiable from each other.

This latter change did improve memory performance. In Experiments 6 and 7, participants' memory performance was only slightly above chance. However, in Experiment 3, participants correctly identified more than 70% of old images as old, and memory sensitivity (*d'*) was well above 0, indicating that participants distinguished old from new images.

Still, though we observed the expected effects of memory cue condition on orienting accuracy, and a marginal effect of memory cue condition on orienting reaction times, we did not observe any relationship between orienting condition and performance on the subsequent test of recognition memory. In other words, participants demonstrated evidence of attentional facilitation to the location cued by memory, but this facilitation did not seem to influence item encoding.

## GENERAL DISCUSSION

We ran three experiments to determine the effect of memory-guided attention on subsequent encoding of novel information. Specifically, we tested whether attention orienting facilitated by long-term memory would enhance encoding of novel objects presented at learned locations. Across our experiments, though the observed effects of memories on attention largely aligned with our expectations, we observed no evidence that memory-guided attention enhanced memory encoding.

Previous work using other types of cues has found that facilitating attention to specific spatial locations boosts encoding of information presented in those locations (Hauer & MacLeod, 2006; Markant et al., 2015; Uncapher & Wagner, 2010). Attention strengthens representations of information in visual cortex (Uncapher & Rugg, 2009) and may promote hippocampal representations that prioritize relevant features of target items (Aly & Turk-Browne, 2016a, 2016b).

Still, across previous studies, the effects of attention on memory only emerge consistently when the attentional cues employed trigger the engagement of fronto-parietal control regions (Brown et al., 2017; Krebs, Boehler, De Belder, & Egner, 2013; Markant & Amso, 2013; Markant et al., 2015; Turk-Browne, Golomb, & Chun, 2013; Uncapher

& Wagner, 2010). Simple exogenous cues often *do not* result in memory benefits for targets presented at cued relative to un-cued locations (Markant & Amso, 2013; Markant et al., 2015). This may be because the engagement of fronto-parietal control mechanisms also enables the suppression of irrelevant distractor items or locations (Krebs et al., 2013; Markant et al., 2015), and leads to a more robust representation of the target item in the visual cortex (Uncapher, Hutchinson, & Wagner, 2011; Zhang et al., 2011) and/or hippocampus (Aly & Turk-Browne, 2016a).

Considering this work leads to the question of whether the memory cues used in our tasks operate more like simple exogenous cues, and only facilitate attention toward cued locations, or whether they engage top-down attentional control processes that further serve to suppress information presented in un-cued locations. Previous work has suggested that memory-guided attention *does* invoke cognitive control processes (Rosen et al., 2016) that enhance representations in the visual cortex (Stokes et al., 2012), but future neuroimaging studies of memory-guided attention should also directly test whether the strength of the engagement of these top-down processes modulates encoding of novel targets on a trial-by-trial basis.

Additionally, as mentioned in the Experiment 6 discussion, we may not have observed effects of memory-guided attention on subsequent recognition memory due to interference from previous memories. Specifically, in our learning task, participants learned to associate a small, yellow star with a target location within a scene. During the orienting task, participants may have retrieved the representation of the star and its associated location. This memory for the star may have then proactively interfered with participants' ability to encode the novel item, particularly when that item appeared in the same location as the star (Jonides & Nee, 2006; Makovski & Jiang, 2008). However, if this were the case, we would expect to see the best memory performance for targets cued

by neutral or novel scenes, for which no prior association was learned. Instead, we observed no differences in target encoding between any of our conditions.

Perhaps the most likely reason for why we did not observe any effect of memory-guided attention on subsequent recognition memory is simply because the design of our experiments was such that they were not sensitive enough to reveal an effect that, based on previous findings, we would expect to be relatively small (Krebs et al., 2013; Uncapher et al., 2011). In general, it is difficult to design studies that examine both attention-orienting and long-term memory, because aspects of an experimental design that are advantageous for observing one effect limit one's ability to observe the other. For example, to get the "cleanest" measure of how an attentional cue affects participant's orienting accuracy and reaction time, targets in an orienting task should be kept consistent, so that differences in the ease with which a target can be seen or categorized do not affect orienting performance. But to test the effects of attention on memory, the orienting targets must be differentiable. Additionally, for tasks measuring attention, having hundreds of trials can boost the power of the design — but participants cannot encode hundreds of different images in a short period of time. Examining memory-guided attention further exacerbates these difficulties: prior to any orienting task, participants must first learn to associate contexts with locations. Even with only 60 – 80 scenes, this process itself takes between 1 and 2 hours in the lab, further limiting the number of trials possible to include in either one- or two-day testing protocol.

Future work should explore avenues to overcome these limitations. One possibility may be to transfer the learning phase of the task into an online platform. That way, participants could complete the learning phase at home, over a number of days (or even weeks), and build many more scene-based associations that could be used during orienting. Another possibility would be to repeat scene cues and orienting targets multiple

times during orienting, within the same condition. The risk with this approach is that once participants see a scene used on an un-cued trial, they may overwrite in memory the original location they associated with the scene, weakening its effects on further trials. However, if participants form strong enough memories during the learning phase, a few exposures during orienting may not significantly erode the original memory association. Future work could directly compare the orienting effects of repeated scenes to scenes used only once, to determine if boosting the number of orienting trials through repetition is a plausible solution to increase the power of these designs.

The question this chapter posed — whether and how past experience influences future memories via modulations of visual attention — is worthy of further investigation. Implicit in most of the past work on memory-guided attention is the idea that attention itself has downstream consequences for adaptive behavior and for memory formation. But this has never been demonstrated directly. Still, to investigate this question, researchers will need to design better tasks, and perhaps entirely rethink the paradigm we used, to overcome some of the barriers we faced.

# 6. General discussion

The influence of past experience on guiding attention and perception is now well established (e.g. Chun, 2000; Summerfield et al., 2006). The studies described in this thesis sought to advance our understanding of the influence of memory on attention by focusing on three main questions. Specifically, the studies aimed to probe how past experiences guide attention when salient visual events occur within familiar contexts, whether different sources of attention orienting differentially influence children and adults, and whether memory-guided attention influences future learning.

In Experiment 1, we found that when salient visual events occur within scenes with associated spatial memories, children but not adults, continue to use memories to orient their attention. In Experiment 2, we determined that the developmental difference we observed in Experiment 1 could *not* be attributed to differences in strategy use across age groups. Specifically, we found that even when the salient visual events were non-predictive distractors that adults were explicitly instructed to ignore, they still disrupted adults' use of memories to guide attention.

Interestingly, this disruption of memory-guided attention by salient visual events was not permanent. In Experiments 3 and 4, we observed that at longer time-courses, adults *did* use memories to guide attention, even in the presence of salient visual distractors. Specifically, when the amount of time between the presentation of the distractor and the presentation of the target was extended, adults *were* able to use memories to guide attention. It is unclear if the distractor disrupted adults' retrieval of the spatial memory associated with the scene, or with their use of this stored representation to orient their attention. Still, these experiments demonstrate that memory-guided attention is dynamic and that its susceptibility to disruption changes on a millisecond-

level scale. Additionally, they reveal that though easily disrupted, memory-guided attention is also resilient: it re-emerges rapidly after disruption.

Experiment 5 further probed the developmental differences we observed in Experiment 1. Previous work has suggested that the effects of memories on attention in school-aged children are less robust than their effects in adulthood (Couperus et al., 2011; Vaidya et al., 2007). This has led researchers to question whether children's cognitive control networks are mature enough to coordinate the interactions between medial temporal memory systems and fronto-parietal orienting systems necessary for memories to influence visual attention. However, we found that at short time-scales, children demonstrated a *greater* influence of memories on attention-orienting than adults. In Chapter 4, we offered a novel, speculative, interpretation of these findings, suggesting that the greater rigidity children demonstrate in their retrieval of contextual memories (DeMaster et al., 2016; Güler & Thomas, 2013) may lead to *stronger* effects of memories on attention. Perhaps children's reduced ability to flexibly update or generalize contextual associations leads to greater use of specific past experiences during novel tasks.

Finally, in Experiments 6 – 8, we attempted to determine whether and how memory-guided attention influences future encoding. Across all three experiments, results were largely inconclusive. Importantly, even with a 200-ms cue-to-target interval, we did observe effects of memory cue condition on orienting accuracy (Experiments 7 and 8) and orienting reaction time (Experiments 6 and 8) in adults.

**Future directions.** The experiments described in this thesis advance our understanding of the development of memory-guided attention, as well as how memory-guided orienting interacts with other processes, including exogenous orienting and memory encoding. But many future experiments are needed to more fully understand the development of the mechanisms that enable past experience to guide future behavior.

One particularly important avenue of investigation is to examine how memory-guided attention changes continuously, throughout development. In Experiments 1 and 5, we found that school-aged children use memories to a greater degree than adults in orienting their attention, both when salient visual events are present (Experiment 1), and when memories are presented in isolation (Experiment 5). But our experiments relied on cross-age-group comparisons, and thus do not track the emergence of the processes that support memory-guided orienting, nor the developmental period during which the influence of experience on attention may begin to weaken (if it does indeed do so). Examining how memory-guided attention changes from early childhood, across middle childhood and adolescence, and into adulthood, with both neural and behavioral measures, will require a much larger sample of participants, but will be better suited to reveal how the development of different cognitive mechanisms influences memory-guided orienting.

Additionally, very little work has examined how memory-guided attention interacts with other sources of orienting. Though we explored how memories interact with salient visual stimuli, to more fully understand how memories influence attention in real-world settings, it will also be important to examine how they interact with other sources of attention like top-down goals. Examining interactions between memory-guided and goal-directed attention will also help to determine whether they are instantiated by different mechanisms; if memory cues and endogenous cues lead to separable, additive effects on orienting, then it is likely that they are at least partially dependent on separable systems (Berger et al., 2005). However, if memory cues and endogenous cues demonstrate competitive, interactive effects, then it may be the case that memory-guided orienting and goal-directed attention rely on largely overlapping mechanisms.

**Conclusion.** The work presented in this thesis examined, for the first time, *interactions* between memory-guided and exogenously cued attention, as well as how the effects of concurrently presented memory cues and salient visual events may differ between children and adults, and how memory-guided attention may influence future recognition memory formation. The studies described in the thesis represent a starting point from which we can begin to understand how memories influence attention and learning in more naturalistic settings, in which novel events frequently occur within familiar context at different time points. Importantly, many of the results described here hint at intriguing possibilities about how attention and memory may interact over development. These ideas deserve further examination in future experiments.

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