



The functional consequences of social attention on memory precision and on memory-guided orienting in development

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ABSTRACT

Adults are slower at locating targets in naturalistic scenes containing a social distractor compared to an equally salient non-social distractor, and their subsequent memory for targets in social scenes is poorer. Therefore, adults' social biases affect not only attention, but also their memory. Six-to-ten year-old children and young adults took part in the current study, employing a combination of behavioural and eye-tracking measures. Social stimuli in naturalistic scenes distracted both children and adults during visual search, as demonstrated by their gaze behavior and search times. In addition, eye-tracking revealed even greater attentional capture by social distractors for children. Memory for targets was worse in social compared to non-social scenes. Intriguingly, children demonstrated overall better memory precision than adults. Finally, when participants detected previously learnt targets within visual scenes, adults were slower for targets appearing at unexpected (invalid) locations within social scenes compared to non-social scenes, but this was not the case for children. In their entirety, these findings suggest that the interplay between social attentional biases, memory and memory-guided attention is complex and modulated by age-related differences. Complementary methodologies in developmental cognitive neuroscience shed light on the mechanisms through which social attention and memory interact over development.

1. Introduction

Despite parallel literatures investigating selective attention to social stimuli (e.g., Langton and Bruce, 1999; Langton et al., 2008; Ro et al., 2001; Vuilleumier, 2000; Vuilleumier et al., 2001) and memory for social stimuli (e.g., Fagan, 1972; Kapur et al., 1995), little work has investigated the relationship between the two. Recently we have shown that there are functional consequences of attention to task-irrelevant social stimuli on learning and memory in adults. Participants learnt about the location of targets hidden in naturalistic visual scenes that contained either a salient social distractor or an equally salient non-social distractor. Both behavioral and gaze differences occurred during a visual-search learning task that were indicative of social distraction, and these behavioral differences were associated with subsequent poorer memory performance for target locations in social scenes (Doherty et al., 2017). However, many open questions remain about how the relationships between social biases, attention and memory unfold during development. Asking these developmental questions is very interesting, because contrasting mechanisms may be at play when

young individuals deploy their attention to learn, later to remember, and finally to guide attention based on memory in the context of salient but task-irrelevant social stimuli. Do children demonstrate an attention bias similar to adults towards social stimuli compared to non-social stimuli? Do these social biases affect spatial contextual memory, as we have shown previously with adults? As we detail later, children may be differentially more influenced than adults by social items as they are searching for target items, both because of strong social biases and relatively poorer attention guidance. The functional consequences of these social attention biases on memory-guided attention also remain unexplored.

Indeed, although we know that attention influences memory, memory itself also affects attentional orienting, a bidirectional relationship that in adults is well-documented for both short-term (Astle and Scerif, 2011; Griffin and Nobre, 2003; Kuhl and Chun, 2014) and longer term memory (Chun and Turk-Browne, 2007; Goldfarb et al., 2016; Hutchinson and Turk-Browne, 2012; Rosen et al., 2016). Hypotheses about how longer term memory influences attention in adulthood and childhood come from seminal work using the contextual

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cueing paradigm (Chun and Jiang, 1998; although see Smyth and Shanks, 2008; Vadillo et al., 2016 for arguments against the implicit nature of learning in contextual cueing). Other, more recent work has built on these studies (Patai et al., 2013, 2012; Stokes et al., 2012; Summerfield et al., 2006, 2011). Typically, participants search for target objects in natural scenes over several blocks, to form a memory for where the target is located in each scene. Memory precision for target location is also tested. After a break, participants react to the onset of the target superimposed on a previously studied scene in either the learned location (valid trials) or in a different location (invalid trials) while fixating centrally (Salvato et al., 2016a, b; Summerfield et al., 2006). This classic memory-guided Posner-style attention orienting paradigm leads to a validity effect, whereby reaction time (RT) for invalid trials is significantly longer than RT for valid trials. This additional orienting task therefore allows for investigating the effects of memory on attention orienting.

Memory-guided attention orienting in childhood has been investigated primarily using the contextual cueing paradigm. A small and growing literature suggests that children demonstrate contextual cueing effects that are similar to adults, but findings are mixed. Although a study using the original contextual cueing paradigm (Chun and Jiang, 1998) did not report a memory-guided attention effect with 10-year-old children (Vaidya et al., 2007), another study using more child-friendly stimuli (cartoon red and blue fish) found contextual cueing in 5–10 year-old children (Dixon et al., 2010). Further, there is evidence of a relatively stable contextual cueing effect across development, from 6 years to beyond 65-years-old (Merrill et al., 2013). However, it is useful to bear in mind that the psychological and neural mechanisms of contextual cueing demonstrated by children may not be identical to adults. In particular, studies suggest that distractor-target similarity hinders children more than adults (Yang and Merrill, 2014), and that children are more sensitive to the ratio of attended to unattended distractors (Couperus et al., 2010), as well as to the overall ratio of familiar-to-novel search displays (Yang and Merrill, 2015a, b). These differences indicate that potential immaturities in perceptual learning, selective attention, and/or working memory may affect contextual cueing in childhood. In addition, contextual cueing paradigms typically involve searching for target items within arrays of distractors, rather than within naturalistic scenes, a further aspect that may underestimate children's abilities compared to search in naturalistic scenes, especially scenes that contain socially relevant information.

A vast literature describes the presence of a social bias from birth (Morton and Johnson, 1991), and even when faces are presented in complex natural scenes (Amso et al., 2014; Frank et al., 2009). Beyond attention to social stimuli over other stimuli in general, there is evidence that children process face stimuli similarly to adults (e.g. Mondloch et al., 2007), and young children also demonstrate similar attentional biases to adults, specifically towards threatening faces (e.g. LoBue, 2009). It is therefore likely that children possess an attentional bias towards social stimuli that is similar to that of adults. However, although children's social bias may be similar to adults, differences in general attention abilities may lead to differences in performance when compared to adults as in the current study. Following up on a study showing development in attention to faces in natural scenes between 3 to 9 months, Frank and colleagues reported a relationship between attention abilities, as measured by visual search, and face preference in infants between 3–9 months (Frank et al., 2014). This study suggests that what drives increased attention to faces over infancy is not a change in the bias towards social stimuli itself, but rather an increased ability to inhibit competing salient stimuli and/or sustain attention to face stimuli. It is possible that children show greater social-distraction effects, due to immature attention skills, which could lead to a reduced ability to inhibit social distractors when recalling from memory and when directing attention on the basis of their memory.

1.1. The current study

The present study combined behavioral and eye-tracking methods to examine the influence of social distraction on memory and later memory-guided attention orienting in 6- to 10-year-olds and young adults. During an initial visual search phase, repeated across 3 blocks, participants located targets in scenes containing either a social or non-social distractor. Later, their memory for target location was tested. Finally, participants completed an attention-orienting task in which they detected the brief presentation of learned targets within their associated scene (either social or non-social) at either a valid (learned) versus non-valid (new) location. We posed three complementary questions: 1) Do children demonstrate social distraction during visual search within natural scenes, similar to adult participants? 2) Does social distraction influence children's memory performance, such that memory is poorer for social scenes, similar to adult participants? 3) Do the effects of social distraction on memory influence later memory-guided orienting in similar ways in children and adults? Here we cast a broad net and targeted children spanning mid-childhood (6- to 10-years of age).

A number of differential hypotheses emerge. First, we hypothesized that strong social attention biases during learning in children may result in poorer overall memory in children compared to adults. Secondly, we further predicted that stronger social attention biases in children would result in greater costs when using memory to direct attention. However, attentional biases need not necessarily influence subsequent memory and memory guided attention in the same way in children and in adults: the changing interactions between attentional networks over mid-childhood (Pozuelos et al., 2014), and their changing relationships with developing medial temporal lobe structures (e.g., Ghetti et al., 2010) might mean that children attend to, encode and recall naturalistic scenes differently from adults. For example, Gopnik and colleagues have suggested that greater exploration by children compared to adults, rather than highly task-focused behaviour, may paradoxically result in unexpected later benefits in performance (e.g., Gopnik et al., 2017). Thirdly, the role of social attentional biases in how memory-guided effects operate has not been studied in adults, to our knowledge. It is possible that, even in adults, social attention biases may establish different memory traces that in turn may re-inforce differences in attention orienting. In this context, then, studying interactions between social biases, attention and memory affords the opportunity of unveiling potentially differential mechanisms at play in children compared to adults.

2. Methods and materials

2.1. Participants

The University of Oxford Central University Research Ethics Committee (CUREC) approved this research. Eighteen healthy children volunteered to participate in this study. Two were excluded due to not completing the task, leaving 16 participants (aged 6–10, average age 8.44, 9 female). Age was evenly distributed over this age range: there was one participant aged six, three participants aged seven, four participants aged eight, four participants aged nine, and four participants aged 10. Eighteen healthy adult volunteers participated, and sixteen were included in the analysis (aged 19–21, 14 female) to equate the numbers between the two age groups and fully counterbalance for both groups the characteristics of natural scenes to be learnt. All participants had normal or corrected-to-normal vision.

2.2. Stimuli

Stimuli were the same as those used in the previous study (Doherty et al., 2017). Stimuli were counterbalanced across participants as detailed in Fig. 1. Target location, distractor type and validity of the scene

Distractor type	40 social												40 non-social											
Distractor location	20 left								20 right								20 left				20 right			
Target location	10 same				10 Opp				10 same				10 opp				10 same		10 opp		10 same		10 opp	
Validity	5V		5I		5V		5I		5V		5I		5V		5I		5V	5I	5V	5I	5V	5I	5V	5I
Distractor gender	3 M	2 F	2 M	3 F	2 M	3 F	3 M	2 F	2 M	3 F	3 M	2 F	3 M	2 F	2 M	3 F	Not applicable							

Fig. 1. Scenes balanced for distractor type, distractor location, target location, orienting phase validity and distractor gender. Distractor location refers to screen hemifield. Target location is with respect to the distractor: same or opposite (opp) side of the distractor. Validity is with respect to the target appearance during the orienting phase: valid (V) or invalid (I) location. Distractor gender (F: female, M: male) is only applicable to social scenes.

during the orienting phase were counterbalanced (as described below). While half of the participants saw the same 40 scenes as valid and the other 40 scenes as invalid, the other half saw the reverse. Within this counterbalancing, distractor location (left or right side) and gender of social distractors (male or female) were also balanced to the extent possible (Fig. 1). Target location (same or opposite side as distractor), distractor location (left or right side), and validity (valid or invalid scene during the orienting phase) counterbalancing resulted in eight participant groups. We controlled for important differences associated with low-level visual salience, using a graph-based visual saliency algorithm (Harel et al., 2006) to ensure that the physical salience of social vs. non-social distractor items embedded within scenes is matched. For both target locations, paired samples t-tests comparing social and non-social versions of all scenes revealed no significant differences in salience between: (1) social/non-social distractors identified with hand-drawn AOIs ($p > 0.250$), (2) social/non-social scenes overall ($p > 0.250$), and (3) social/non-social scene target objects in the target locations identified with circular AOIs ($p > 0.250$).

2.3. Procedure

2.3.1. Visual search

Participants sat approximately 60 cm away from a 23" monitor with 1920 by 1080 pixel resolution (spanning 45.89 by 26.90° of visual angle). Instructions and task structure were based on a previous study (Doherty et al., 2017). For each trial, participants saw: 1) a fixation square for 1000–1500 ms, 2) the object alone (1.61 by 1.61° of visual angle) for 3000 ms, 3) the scene and embedded object, and 4) feedback for 1000 ms ("Object not found" or "Object found" on blank screen). Maximum search time was 20 s in the first block and decreased by 4 s each subsequent block. Participants observed all 80 scenes in random order during each of three blocks.

There were several small alterations to the task from the previous study. The task was cartoon themed, including images of characters during the feedback and instruction screens, a story for the task including the characters to make the task appear more like a game, and points acquired after each block (which were random and increasing from block to block). A practice phase was included before the task, consisting of twelve trials. When the targets were correctly located, they flashed bigger and smaller for positive reinforcement. These three alterations were included to make the task child-friendly. The child-friendly version was used with adults here for consistency and to enable comparisons between age groups. Furthermore, instead of pressing the spacebar to reveal the cursor, participants pressed the mouse. Because a higher resolution monitor was used for this task, the scenes were displayed centrally to occupy the same number of pixels (1680 by 1050) with a grey (153, 153, 153) border surrounding. To record eye gaze for both children and adults, the current study used a Tobii TX300 eye-tracker with gaze recorded from both eyes at 300 Hz following a 9-point calibration. This eye-tracker was used as it allows for greater head movement and does not require a chin rest, which is more practical and

better suited for children. Participants' eye gaze positions were calibrated before the start of each block.

2.3.2. Memory phase

This phase was identical to the previous study, but also included a cartoon themed introduction. After a short break, explicit memory for target locations was probed. Participants saw each scene with its accompanying social/non-social distractor in a random order. The target appeared in the center of each scene and participants could move it around the scene with the mouse, indicating the remembered location with a mouse click. The timing for these trials was self-paced.

2.3.3. Orienting phase

After the memory phase, participants took a break, which lasted approximately 30 min. Participants then engaged in a memory-guided orienting task in which they responded to the brief appearance of targets within their associated scenes. This task was a covert orienting task—participants were required to hold their gaze at a centrally located fixation cross present during the entire presentation of scenes.

Trials commenced with the presentation of a the central target (2.16 by 2.16° of visual angle) for 3000 ms. The scene appeared after a fixation cross presented on a blank screen for 500–1500 ms. The target object was presented superimposed on the scene for 100 ms after 1000–1500 ms. After target disappearance, the scene remained present for 1000 ms during a response window. A fixation point remained present throughout the trial (Fig. 2). After each trial, a fixation square lasting between 1000–1500 ms appeared, which prompted participants to get ready for the next trial. Participants responded to the presentation of the target object by pressing the left mouse button if the target appeared on the left and the right mouse button if the target appeared on the right. Although several previous studies using this memory-guided orienting task utilized a presence/absence version of the orienting task in which entire scenes were presented briefly (200 ms) (e.g. Patai et al., 2012), this version was chosen for being simpler for use with children. The preference for left / right vs. present / absent demands was driven also by our goal to reduce the overall duration of the session and limit fatigue in all participants and especially children: indeed, present / absent designs double the number of trials necessary to measure cue-validity effects (as these can only be measured in target-present trials). In half the scenes, the object appeared in the learned location (valid trials) and in the other half the object appeared in a new location on the opposite hemisphere (invalid trials).

This procedure was the same for both children and adults, except that, for the memory-guided attention orienting phase alone, eye tracking was used with children and not adults to ensure that child participants maintained fixation. In adults, fixation on the centre was ensured by monitoring lateral eye-movements through eye-channels placed at the outer canthi of their eyes (for adults only, these were used as part of a separate electroencephalographic study). It was important to encourage and ensure fixation on the centre for the orienting task, because overt eye-movements would confound any costs incurred by an

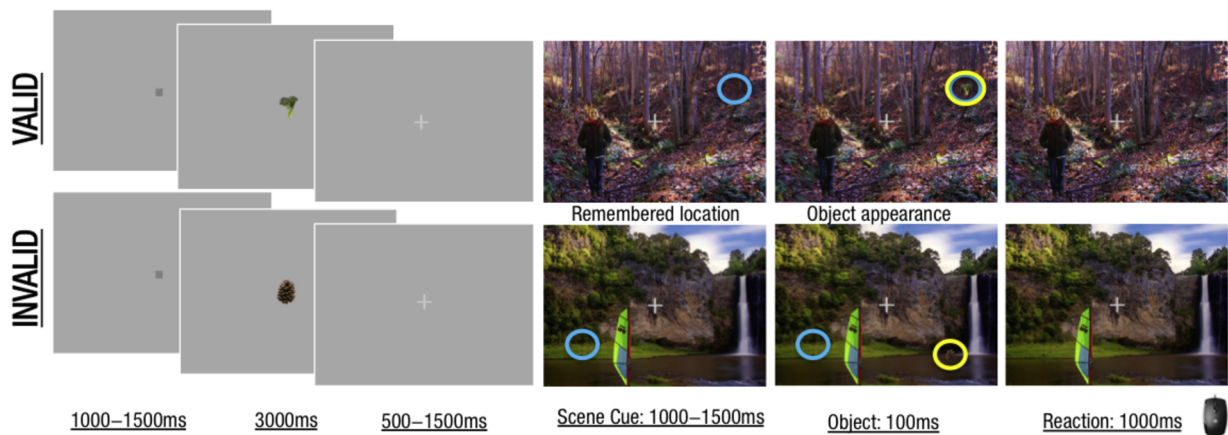


Fig. 2. Trial sequence for the orienting phase. Participants viewed: 1) a fixation square, 2) the centrally presented target, 3) a warning cross, 4) the scene cue, 5) the target appearance, 6) reaction time window.

invalid memory cue. However, here eye-tracking data did not constitute a key outcome measure. This is in contrast to the visual search phase, in which eye tracking was of interest as a technique and used with both children and adults. The experimenter also watched closely and reminded children to fixate centrally when necessary.

2.4. Statistical analysis

2.4.1. Visual search

Accuracy was calculated according to whether participants correctly clicked on the target within a buffer of 0.63° of visual angle. Search time (time from scene onset to click on the target) and first look (whether the first saccade and associated fixation after scene onset was to the distractor), were both calculated only for trials in which the target was accurately located during this phase of the experiment (See Table 1 for number of included trials).

2.4.2. Memory phase

Distance in pixels from the accurate target location to the recalled location for trials in which participants accurately found the target object at least once during the visual search task (See Table 1 for number of included trials).

2.4.3. Orienting phase

Accuracy was calculated as trials in which participants correctly responded to the location of the target appearance (on the left or right hemisphere) with the left or right mouse button, within the reaction time window. Reaction time (RT) from target onset to mouse press was calculated for accurate trials. Included trials for reaction-time analyses were also limited to trials in which participants accurately found the target object at least once during the visual search task, and trials in which the reaction time was within two standard deviations of the mean for that condition for that participant (See Table 1 for number of included trials).

Table 1
Number of trials included in analyses (out of 80).

	First look			Search time			Memory precision	Orienting phase RT
	Block 1	Block 2	Block 3	Block 1	Block 2	Block 3		
Child	60.87(15.94)	68.07(12.55)	70.40(11.71)	76.25(3.36)	77.56(2.06)	78.44(1.82)	79.38(1.02)	67.13(6.97)
Adult	72.25(9.84)	75.06(4.78)	76.81(2.59)	77.75(3.45)	77.94(1.88)	78.31(1.49)	79.38(1.02)	73.88(2.55)

Means with standard deviations in parentheses. See text for exclusion criteria.

2.4.4. AIC modeling

We analyzed each dependent measure via an information-theoretic (IT) approach that involves using Akaike’s information criterion (AIC) modeling (Burnham and Anderson, 2002). In this approach, a global linear mixed-effects model was created using all fixed predictor variables of interest, with subject and scene as random variables to account for the non-independence across trials within subjects and across blocks of the visual search task within scenes. Random slopes were included in the mixed-effects models according to the “best-path” method described in the literature (Barr et al., 2013). Next, a subset of candidate models that contained all possible combinations of the fixed effects included in the global model were specified. These candidate models were ranked according to their AIC score (lower scores indicate better fit), and the delta AIC (Δ_i) in relation to the highest-ranking model as well as the Akaike weight (w) were calculated using the R package MuMin (Bartón, 2015). Akaike weight based averaging over all candidate models allowed for the derivation of the mean estimates of the coefficients (θ) (calculated by averaging the estimates over all candidate models that included the θ of interest, weighted by w) and the 95% confidence intervals (CI) to determine which coefficients were statistically significantly different from zero.

We utilized this approach as it allowed us to include all trials in the analyses in contrast to averaging over trials, which incorporates the variance within subjects into the model. It also offers a more appropriate analysis of proportion data by using logit linear mixed-effects models for binomially distributed outcomes with the binary response variable first look (Jaeger, 2008). Finally, including scene as a random variable additionally accounted for variance between scenes, which aids in determining the strength of distractor effects beyond variability across scenes, also known as controlling for item effects (Baayen et al., 2008; Judd et al., 2012).

All models were checked for the assumptions of normality and homogeneity of variance using visual inspection in R. If data were not normally distributed, data were transformed with natural log (ln). The variable manual search time was transformed due to positive skew.

2.4.5. Eye-tracking processing

Eye-tracking data from the left eye were processed and analyzed using custom Matlab scripts. Gaze data was pre-processed for two purposes: 1) to replace invalid data or data during blinks with last good values, and 2) to exclude invalid trials from analyses. Gaze data points were considered invalid if one or both eyes were not found or recorded gaze was outside the screen area. Blinks were detected by zero values for pupil diameter, as well as instantaneous rate of change of pupil diameter greater than approximately 0.05 mm/ms for both eyes. Trials were flagged as invalid for any of the following reasons: 1) more than 1000 ms of consecutive invalid gaze points after scene onset, 2) more than 1000 ms of consecutive invalid gaze points immediately prior to target location, or 3) more than 40% of invalid gaze points throughout the trial. On average, approximately 4% of trials were excluded using these criteria. Fixations were calculated using a maximum velocity threshold of 75° of visual angle/second, a dispersion threshold of 0.5° of visual angle around the fixation centroid and a minimum duration threshold of 50 msec. Areas of Interest (AOIs) were hand drawn around distractors.

3. Results

3.1. Visual search

3.1.1. Accuracy (%)

For this analysis, logit mixed-effects models (Generalized Linear Mixed Effects Models for binomially distributed outcomes) were used in AIC modeling because accuracy was operationalized as a binary variable. Model averaging revealed a significant effect of both age and block on the model (Table 2), with poorer accuracy for children ($M = 96.77\%$, $SD = 2.64\%$) compared to adults ($M = 98.27\%$, $SD = 2.09\%$). Overall, accuracy increased over blocks (block 1: $M = 96.63\%$, $SD = 2.83\%$; block 2: $M = 97.57\%$, $SD = 2.08\%$; block 3: $M = 98.36\%$, $SD = 1.91\%$).

3.1.2. Search time (s)

AIC model averaging on search time during the visual search task revealed that the coefficient estimates for both age (with slower search times for children compared to adults) and block (with search time decreasing over blocks) were significantly different from zero, as well as the estimates for the block-by-distractor and age-by-block interactions (Table 2). In order to interpret the estimates for these interactions effects, a mixed-model ANOVA with two within-subjects factors (distractor: social, non-social; block: one, two, three) and one between-subjects factor (age: child, adult) was carried out. The linear contrast of the block-by-distractor interaction reached significance, $F(1, 30) = 6.12$, $p = 0.019$, $\eta^2 = 0.17$. Extracting the regression slopes for each participant for social and non-social scenes separately showed steeper negative slopes for non-social scenes ($M = -0.31 \ln(s)$, $SD = 0.04 \ln(s)$) compared to social scenes ($M = -0.29 \ln(s)$, $SD = 0.04 \ln$

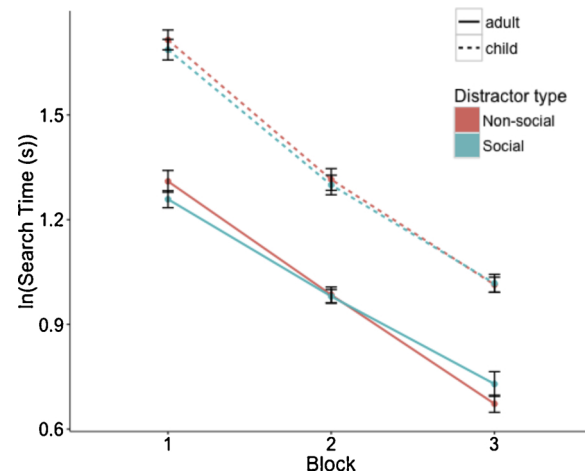


Fig. 3. Log-transformed visual-search time over three blocks for children and adults. The distractor-by-block interaction had a significant effect on the model, with shallower search slopes for social scenes compared to non-social scenes for both children and adults, indicative of slower improvement over blocks for social scenes. Error bars are standard errors of the mean (SEMs).

(s)) (Fig. 3). There were significant differences between blocks for children and adults separately (all $p < 0.001$), and likewise significant differences between adults and children for each block separately (block one: $p < 0.001$, block two: $p = 0.002$, block three: $p = 0.003$), therefore it was difficult to determine the source of this interaction effect.

3.1.3. First look (yes/no)

For this analysis, logit mixed-effects models (Generalized Linear Mixed Effects Models for binomially distributed outcomes) were used in AIC modeling because first looks on the distractor were operationalized as a binary variable. There were significant effects of distractor (with more first looks to social compared to non-social distractors), as well as the age-by-distractor and distractor-by-block interactions on the model (Table 2). A mixed-model ANOVA with two within-subjects factors (distractor: social, non-social; block: one, two, three) and one between-subjects factor (age: child, adult) was carried out to interpret the estimates for these interaction effects. Post-hoc analyses revealed the distractor-by-block interaction to be driven by significantly greater proportion of first looks to social distractors compared to non-social distractors in block one ($p < 0.001$), but no significant difference in blocks two ($p = 0.087$) or three ($p = 0.101$). Post-hoc analyses revealed the age-by-distractor interaction to be driven by significantly greater proportion of first looks to social compared to non-social distractors for children ($p < 0.001$), but not for adults ($p > 0.250$). This was due to a significantly greater proportion of first looks to social distractors for children compared to adults ($p > 0.001$), however no

Table 2

Model averaging with parameters related to the dependent measures during visual search.

Predictor	Search time (ln(s))				First look (yes/no)				Accuracy (%)			
	Estimate	l-95% CI	u-95% CI	p-value	Estimate	l-95% CI	u-95% CI	p-value	Estimate	l-95% CI	u-95% CI	p-value
(Intercept)	1.188	1.08	1.295	< 0.001	-1.953	-2.304	-1.61	< 0.001	4.521	3.792	5.245	< 0.001
Age	0.434	0.297	0.573	< 0.001	0.273	-0.024	0.569	0.071	-0.882	-1.686	-0.079	0.032
Block	-0.556	-0.638	-0.468	< 0.001	-0.108	-0.363	0.158	0.433	0.706	0.227	1.205	0.006
Distractor	-0.025	-0.062	0.011	0.175	0.615	0.229	0.996	0.002	0.129	-0.284	0.515	0.559
Age x Distractor	-0.011	-0.058	0.037	0.632	0.472	0.092	0.853	0.015	-0.329	-0.927	0.262	0.283
Block x Distractor	0.06	0.013	0.106	0.012	-0.484	-0.822	-0.146	0.005	0.024	-0.741	0.788	0.952
Age x Block	-0.116	-0.196	-0.036	0.004	0.226	-0.125	0.579	0.202	0.508	-0.24	1.25	0.185
Age x Block x Distractor	-0.061	-0.138	0.017	0.128	-0.319	-0.952	0.313	0.322	-1.067	-2.588	0.454	0.169

For each parameter and dependent measure, this table presents the averaged coefficient estimates (θs), and the 95% confidence intervals (CI, l = lower, u = upper) based on estimated unconditional variance. Estimates in bold differed statistically from zero based on 95% CIs with $p < 0.05$.

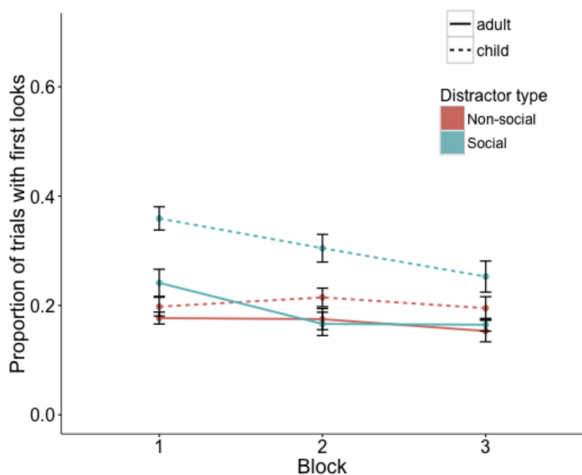


Fig. 4. Proportion of trials with first looks to the distractor over three blocks for both children and adults. While children demonstrated a significantly greater proportion of first looks to social distractors compared to non-social distractors overall, adults showed only a significant difference in the first block, indicative of a rapidly diminishing attentional capture. Error bars are SEMs.

difference in proportion of looks to non-social distractors ($p = 0.207$) (Fig. 4).

3.1.4. Memory phase

AIC model averaging revealed the coefficient estimates for age and distractor to be significantly different from zero (Table 3), with better memory precision (smaller distance in pixels between recalled and actual target location) for children compared to adults, and with poorer precision for social compared to non-social scenes (Fig. 5).

3.2. Orienting phase

3.2.1. Accuracy (%)

For this analysis, logit mixed-effects models (Generalized Linear Mixed Effects Models for binomially distributed outcomes) were used in AIC modeling because accuracy was operationalized as a binary outcome. Model analysis of accuracy in the orienting task revealed a significant effect of age on the model (Table 4), with poorer accuracy for children ($M = 88.62\%$, $SD = 9.83\%$) compared to adults ($M = 98.26\%$, $SD = 3.06\%$).

3.2.2. RT (s)

With RT during the orienting phase as the dependent measure, AIC model averaging revealed a significant effect of age (with children being slower than adults), validity (with RT slower on invalid compared to valid trials, and the age-by-validity interaction on the model (Table 4). There were also marginally significant effects of the distractor-by-validity, age-by-distractor, and the age-by-distractor-by-validity interactions. A mixed-model ANOVA with two within-subjects factors (distractor: social, non-social; validity: valid, invalid) and one

Table 3
Model averaging with parameters related to memory error (pixels from target).

H	Estimate	l-95% CI	u-95% CI	p-value
(Intercept)	162.48	123.206	201.637	< 0.001
Age	-85.14	-139.719	-29.91	0.002
Distractor	25.36	3.705	47.134	0.022
Age x Distractor	-18.78	-48.385	10.833	0.214

For each parameter, this table presents the averaged coefficient estimates (θ s), and the 95% confidence intervals (CI, l = lower, u = upper) based on estimated unconditional variance. Estimates in bold differed statistically from zero based on 95% CIs with $p < 0.05$.

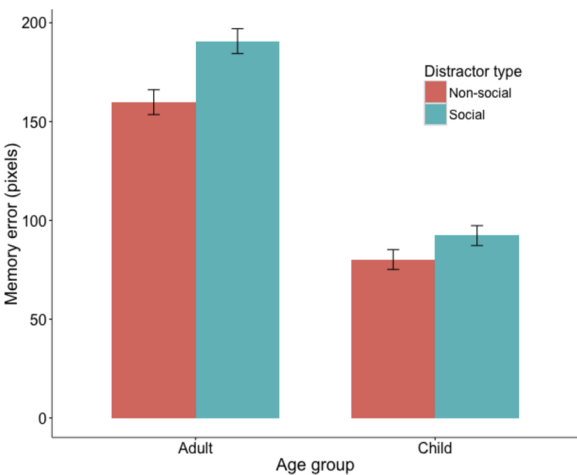


Fig. 5. Memory error (distance in pixels between the recalled and accurate target location) for children and adults. Children demonstrated better memory precision compared to adults, while overall memory precision for social scenes was poorer compared to non-social scenes. Error bars are SEMs.

between-subjects factor (age: adult, child) was carried out to interpret these effects. The significant interaction between age and validity was driven by significant differences between children and adults for both valid and invalid trials ($p < 0.001$) as well as significant differences between valid and invalid trials for both children and adults ($p < 0.001$). However, examining the difference score between invalid and valid trials showed a significantly greater validity effect for children compared to adults ($p = 0.015$) (Fig. 6).

3.3. Cross-measure relationships

3.3.1. Visual search, search time (s)

To investigate whether gaze behavior towards distractors predicted search time during the visual-search task, similar to adults in the previous study, and to test whether this relationship differed between children and adults, AIC model averaging was conducted with first look, distractor, age, and block as well as all possible interactions between these variables entered as predictors for search time. No significant effects or interactions occurred for first look (results not shown here).

3.3.2. Memory phase, memory error (pixels)

To investigate whether gaze behavior or search slope during the visual-search task predicted memory error during the memory phase, as well as whether this relationship differed between children and adults, search-time slope (the slope of the search times across all three blocks for a particular scene), first-look proportion (the proportion of the blocks out of three in which the participant made a first look at the distractor for a particular scene), distractor, age, and their interactions were entered as predictors for memory error in model averaging. In addition to the effects seen in the memory-phase analyses above (age, distractor), there was a significant effect of search-time slope, with shallower slopes associated with poorer memory precision, similar to the adults in Doherty et al. (2017). However, this effect was also qualified by a significant interaction between age and search-time slope (Table 5). Post-hoc analyses with subject averages revealed this interaction to be driven by a significant positive relationship between search-time slope and memory precision for adults ($r = 0.71$, $p = 0.002$), but not for children ($r = 0.14$, $p > 0.250$).

3.3.3. Orienting phase, RT (s)

Finally, to determine the presence of a relationship between memory precision during the memory phase and the validity effect in

Table 4
Model averaging with parameters relevant for dependent measures during the orienting phase.

Predictor	RT (s)				Accuracy (%)			
	Estimate	l-95% CI	u-95% CI	p-value	Estimate	l-95% CI	u-95% CI	p-value
(Intercept)	0.399	0.354	0.441	< 0.001	4.89	3.914	5.83	< 0.001
Age	0.175	0.116	0.24	< 0.001	-2.412	-3.492	-1.294	< 0.001
Distractor	0.011	-0.006	0.029	0.209	-0.264	-0.806	0.295	0.388
Validity	-0.035	-0.054	-0.013	0.002	-0.1	-0.805	0.667	0.804
Age x Validity	-0.037	-0.064	-0.009	0.009	0.549	-0.394	1.497	0.261
Distractor x Validity	-0.02	-0.042	0.002	0.073	-0.068	-0.736	0.609	0.86
Age x Distractor	-0.019	-0.042	0.003	0.097	0.231	-0.711	1.181	0.636
Age x Distractor x Validity	0.026	-0.004	0.056	0.087	0.225	-1.688	2.139	0.818

For each parameter and dependent measure, this table presents the averaged coefficient estimates (θ s), and the 95% confidence intervals (CI, l = lower, u = upper) based on estimated unconditional variance. Estimates in bold differed statistically from zero based on 95% CIs with $p < 0.05$.

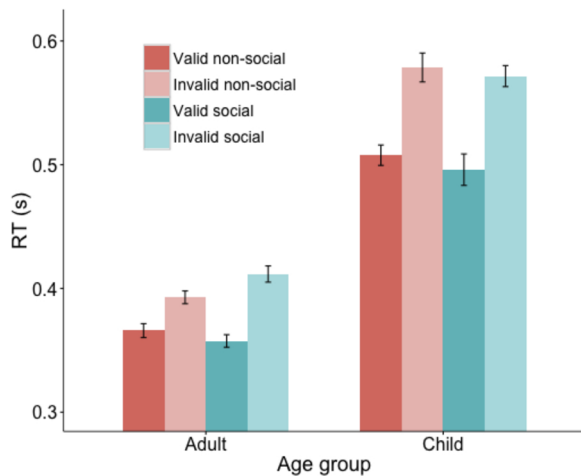


Fig. 6. Reaction time (RT) in seconds during the orienting phase for both children and adults. Children were slower to react, but also demonstrated a larger validity effect (the difference between invalid and valid trials) when compared to adults. Error bars are SEMs.

Table 5
Visual search measures (search-time slope and first-look proportion) as predictors for memory error during the memory phase.

Predictor	Estimate	l-95% CI	u-95% CI	p-value
(Intercept)	159.211	120.953	197.482	< 0.001
Age	-81.99	-135.919	-28.178	0.003
Search-time slope	27.785	9.736	46.429	0.003
Distractor	26.691	4.794	48.465	0.017
Age x search-time slope	-25.894	-47.461	-4.358	0.019
Distractor x learn slope	15.74	-4.988	36.437	0.138
First-look proportion	10.467	-6.147	26.779	0.216
Age x first-look proportion	-15.292	-36.421	5.929	0.159
Distractor x first-look proportion	-12.364	-33.323	8.667	0.251
Age x distractor	-3.815	-45.134	37.501	0.857
Age x search-time slope x distractor	-6.862	-48.38	34.151	0.745
Age x first-look proportion x distractor	15.005	-25.849	56.14	0.473

For each parameter and dependent measure, this table presents the averaged coefficient estimates (θ s), and the 95% confidence intervals (CI, l = lower, u = upper) based on estimated unconditional variance. Estimates in bold differed statistically from zero based on 95% CIs with $p < 0.05$.

the orienting phase, as well as any differences in this relationship between children and adults, memory error, distractor, validity, age, and their interactions were entered as predictors for RT in the orienting phase. In addition to the effects seen in the orienting phase analysis above (age, validity, age-by-validity), AIC model averaging revealed

Table 6
Memory error during the memory phase as a predictor for orienting phase RT.

Predictor	Estimate	l-95% CI	u-95% CI	p-value
(Intercept)	0.4	0.352	0.446	< 0.001
Age	0.178	0.109	0.249	< 0.001
Memory error	-0.002	-0.011	0.006	0.557
Distractor	0.013	-0.005	0.032	0.179
Validity	-0.036	-0.06	-0.011	0.004
Age x distractor	-0.025	-0.054	0.003	0.095
Age x validity	-0.045	-0.081	-0.009	0.014
Memory error x validity	0.011	0.001	0.021	0.028
Distractor x validity	-0.025	-0.05	-0.001	0.047
Age x distractor x validity	0.042	0.008	0.076	0.015
Memory error x distractor	-0.004	-0.015	0.006	0.415
Age x memory error	-0.009	-0.036	0.018	0.51
Age x memory error x distractor	0.026	-0.007	0.059	0.122
Age x memory error x validity	0.013	-0.018	0.042	0.411
Memory error x distractor x validity	-0.003	-0.021	0.016	0.756
Age x memory error x distractor x validity	0.037	-0.029	0.103	0.268

For each parameter, this table presents the averaged coefficient estimates (θ s), and the 95% confidence intervals (CI, l = lower, u = upper) based on estimated unconditional variance. Estimates in bold differed statistically from zero based on 95% CIs with $p < 0.05$.

significant interactions between memory error and validity, distractor and validity, and among age, distractor and validity (Table 6). Following up the interaction between memory error and validity showed there was a significant negative correlation between memory error and the validity effect (invalid – valid trials), $r = -0.38$, $p = 0.033$. Better memory precision (smaller error value) was associated with a larger validity effect. There were, however no significant correlations between memory error and RT for valid and invalid trials separately ($p > 0.250$).

To follow up the age-by-distractor-by-validity interaction, model averaging was run for adults and children separately. Whereas adults demonstrated a significant effect of the distractor-by-validity interaction ($p < 0.001$), children did not ($p > 0.250$) (results not shown). Although post-hoc analyses with adults show very significant differences between valid and invalid trials for social and non social scenes separately ($p < 0.001$), and no significant differences between social and non-social scenes for valid ($p > 0.250$) and invalid trials ($p = 0.220$), examining validity scores (invalid-valid trials) reveals a significant difference in scores between social and non-social scenes, with a larger validity effect for social scenes compared to non-social scenes for adults only (Fig. 6). Interestingly, while adults demonstrated the memory error-by-validity interaction ($p = 0.045$), children did not ($p = 0.190$) (results not shown).

4. Discussion

The current study sought to investigate the developmental interplay

between social attention biases, memory and attention orienting, by comparing children 6–10 years-old and young adults, as well as investigating any age-related similarities or differences in the functional consequences of social distraction on memory and subsequent memory-guided attention orienting. Overall, our findings suggest complex interactions between social attentional biases during learning, their impact on memory and memory-guided orienting. Crucially, these interactions are modulated by age in both expected and surprising ways.

As we had predicted, children were indeed distracted by social stimuli, as were adults. Although children were overall slower to locate targets in the visual search task, they demonstrated a similar difference in search slopes, with shallower search slopes for social scenes. In addition, eye-tracking revealed even greater attentional capture by social distractors for children, who showed a greater proportion of first looks to social distractors over all three blocks, whereas adults only demonstrated greater attentional capture to social distractors in the first block. Children's social distraction during visual search was followed by differential memory performance between social and non-social scenes. Intriguingly, children demonstrated better overall memory precision than young adults; however, both adults and children showed poorer memory precision for social scenes. Adults demonstrated a greater validity effect when orienting attention in social scenes. Interestingly, this was not the case for children: poorer explicit memory for social scenes did not translate into differences in subsequent memory-guided attention orienting for children. Children demonstrated a strong validity effect overall, but no difference in this effect between social and non-social scenes. As several novel findings emerged, we begin by focusing on those of greater interest to developmentalists, the age-related differences, to then detail further observations that emerge from the adult data alone.

4.1. Age differences in social attention, memory precision and memory-guided orienting

The current study extends significantly the literature on social attention, memory and memory-guided orienting in children. While it has been reported previously that school-age children are capable of implicit memory-guided attention via the contextual cuing literature (Couperus et al., 2010; Dixon et al., 2010; Merrill et al., 2013; Yang and Merrill, 2014, 2015a, b), we report that children are capable of memory-guided attention even when memories are acquired through a separate learning task with naturalistic stimuli. These findings converge with a recent developmental study of memory-guided attention (Nussenbaum et al., 2018). Previous fMRI studies using the same memory-guided attentional orienting paradigm as the current study have implicated both the fronto-parietal orienting network, which has been described for perceptual-cue driven orienting as well as for memory-guided orienting, as well as a unique contribution of the hippocampus to memory-guided orienting exclusively (Stokes et al., 2012; Summerfield et al., 2006), although these associations have yet to be tested more causally with lesion patients. The current study therefore supports the idea that although the medial temporal lobe, including the hippocampus, continues to develop into adolescence, (Ghetti and Bunge, 2012; Ghetti et al., 2010; Menon et al., 2005; Paz-Alonso et al., 2008), some functional aspects of this brain system may be early developing (e.g., Suddendorf et al., 2011) and may interact quite efficiently with the developing dorsal fronto-parietal attention network (Pozuelos et al., 2014) to guide attention in childhood (Nussenbaum et al., 2018). As a whole these data suggest a subtle view on the developmental cognitive neuroscience of memory-guided attention: while the basic circuitry might be set up early, there also seems to be considerable development in recruitment of medial temporal cortex and its connections with other regions. Indeed, several studies support the emergence of episodic memory relatively early in development, with some aspects apparent from early childhood (Suddendorf et al., 2011) and considerable later changes (Ghetti and Bunge, 2012; Ghetti et al.,

2010).

Open questions stem from the finding of greater attentional capture by social stimuli for children compared to adults, indexed by eye-movements. The fact that there was no difference in attentional capture to equally salient non-social distractors between children and adults suggests that both groups were attracted by social stimuli rather than by perceptual salience *per se*. This finding is consistent with literature demonstrating a bias towards social stimuli in young children that goes beyond low-level perceptual salience (Amso et al., 2014; Frank et al., 2009). Of note, children's attentional capture was greater during learning than adults' and this extends the literature that suggests a similar bias towards and processing of faces between children and adults (LoBue, 2009; Mondloch et al., 2007), to suggest an even stronger attentional capture by social stimuli in children. Whether this was due to a greater social bias or rather due to more general attention immaturity, such as a poorer ability to inhibit attention capture by the irrelevant social stimuli, could not be determined by the current study. Further work is necessary to explore the mechanism behind greater attentional capture by social stimuli in children.

Perhaps one of the most surprising aspects of the current study is the overall enhanced memory precision for children compared to adults in the explicit memory task. Previous studies have shown protracted development of memory precision between 6–10 years for working memory (Burnett Heyes et al., 2016), episodic memory (e.g. DeMaster and Ghetti, 2013), as well as spatial relational place learning (Townsend et al., 2010). A simple possibility is that children here may have been more motivated to complete the task well. Although adults and children participated in the same task, including the cartoon themed features, and both groups reported appreciating the cartoon theme as alleviating fatigue, anecdotally children were much more engaged with earning points. Could differences in engagement and task demands have resulted in greater memory precision for children? The child friendly nature of protocol was necessary to keep children engaged in a relatively long and demanding task, and is common when tasks are adapted for use with young participants, adults may not have performed at their best, given the child friendly theme. Indeed, task demands may play an important role in age-related differences in performance (e.g., Imuta et al., 2015; Gross et al., 2016). However, we do not believe that these demand differences account for adults' poorer performance here. The pattern of results obtained with this child-friendly theme and performance by a different sample of adults, assessed with the same natural scenes and task demands, but without the child friendly theme (in Doherty et al., 2017), showed no qualitative difference in performance by the two groups of adults.

Another possibility is that the significantly longer time and effort spent searching by children during the visual-search task proved beneficial for exploration of the scenes, and therefore, in the long run, memory performance. Longer search times compared to adults may have allowed children to encode the context of the scenes better, enhancing memory precision for target locations. Indeed, a study with children 8–12 years old found a u-shaped relationship between search speed and contextual cueing effects, with intermediate length search speed associated with the largest contextual cueing effect (Darby et al., 2014). Furthermore, other work suggests that attentional guidance only improves contextual cueing in adults when participants are forced to take longer to find targets due to increased difficulty (Kunar et al., 2008). Broader work on greater exploratory behaviour in children compared to adults (Gopnik et al., 2017) is also consistent with better memory precision by children here.

Interestingly, although adults showed a relationship between search slope in the visual-search task and memory precision in the memory phase followed by a relationship between memory precision and RT in the memory-guided orienting phase, within the constraints of our small sample, for children these relationships did not reach statistical significance. At first glance, this difference may suggest that only in adults does social distraction act mechanistically to affect explicit memory,

which in turn affects subsequent attention orienting. However, this is very unlikely, and will need to be investigated in a larger sample of children, who will also allow testing alternative hypotheses about cross-task relationships. For example, it is possible that this discrepancy is due to overall better memory precision for children discussed above, as well as the overall slower RT in the orienting phase—general performance differences that may overpower any relationships across the tasks. Moreover, it may be that for children what is more relevant to memory performance is not the learning slope over blocks, but simply length of time spent searching. It is perhaps overall slower search times, either calculated by the average of the three blocks or the intercept, that may lead to better memory performance for children, whereas in adults improvement over blocks may be more important. A preliminary analysis of the current data, however, shows that search time does not remove the greater precision by children and it is not an overall predictor of memory precision across this sample. Further study could test these hypotheses. It is also possible that the mechanism underlying these tasks is different for children. While memory-guided orienting in the current study may be driven by more explicit memory for adults, it is possible that implicit memory is more important for children. Further study is necessary to investigate these hypotheses.

Indeed, a number of limitations need to be addressed before conclusions on these developmental differences can truly be drawn. First of all, the sample of children assessed here was small and covered a broad age range over mid-childhood. This requires addressing, as both attentional (Pozuelos et al., 2014) and medial temporal circuits (Ghetti et al., 2010) develop over this period. A much larger replication exercise is under way, with a larger sample and one that is optimized to test differences in behaviour and eye-movements *within* childhood, both of which fall out the important developmental literature on memory development over childhood (DeMaster and Ghetti, 2013; Ghetti and Bunge, 2012), but could not be studied because of the small sample size. Another limitation of this study was the use of images of adults as stimuli, which may not have been the best for eliciting social distraction in children. This is particularly relevant in light of the literature that demonstrates an “own-age bias” for face recognition, such that memory for faces is poorer for faces that are of a different age group than yourself (see Rhodes and Anastasi, 2012 for a meta-analysis). This may account for the fact that although there was poorer memory for social scenes when including both children and adults, this difference was not as pronounced for children. Again, this suggestion would need to be investigated further in children using children as social distractors. We now turn to novel mechanistic insights that come from our data alone.

4.2. Adult mechanisms of social distraction and memory guidance

Important to note is the fact that the current study replicated the main results from a previous study (Doherty et al., 2017), despite several differences in methodology and narrative used to introduce the task. First, we replicated the difference in search time slopes for social and non-social scenes during the visual search task, with shallower slopes over three blocks for social scenes. This subtle difference was subsequently followed by a pronounced difference in memory precision, with poorer memory for social scenes, similar to the previous study. Finally, we replicated the cross-task relationship whereby search slope during visual search predicted memory precision in the memory phase, with shallow search slopes relating to poorer precision, but we also extended this previous study by showing that memory precision is also correlated with subsequent attention orienting.

Despite the similarities, there are also subtle differences in the results between these two adult studies. Whereas participants in previous study made more first looks to social distractors compared to non-social distractors across blocks, participants in the current study only made more first looks to social distractors in the first block. Gaze behavior and search time therefore diverged with regards to social distraction—while search time indicated social distraction over all three

blocks, first look suggested social distraction only in the first block. It is therefore possible that these measures reflect different aspects of social distraction: while first looks may index more automatic distraction effects, search time may index more voluntary processes that are then related to how efficient the search is. This hypothesis would need to be investigated further. Additionally, although we demonstrated a relationship between first looks and search time in the previous study, we did not observe this relationship here. Given these discrepancies, it becomes clear that although participants may consistently demonstrate social distraction in their search times and memory precision, there is more variability in the degree of overt attention capture as measured by gaze behavior.

One intriguing finding from the current study is the fact that although we show *poorer* explicit memory for social compared to non-social scenes, adults show a *greater* validity effect for social scenes. This is particularly surprising as we also show a cross-task relationship whereby greater memory performance is associated with a greater validity effect in adults. One hypothesis is that while explicit memory for social scenes is poorer, implicit memory, which has also been implicated in the orienting phase in addition to explicit memory (Summerfield et al., 2006), may be better. Indeed, other work with a similar paradigm and healthy ageing participants suggests that explicit contextual memory is not necessary for memory-guided attention to spatial locations in natural scenes (Salvato et al., 2016a, b). Further research is necessary to explore this hypothesis. Another possibility is that the orienting phase was overall more difficult in trials with social scenes compared to non-social scenes. Previous literature reports larger validity effects with increased task difficulty for endogenous cues (arrow cues) compared to exogenous cues (Berger et al., 2005). Inclusion of neutral trials may help in exploring this hypothesis by determining if RTs are longer for neutral social compared to neutral non-social trials. There is also the possibility that social memories carry added arousal value, which may in turn potentiate attention orienting effects (Fan et al., 2009; Petersen and Posner, 2012).

Overall, our study highlights both expected and surprising differences in social attentional biases, memory for target locations and memory-guided attention in children and adults. The current study extends the literature on memory-guided attention in children by demonstrating the capacity for acquired memories to affect attention orienting in 6–10 year-old children. The current study also demonstrates that social stimuli attract children's attention during visual search with natural scenes. Of note, while social distraction during learning has an effect on subsequent memory, and on memory-guided attention orienting in young adults, for children these effects are more subtle. Most intriguingly, children's memory precision for target location is better than adults' memory. In turn, our findings suggest that attentional guidance is exquisitely dependent on the age of the observers, on the characteristics of the learning context (e.g., social vs. non-social) and the resulting memory traces.

Conflict of Interest

None.

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References

- Amso, D., Haas, S., Markant, J., 2014. An eye tracking investigation of developmental change in bottom-up attention orienting to faces in cluttered natural scenes. *PLoS One* 9 (1), e85701. <https://doi.org/10.1371/journal.pone.0085701>.
- Astle, D.E., Scerif, G., 2011. Interactions between attention and visual short-term memory (VSTM): what can be learnt from individual and developmental differences? *Neuropsychologia* 49 (6), 1435–1445. <https://doi.org/10.1016/j.neuropsychologia.2010.12.001>.
- Baayen, R.H., Davidson, D.J., Bates, D.M., 2008. Mixed-effects modeling with crossed random effects for subjects and items. *J. Memory Lang.* 59 (4), 390–412. <https://doi.org/10.1016/j.jml.2007.12.005>.
- Barr, D.J., Levy, R., Scheepers, C., Tily, H.J., 2013. Random effects structure for confirmatory hypothesis testing: keep it maximal. *J. Mem. Lang.* 68 (3), 255–278. <https://doi.org/10.1016/j.jml.2012.11.001>.
- Bartón, K., 2015. MuMIn: Multi-Model Inference. February 25 Retrieved from. <http://CRAN.R-project.org/package=MuMIn>.
- Berger, A., Henik, A., Rafal, R., 2005. Competition between endogenous and exogenous orienting of visual attention. *J. Exp. Psychol. Gen.* 134 (2), 207–221. <https://doi.org/10.1037/0096-3445.134.2.207>.
- Burnett Heyes, S., Zokaei, N., Husain, M., 2016. Longitudinal development of visual working memory precision in childhood and early adolescence. *Cogn. Dev.* 39, 36–44. <https://doi.org/10.1016/j.cogdev.2016.03.004>.
- Burnham, K.P., Anderson, D.R., 2002. *Model Selection and Multi-model Inference: a Practical Information-theoretic Approach*. Springer New York, New York, NY. <https://doi.org/10.1007/b97636>.
- Chun, M.M., Jiang, Y., 1998. Contextual cueing: implicit learning and memory of visual context guides spatial attention. *Cogn. Psychol.* 36 (1), 28–71. <https://doi.org/10.1006/cogp.1998.0681>.
- Chun, M.M., Turk-Browne, N.B., 2007. Interactions between attention and memory. *Curr. Opin. Neurobiol.* 17 (2), 177–184. <https://doi.org/10.1016/j.conb.2007.03.005>.
- Couperus, J.W., Hunt, R.H., Nelson, C.A., Thomas, K.M., 2010. Visual search and contextual cueing: differential effects in 10-year-old children and adults. *Atten. Percept. Psychophys.* 73 (2), 334–348. <https://doi.org/10.3758/s13414-010-0021-6>.
- Darby, K., Burling, J., Yoshida, H., 2014. The role of search speed in the contextual cueing of children's attention. *Cogn. Dev.* 29, 17–29. <https://doi.org/10.1016/j.cogdev.2013.10.001>.
- DeMaster, D.M., Gheiti, S., 2013. Developmental differences in hippocampal and cortical contributions to episodic retrieval. *Cortex* 49 (6), 1482–1493.
- Dixon, M.L., Zelazo, P.D., De Rosa, E., 2010. Evidence for intact memory-guided attention in school-aged children. *Dev. Sci.* 13 (1), 161–169. <https://doi.org/10.1111/j.1467-7687.2009.00875.x>.
- Doherty, B.R., Patai, E.Z., Duta, M., Nobre, A.C., Scerif, G., 2017. The functional consequences of social distraction: attention and memory for complex scenes. *Cognition* 158 (C), 215–223. <https://doi.org/10.1016/j.cognition.2016.10.015>.
- Fagan, J.F., 1972. Infants' recognition memory for faces. *J. Exp. Child Psychol.* 14 (3), 453–476.
- Fan, J., Gu, X., Guise, K.G., Liu, X., Fossella, J., Wang, H., Posner, M.I., 2009. Testing the behavioral interaction and integration of attentional networks. *Brain Cogn.* 70 (2), 209–220. <https://doi.org/10.1016/j.bandc.2009.02.002>.
- Frank, M.C., Vul, E., Johnson, S.P., 2009. Development of infants' attention to faces during the first year. *Cognition* 110 (2), 160–170. <https://doi.org/10.1016/j.cognition.2008.11.010>.
- Frank, M.C., Amso, D., Johnson, S.P., 2014. Visual search and attention to faces during early infancy. *J. Exp. Child Psychol.* 118, 13–26. <https://doi.org/10.1016/j.jecp.2013.08.012>.
- Gheiti, S., Bunge, S.A., 2012. Neural changes underlying the development of episodic memory during middle childhood. *Dev. Cogn. Neurosci.* 2 (4), 381–395. <https://doi.org/10.1016/j.dcn.2012.05.002>.
- Gheiti, S., DeMaster, D.M., Yonelinas, A.P., Bunge, S.A., 2010. Developmental differences in medial temporal lobe function during memory encoding. *J. Neurosci.* 30, 9548–9556. <https://doi.org/10.1523/JNEUROSCI.3500-09.2010>.
- Goldfarb, E.V., Chun, M.M., Phelps, E.A., 2016. Memory-guided attention: independent contributions of the Hippocampus and striatum. *Neuron* 89 (2), 317–324. <https://doi.org/10.1016/j.neuron.2015.12.014>.
- Gopnik, A., O'Grady, S., Lucas, C.G., Griffiths, T.L., Wente, A., Bridgers, S., Aboody, R., Fung, H., Dahl, R.E., 2017. Changes in cognitive flexibility and hypothesis search across human life history from childhood to adolescence to adulthood. *Proc. Natl. Acad. Sci. U. S. A.* <https://doi.org/10.1073/pnas.1700811114>.
- Griffin, I.C., Nobre, A.C., 2003. Orienting attention to locations in internal representations. *J. Cogn. Neurosci.* 15 (8), 1176–1194. <https://doi.org/10.1162/08999290322598139>.
- Gross, J., Gardiner, B., Hayne, H., 2016. Developmental reversals in recognition memory in children and adults. *Dev. Psychobiol.* 58, 52–59. <https://doi.org/10.1002/dev.21344>.
- Harel, J., Koch, C., Perona, P., 2006. Graph-based visual saliency. *Proceedings of Neural Information Processing Systems (NIPS)*.
- Hutchinson, J.B., Turk-Browne, N.B., 2012. Memory-guided attention: control from multiple memory systems. *Trends Cogn. Sci.* 16 (12), 576–579. <https://doi.org/10.1016/j.tics.2012.10.003>.
- Imuta, K., Hewitt, J., Scarf, D., 2015. Gollin's (1965) levels-by-levels approach: the importance of manipulating the task dimension when assessing age-related changes and individual differences in decision making. *Front. Psychol.* 541, 1–4. <https://doi.org/10.3389/fpsyg.2015.00541>.
- Jaeger, T.F., 2008. Categorical data analysis: away from ANOVAs (transformation or not) and towards logit mixed models. *J. Memory Lang.* 59 (4), 434–446. <https://doi.org/10.1016/j.jml.2007.11.007>.
- Judd, C.M., Westfall, J., Kenny, D.A., 2012. Treating stimuli as a random factor in social psychology: a new and comprehensive solution to a pervasive but largely ignored problem. *J. Personality Social Psychol.* 103 (1), 54–69. <https://doi.org/10.1037/a0028347>.
- Kapur, N., Friston, K.J., Young, A., Frith, C.D., Frackowiak, R.S., 1995. Activation of human hippocampal formation during memory for faces: a PET study. *Cortex* 31 (1), 99–108.
- Kuhl, B.A., Chun, M.M., 2014. Memory and attention. In: Nobre, A.C.K., Kastner, S. (Eds.), *The Oxford Handbook of Attention Vol. 1*. Oxford University Press. <https://doi.org/10.1093/oxfordhob/9780199675111.001.0001>.
- Kunar, M.A., Flusberg, S.J., Wolfe, J.M., 2008. Time to guide: evidence for delayed attentional guidance in contextual cueing. *Vis. Cogn.* 16 (6), 804–825. <https://doi.org/10.1080/13506280701751224>.
- Langton, S.R., Bruce, V., 1999. Reflexive visual orienting in response to the social attention of others. *Vis. cogn.* 6 (5), 541–567. <https://doi.org/10.1080/135062899394939>.
- Langton, S.R., Law, A.S., Burton, A.M., Schweinberger, S.R., 2008. Attention capture by faces. *Cognition* 107 (1), 330–342. <https://doi.org/10.1016/j.cognition.2007.07.012>.
- LoBue, V., 2009. More than just another face in the crowd: superior detection of threatening facial expressions in children and adults. *Dev. Sci.* 12 (2), 305–313. <https://doi.org/10.1111/j.1467-7687.2008.00767.x>.
- Menon, V., Boyett-Anderson, J.M., Reiss, A.L., 2005. Maturation of medial temporal lobe response and connectivity during memory encoding. *Brain Res. Cogn. Brain Res.* 25 (1), 379–385. <https://doi.org/10.1016/j.cogbrainres.2005.07.007>.
- Merrill, E.C., Conners, F.A., Roskos, B., Klinger, M.R., Klinger, L.G., 2013. Contextual cueing effects across the lifespan. *J. Genet. Psychol.* 174 (4), 387–402. <https://doi.org/10.1080/00221325.2012.694919>.
- Mondloch, C.J., Pathman, T., Maurer, D., Le Grand, R., de Schonen, S., 2007. The composite face effect in six-year-old children: evidence of adult-like holistic face processing. *Vis. Cogn.* 15 (5), 564–577. <https://doi.org/10.1080/13506280600859383>.
- Morton, J., Johnson, M.H., 1991. CONSPEC and CONLERN: a two-process theory of infant face recognition. *Psychol. Rev.* 98 (2), 164–181.
- Nussenbaum, K., Scerif, G., Nobre, A.C., 2018. Differential effects of salient visual events on memory-guided attention in adults and children. *Child Dev.* <https://doi.org/10.1111/cdev.13149>. [Epub ahead of print].
- Patai, E.Z., Doallo, S., Nobre, A.C., 2012. Long-term memories bias sensitivity and target selection in complex scenes. *J. Cogn. Neurosci.* 24 (12), 2281–2291. <https://doi.org/10.1162/jocn.a.00294>.
- Patai, E.Z., Buckley, A., Nobre, A.C., 2013. Is attention based on spatial contextual memory preferentially guided by low spatial frequency signals? *PLoS One* 8 (6), e65601. <https://doi.org/10.1371/journal.pone.0065601>.
- Paz-Alonso, P.M., Gheiti, S., Donohue, S.E., Goodman, G.S., Bunge, S.A., 2008. Neurodevelopmental correlates of true and false recognition. *Cereb. Cortex* 18 (9), 2208–2216. <https://doi.org/10.1093/cercor/bhm246>.
- Petersen, S.E., Posner, M.I., 2012. The attention system of the human brain: 20 years after. *Annu. Rev. Neurosci.* 35, 73–89. <https://doi.org/10.1146/annurev-neuro-062111-150525>.
- Pozuelos, J.P., Paz-Alonso, P.M., Castillo, A., Fuentes, L.J., Rueda, M.R., 2014. Development of attention networks and their interactions in childhood. *Dev. Psychol.* 50, 2405–2415. <https://doi.org/10.1037/a0037469>.
- Rhodes, M.G., Anastasi, J.S., 2012. The own-age bias in face recognition: a meta-analytic and theoretical review. *Psychol. Bull.* 138 (1), 146–174. <https://doi.org/10.1037/a0025750>.
- Ro, T., Russell, C., Lavie, N., 2001. Changing faces: a detection advantage in the flicker paradigm. *Psychol. Sci.* 12 (1), 94–99.
- Rosen, M.L., Stern, C.E., Michalka, S.W., Devaney, K.J., Somers, D.C., 2016. Cognitive control network contributions to memory-guided visual attention. *Cereb. Cortex* 26 (5), 2059–2073. <https://doi.org/10.1093/cercor/bhv028>.
- Salvato, G., Patai, E.Z., Nobre, A.C., 2016a. Preserved memory-based orienting of attention with impaired explicit memory in healthy ageing. *Cortex* 74, 67–78. <https://doi.org/10.1016/j.cortex.2015.10.019>.
- Salvato, G., Patai, E.Z., McCloud, T., Nobre, A.C., 2016b. Apolipoprotein e4 breaks the association between declarative long-term memory and memory-based orienting of spatial attention in middle-aged individuals. *Cortex* 82, 206–216. <https://doi.org/10.1016/j.cortex.2016.06.002>.
- Smyth, A.C., Shanks, D.R., 2008. Awareness in contextual cuing with extended and concurrent explicit tests. *Mem. Cognit.* 36 (2), 403–415.
- Stokes, M.G., Atherton, K., Patai, E.Z., Nobre, A.C., 2012. Long-term memory prepares neural activity for perception. *Proc. Natl. Acad. Sci. U. S. A.* 109 (6), E360–7. <https://doi.org/10.1073/pnas.1108555108>.
- Suddendorf, T., Nielsen, M., von Gehlen, R., 2011. Children's capacity to remember a novel problem and to secure its future solution. *Dev. Sci.* 14, 26–33. <https://doi.org/10.1111/j.1467-7687.2010.00950.x>.
- Summerfield, J.J., Lepson, J., Gitelman, D.R., Mesulam, M.M., Nobre, A.C., 2006. Orienting attention based on long-term memory experience. *Neuron* 49 (6), 905–916. <https://doi.org/10.1016/j.neuron.2006.01.021>.
- Summerfield, J.J., Rao, A., Garside, N., Nobre, A.C., 2011. Biasing perception by spatial long-term memory. *J. Neurosci.* 31 (42), 14952–14960. <https://doi.org/10.1523/JNEUROSCI.5541-10.2011>.
- Townsend, E.L., Richmond, J.L., Vogel-Farley, V.K., Thomas, K., 2010. Medial temporal lobe memory in childhood: developmental transitions. *Dev. Sci.* 13 (5), 738–751. <https://doi.org/10.1111/j.1467-7687.2009.00935.x>.
- Vadillo, M.A., Konstantinidis, E., Shanks, D.R., 2016. Underpowered samples, false

- negatives, and unconscious learning. *Psychon. Bull. Rev.* 23 (1), 87–102. <https://doi.org/10.3758/s13423-015-0892-6>.
- Vaidya, C.J., Huger, M., Howard, D.V., Howard, J.H., 2007. Developmental differences in implicit learning of spatial context. *Neuropsychology* 21 (4), 497–506. <https://doi.org/10.1037/0894-4105.21.4.497>.
- Vuilleumier, P., 2000. Faces call for attention: evidence from patients with visual extinction. *Neuropsychologia* 38 (5), 693–700.
- Vuilleumier, P., Armony, J.L., Driver, J., Dolan, R.J., 2001. Effects of attention and emotion on face processing in the human brain: an event-related fMRI study. *Neuron* 30 (3), 829–841.
- Yang, Y., Merrill, E.C., 2014. The impact of distracter–target similarity on contextual cueing effects of children and adults. *J. Exp. Child Psychol.* 121, 42–62. <https://doi.org/10.1016/j.jecp.2013.10.009>.
- Yang, Y., Merrill, E.C., 2015a. Age-related similarities in contextual cueing in the presence of unpredictable distracters. *J. Genet. Psychol.* 176 (1-2), 11–25. <https://doi.org/10.1080/00221325.2014.995585>.
- Yang, Y., Merrill, E.C., 2015b. The impact of signal-to-noise ratio on contextual cueing in children and adults. *J. Exp. Child Psychol.* 132, 65–83. <https://doi.org/10.1016/j.jecp.2014.12.005>.