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Playing hide and seek: Contextual regularity learning develops between 3 and 5 years of age

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ABSTRACT

The ability to acquire contextual regularities is fundamental in everyday life because it helps us to navigate the environment, directing our attention where relevant events are more likely to occur. Sensitivity to spatial regularities has been largely reported from infancy. Nevertheless, it is currently unclear when children can use this rapidly acquired contextual knowledge to guide their behavior. Evidence of this ability is indeed mixed in school-aged children and, to date, it has never been explored in younger children and toddlers. The current study investigated the development of contextual regularity learning in children aged 3 to 5 years. To this aim, we designed a new contextual learning paradigm in which young children were presented with recurring configurations of bushes and were asked to guess behind which bush a cartoon monkey was hiding. In a series of two experiments, we manipulated the relevance of color and visuospatial cues for the underlying task goal and tested how this affected young children's behavior. Our results bridge the gap between the infant and adult literatures, showing that sensitivity to spatial configurations persists from infancy to childhood, but it is only around the fifth year of life that children naturally start to integrate multiple cues to guide their behavior.

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Introduction

Natural visual scenes are richly structured and contain many statistical regularities (Field, 1994; Saffran & Kirkham, 2018). Objects tend to occur in stable spatial locations and covary over time and space (Chun, 2000; Chun & Jiang, 1998; Jiang & Chun, 2001). If encoded into memory, these regularities help us to navigate the environment, directing our attention to where relevant events are more likely to occur (Aly & Turk-Browne, 2017; Amso & Kirkham, 2021; Castelhano & Krzyś, 2020). For example, without requiring conscious awareness or intentional effort, we can learn how products are organized at our favorite supermarket and become faster at orienting our attention toward them.

The interplay between memory and attention has come under increasing interest in recent attention models of adult processing (Chun et al., 2011; Nobre & van Ede, 2023), employing a variety of behavioral and neural indices. In adults, this phenomenon has been largely investigated by employing the contextual cueing (CC) paradigm (Chun, 2000; Chun & Jiang, 1998). This paradigm requires participants to find a target among distractors whose location, unbeknownst to them, is fixed across trials (Chun & Jiang, 1998). The repeated exposure to the same visual context facilitates attentional deployment, leading to faster response times (RTs) and target detection (Chun, 2000; Chun & Jiang, 1998; Sisk et al., 2019). This can be seen across multiple methodologies (e.g., eye movements, fixations, manual reaction times; Sisk et al., 2019). Change detection tasks offer another example of memory guidance over attention (Aly & Turk-Browne, 2017): When presented with the same image several times, adults are faster at detecting new objects in old locations than at detecting new objects in new locations (Becker & Rasmussen, 2008; Rosen et al., 2014). Wang and Theeuwes (2018a, 2018b, 2018c) recently reported a similar effect using a modified version of the additional singleton paradigm (Theeuwes, 1991). In a series of reaction time studies, participants were asked to press a key when they located a target among distractors. Unbeknownst to them, salient but irrelevant color singletons were more likely to appear in one location than in all other locations on the screen. Results showed that target search time was delayed by the presence of the singletons relative to the baseline (i.e., no distractors), replicating the classical attentional capture effect. Critically, this effect was attenuated when distractors appeared in high-probability versus low-probability locations, suggesting that contextual regularities guide attention allocation.

Notably, these findings have been largely replicated with adult participants (Aly & Turk-Browne, 2017; Chun, 2000) but are less robust in the field of developmental psychology, with some evidence of contextual knowledge during infancy, mixed findings in school-aged children, and no studies in toddlers and young children (see Jiang et al., 2019 for a review of developmental evidence).

The infant literature reports a robust and early developing sensitivity to environmental regularities from the first year of life (Saffran & Kirkham, 2018). For example, Saffran et al. (1996) showed that 8-month-old infants can segment words in a continuous stream of syllables based on their statistical properties after only 2 min of exposure. This ability extends to the tactile and visual domains (Frost et al., 2015; Santolin & Saffran, 2018), allowing the developing brain to detect how events covary over time (Kirkham et al., 2002) and space (Fiser & Aslin, 2002) and use this information for further processing and learning (Aslin, 2017). Indeed, this mechanism—often referred to as statistical learning—facilitates information processing, promoting the emergence of different skills such as language acquisition (Romberg & Saffran, 2010), motor learning (Hunnius & Bekkering, 2014; Monroy et al., 2017), multimodal integration (Kirkham et al., 2007; Mitchel et al., 2014), and, importantly, attention allocation and spatial exploration (Bertels et al., 2017; Tummeltshammer & Amso, 2018).

Of particular interest in the study of memory-guided attention, Tummeltshammer and Amso (2018) recently demonstrated that contextual regularities guide visual attention during infancy. In an eye-tracking paradigm, 6- to 10-month-old infants searched for a target face hidden in random or recurring configurations of shapes while the speed of overorienting toward the target was recorded. Infants showed faster search times and more target anticipations when exposed to the recurring configurations versus the random ones. Similarly, Bertels et al. (2017) employed a novelty preference paradigm, inspired by the CC literature, to measure infants' ability to learn target–context associations. Results showed that 8- to 12-month-old infants are sensitive to spatial covariations between a visual context and a target location, as demonstrated by differences in looking times between scenes that respected or violated these associations. These findings confirm the presence of an early sensitivity to the visuospatial regularities embedded in our environment (Fiser & Aslin, 2002; Saffran & Kirkham, 2018). Furthermore, they show that infants can take advantage of these regularities to support attention allocation.

Surprisingly, evidence of this ability is less consistent in school-aged children, and it has been mainly investigated through the CC paradigm (Couperus et al., 2011; Dixon et al., 2010; Merrill et al., 2013; Vaidya et al., 2007; Yang & Merrill, 2014, 2015, 2018). Findings from the CC literature suggest that the ability to learn spatial layouts is present in school-aged children but that it undergoes significant development throughout childhood and is more susceptible to certain experimental manipulations compared with adults (Jiang et al., 2019; Yang et al., 2020; Yang & Merrill, 2018). Methodological factors such as the length of the task (Yang & Merrill, 2015), the apparatus used to test children (i.e., keypress vs. touchscreen devices) (Dixon et al., 2010), the type and number of stimuli in each display (Yang & Merrill, 2014), and the similarity between target and distractor stimuli (Yang & Merrill, 2014) may help to explain the inconsistencies found across infant, child, and adult studies (Nussenbaum et al., 2019).

CC paradigms are usually modeled after the adult literature, require speeded responses, and often include complex visual scenes and long subsets of trials that might exceed young children's cognitive capacity, masking their sensitivity to contextual regularities (Jiang et al., 2019). In light of this, Dixon et al. (2010) designed a simplified version of the CC paradigm to study the development of memory-guided attention in children aged 5 to 9 years. The new paradigm was characterized by fewer trials and fewer search displays compared with the classical CC paradigms. Furthermore, it involved a touchscreen computer that allowed children to interact directly with the stimuli, avoiding use of the keyboard and thus minimizing task cognitive demands. Results revealed that, as a group, school-aged children efficiently used contextual regularities to guide spatial attention.

The role of the context for the underlying task is another critical factor to consider when comparing studies across different age groups. In Tummeltshammer and Amso's (2018) infancy paradigm, the visual context cued the location of the target, but the target position was revealed only after the start of the trial. Therefore, contextual regularities constituted central information to predict the target location for infants. In CC paradigms, for both children and adults, the target is present in the search display from the beginning of the trial. Hence, the spatial context supports visual search efficiency, but it is not a prerequisite to complete the task.

In addition, it must be acknowledged that experimental paradigms with school-aged children tend to rely on manual RTs, whereas infant paradigms generally use eye movements to target locations or preferential looking as indices of attention deployment and learning. Even if the two indices can show overlap in the adult and child literatures (i.e., Mooij et al., 2021; van Asselen et al., 2011; Zhao et al., 2012), the differences in task demands can be problematic when working with developmental populations (Keen, 2003). In particular, Keen (2003) suggested that the ability to coordinate knowledge and action planning might not be fully developed before the fifth year of life, leading to confounding results when comparing eye behavior with tasks involving motor planning in more complex settings.

To summarize, the developmental evidence corroborates the presence of an early sensitivity to visuospatial regularities (Saffran & Kirkham, 2018) and shows that contextual regularities can guide attention deployment in simplified learning conditions (Bertels et al., 2017; Tummeltshammer & Amso, 2018). However, the conflicting findings across the different age groups suggest a development in this ability that needs systematic investigation, with attention to methodological appropriateness. In particular, important questions remain open about young children's sensitivity to contextual information. What factors promote the emergence of this mechanism, and in what conditions can contextual regularities help young children to navigate their complex environments? This is of particular interest when multiple cues are available and the spatial context supports but is not essential to the learning process itself.

To shed light on this and to extend these research questions to toddlers and preschool children, we designed a new simplified learning paradigm building on the CC literature. In a series of two experiments, we manipulated the relevance of the spatial layout for the underlying learning task and measured its impact on young children's behavior. In Experiment 1, we examined when young children aged 3 to 5 years begin to assimilate and use contextual regularities to guide behavior. We presented children with two cues to succeed in the task: the color of the stimuli and their spatial arrangements. Although both cues alone were sufficient to complete the task, the former was more informative and perceptually salient. This allowed us to measure the extent to which young children assimilated the spatial context when it was marginal to a given task and further used it to guide their behavior. Building on the results of Experiment 1, in Experiment 2 we increased the behavioral relevance of the spatial layout and measured how this affected children's ability to perform the task .

Experiment 1

Experiment 1 was designed to investigate the ability to acquire contextual information between 3 and 5 years of age. Previous studies have shown that infants can take advantage of contextual regularities to guide attention deployment in simplified learning conditions (Bertels et al., 2017; Tummeltshammer & Amso, 2018). However, as reviewed above, evidence for this ability in children is less consistent and has only been investigated from 5 years of age and up, using the CC paradigm (Jiang et al., 2019). Although this paradigm is the gold standard to study memory-guided attention in adults, it might not be suited for the investigation of this phenomenon in young children due to its methodological complexity (Dixon et al., 2010; Nussenbaum et al., 2019).

In the current experiment, we presented young children with a new contextual learning task with reduced complexity and cognitive load. Children viewed several cartoon scenes in which the color and location of the stimuli (bushes) cued the location of a hidden target (a monkey). Importantly, we let the children engage with the scenes without explicitly directing their attention to the spatial context. This allowed us to get a better insight into children's sensitivity to contextual information, simulating everyday learning experience.

In line with the CC paradigm, the spatial context supported visual search but was not essential to succeed in the task. However, we simplified the structure of the visual scenes compared with the classical CC paradigm (Chun, 2000), using fewer stimuli to avoid any confounding factors, and we measured accuracy instead of RTs as an index of learning. This allowed us to reduce the number of trials compared with the classical CC paradigms and to rule out the possibility that differences in the development of motor planning interfered with the results (Keen, 2003).

We hypothesized that participants could take advantage of the multiple hints to find the hidden target and that this would result in better performance across trials. In the second part of the experiment, we explored what cues participants used to guide their behavior, paying particular attention to participants' learning of contextual regularities and the developmental trajectory of this ability. The study was preregistered at AsPredicted (https://aspredicted.org/blind.php?x=tu2nk2).

Method

Participants

In total, 83 healthy full-term children participated in the experiment: 28 3-year-olds (17 girls and 11 boys; *M* = 42 months, *SD* = 3), 30 4-year-olds (15 girls and 15 boys; *M* = 55 months, *SD* = 3), and 25 5- and 6-year-olds (15 girls and 10 boys; *M* = 67 months, *SD* = 4). The number of participants was selected based on power analysis, estimating 80% power for detecting a medium effect size (Cohen, 1988). Due to unforeseen circumstances related to COVID-19 timings with shutting of labs, the task was run both in the United Kingdom and in Italy, where it was translated from English into Italian. A total of 76 children were recruited from and tested in a nursery in Italy. A subgroup of 7 3-year-olds were recruited via birth records and tested at the [Birkbeck, University of London].[1] The study was approved by the ethical committee of the School of Sciences at Centre for Brain and Cognitive Development, Birkbeck, University of London School of Sciences at Birkbeck, University of London.

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[1] Differences between the two groups of participants were inspected. None of the participants tested at [XXXX] resulted in an outlier when data were pooled.

Materials

The experiment was built and hosted using the Gorilla Experiment Builder (www.gorilla.sc; Anwyl-Irvine et al., 2020) and was presented on an Apple 11-inch iPad. Interactive video instructions were created using two cartoon characters downloaded from www.freepik.com and the voice recordings of two children (one in Italian for the Italian participants and one in English for the English participants). The experimental stimuli were designed using Adobe Illustrator (www.adobe.com) and consisted of spatial configurations of green and pink bushes. We divided the screen into 20 equal quadrants and then generated three fixed configurations and 30 random configurations of bushes. The fixed configurations were composed of three green bushes and one pink flowered bush, behind which the target stimulus was always placed. To make the configurations more distinguishable, no bush occupied the same location within and between the three fixed spatial configurations (Fig. 1A). Each fixed configuration was presented 10 times in the first part of the experiment (the learning phase). Random configurations were also composed of green and pink flowered bushes, but the bushes were randomly displayed in one of the 20 quadrants. The location of the bushes in the random configurations never overlapped with the locations of the pink bushes in the fixed configurations.

Design and procedure

Children were tested in a quiet room either in their school or in the in the Home Lab of the Toddler Lab at the Centre for Brain and Cognitive Development, Birkbeck University of London. They were provided with a touchscreen device and were invited to play where they felt more comfortable in the room: either on a small children’s table or on a play mat. A researcher was present during the execution of the task. The experimental paradigm consisted of a learning phase followed by a test phase.

In the learning phase, participants were told that a monkey and an elephant were playing hide and seek. They were invited to help the elephant find the monkey. The cartoon elephant instructed children on how to play (i.e., to touch the bush on the screen, to get the monkey to appear from behind it) and supervised them in three practice trials. The experimental trials then began.

At the beginning of each trial, a cartoon monkey appeared in the middle of the screen, and the participants were asked to touch it. This acted as a central fixation point for the following response. After an interstimulus interval (ISI) of 800 ms, one of the three fixed spatial configurations of bushes was displayed. Participants were asked to guess the location of the hiding monkey by touching one of the bushes. Once a bush was selected, the correct position of the monkey was revealed after 1000 ms, regardless of whether the selected bush was correct or incorrect, and remained on the screen for 1000 ms (Fig. 1B).

Fixed spatial configurations were made of three green bushes and one pink flowered bush, held in a constant location across trials. Importantly, the color and location of the bushes within a configuration acted as a cue to find the target; the monkey was always behind the pink bush across all trials and always behind the same bush within a fixed spatial configuration (Fig. 1A).

Children completed five blocks of 6 trials for a total of 30 trials. Overall, all participants saw the same configurations of bushes, but the order of configuration appearances was randomized across participants, with the added constraint that the same configuration could not appear more than twice in a row. Furthermore, to make the task more engaging for young children, a video of the monkey and the elephant dancing together was played at the end of each block for 10 s and a map with five colorless forests was displayed at the beginning of each block. Each forest turned green after the completion of the block.

Following the learning phase, participants completed the test phase, a preferential choice task designed to investigate whether participants assimilated both the color and spatial cues in the learning phase. To accomplish this, we manipulated the color and location of the bushes in the fixed (familiar) configurations of the learning phase and new random (unfamiliar) configurations across three different types of trials (i.e., control, color, and spatial trials; Fig. 2A), and we asked participants to indicate where the monkey had previously been hiding.

As in the learning phase, participants completed two practice trials and were instructed by a cartoon character before the start of the task. At the beginning of each trial, a cartoon monkey appeared in the upper part of the screen, and participants were asked to touch it. This acted as a fixation point for

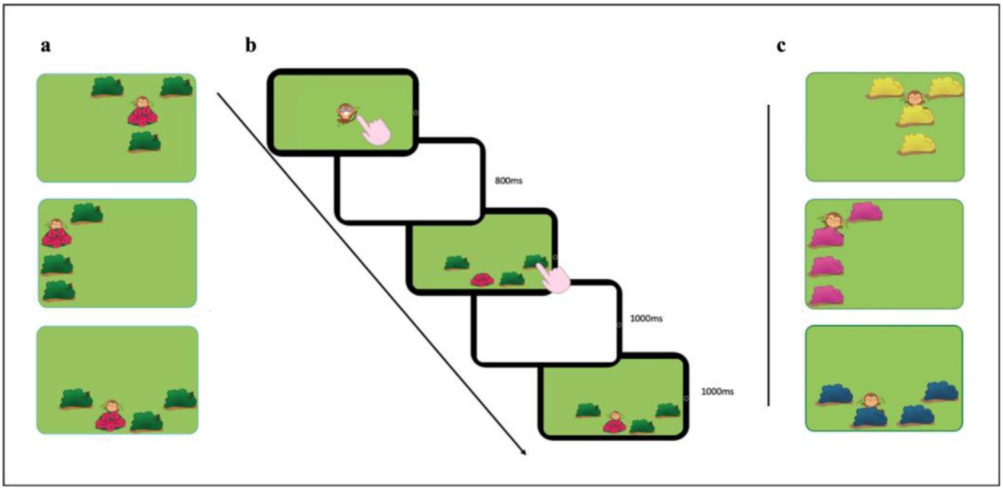

Fig. 1. (A) Fixed spatial configurations employed in the learning phase of Experiment 1. (B) Example of learning trial in Experiment 1. (C) Fixed spatial configurations employed in the learning phase of Experiment 2.

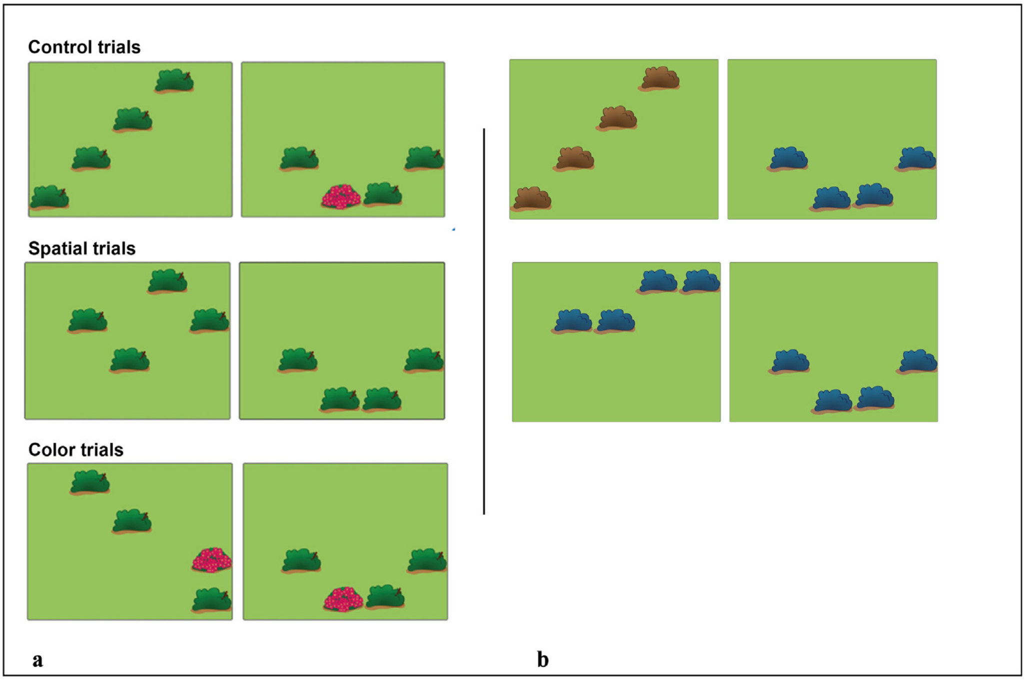

Fig. 2. Example of the test phase trials in Experiment 1 (A) and Experiment 2 (B).

the subsequent response. After an ISI of 800 ms, familiar (fixed) and unfamiliar (random) configurations were simultaneously displayed side by side, and participants were asked to touch the bush behind which the monkey was hiding before. This enabled us to examine the extent to which children were more likely to choose the familiar or unfamiliar configuration as well as their accuracy in selecting the correct bush within the familiar configurations. Following the selection of a bush, the position of the hiding monkey was revealed and displayed on the screen for 1500 ms. The monkey was always behind one bush in the familiar configuration, in accordance with its location during the learning phase. No monkey was present in the unfamiliar configurations.

A video of the elephant and monkey dancing together was displayed for 10 s after the completion of 6 trials. All participants were exposed to the same spatial configurations, but the order of presentation was pseudorandomized between participants, so that the same familiar configuration could not appear more than twice in a row.

Participants completed 30 trials in the following order: 6 control trials, 12 color trials, and 12 spatial trials (Fig. 2A). In the control trials, the familiar configurations (three green bushes and one pink flowered bush) were contrasted against random configurations that consisted only of green bushes. This condition allowed us to test whether participants understood the task and had learned the association between the pink flowered bush and the target. In the spatial trials, children were told that a bunny ate all the flowers and because of this all the bushes were now green. The employment of solely green bushes in the familiar and unfamiliar configurations required participants to use the spatial context to find the target (i.e., they could not rely on the color of the bushes anymore). But, at the same time, it slightly changed the appearance of the fixed (familiar) configurations at the risk of affecting participants' ability to recognize them. To control for this, the color trials were added to the paradigm. In these trials, the familiar configurations (three green bushes and one pink flowered bush) were contrasted against unfamiliar configurations in which a pink flowered bush was present. The inclusion of a pink bush in both configurations compelled children to rely on the spatial context to find the target while maintaining invariant the visual appearance of the familiar configurations. However, the presence of two pink bushes could also act as a confounding factor, moving children's attention to the color rather than the location of the bushes. For this reason, both spatial and color trials were included in the paradigm.

In summary, the control trials allowed us to test whether children understood the task and had learned the pink bush–target association. The color and spatial trials allowed us to test whether children had learned the contextual regularities and could take advantage of them to deploy their attention and guide behavior when the context became the only reliable cue.

Results

Multilevel modeling was employed for data analysis due to its greater flexibility with developmental data compared with linear models (Bono et al., 2021). Multilevel models (MLMs) allow for the overcoming of the assumptions regarding the independence of residuals and do not require listwise deletion, so that participants with only partial responses—which is often the case in developmental studies—can be included in the analysis. Furthermore, MLMs account for the multilevel nature of developmental data (Boyle & Willms, 2001). They can be considered a natural extension to conventional regression models for analyzing clustered and nested data. They comprise fixed effects or fixed parameters that describe the relationship between the dependent variable and predictor variables (similar to regression coefficients in linear models) and random effects that represent the random deviations from the relationship described by fixed effects. As such, MLMs allow for estimating fixed parameters while accounting for between- and within-person variability in the data (Boyle & Willms, 2001; Nezlek, 2008).

Learning phase

The probability of selecting the correct bush varied from .63 to .88 at the start of the task for 3- and 5-year-olds, respectively, and was above .95 for all age groups by the end of the learning phase (Table 1A). To further investigate this improvement, a multilevel modeling analysis was conducted on the dataset. Models were built using the "lme4" R package (Bates et al., 2015). First, we modeled accuracy (the likelihood of selecting the correct target location) as a binomial variable. The intraclass correlation coefficient (ICC) for accuracy was then calculated based on the empty model. The ICC of accuracy was .31, indicating a substantial person-to-person variance (Nakagawa et al., 2017). In Model 1, we tested whether accuracy improved across trials and whether this effect was modulated by age.

Table 1
Learning phase (A) and test phase (B) of Experiment 1

(A) Learning phase			Trial							
Age group	*N*		1	5	10	15	20	25	30	Total
3 years	27	Correct bush	17	23	27	22	25	27	27	717
		Wrong bush	10	4	0	5	2	0	0	93
		%	62.96%	85.19%	100.00%	81.48%	92.59%	100.00%	100.00%	88.52%
4 years	30	Correct bush	20	28	28	28	29	30	29	832
		Wrong bush	10	2	2	2	1	0	1	68
		%	66.67%	93.33%	93.33%	93.33%	96.67%	100.00%	96.67%	92.44%
5 years	25	Correct bush	22	23	25	25	24	24	25	714
		Wrong bush	3	2	0	0	1	1	0	36
		%	88.00%	92.00%	100.00%	100.00%	96.00%	96.00%	100.00%	95.20%

(B) Test phase			Trial type					
Age group	*N*		Control (6 trials)		Color (12 trials)		Spatial (12 trials)	
3 years	28	Familiar	152	90.48%	166	49.40%	149	44.35%
		Unfamiliar	16		170		187	
		Correct bush	142	93.42%	158	95.18%	35	23.49%
		Wrong bush	10		8		114	
4 years	30	Familiar	179	99.44%	172	47.78%	154	42.78%
		Unfamiliar	1		188		206	
		Correct bush	176	98.32%	171	99.42%	54	35.06%
		Wrong bush	3		1		100	
5 years	25	Familiar	146	97.33%	169	56.33%	174	58.00%
		Unfamiliar	4		131		126	
		Correct bush	144	98.63%	167	98.82%	85	48.85%
		Wrong bush	2		2		89	

Note. For the learning phase (A), participants' correct bush selection across trials and percentage of correct responses by age group are shown. For the test phase (B), participants' selection of familiar and unfamiliar configurations by age group, correct bush selection within the familiar configurations, and percentage of correct responses in the control, color, and spatial trials are shown.

We fitted a generalized linear model on binomial data with trials and participants' age as predictors. Age was standardized and modeled as a continuous variable. Participants and trials were added as a random intercept and slope, respectively, following a visual inspection of the data. Results showed a main effect of trial, Wald $\chi^2(1) = 36.70$, $p < .001$, and a main effect of age, Wald $\chi^2(1) = 9.80$, $p = .002$. (Regression coefficients were extracted using the *Anova* function from the R "car" package [Fox & Weisberg, 2019]. For comprehensive information regarding the models, refer to Table 1 in the online supplementary material.) In addition, results showed a significant between-person variability in the intercepts of accuracy (variance = 1.18, SD = 1.09, 95% confidence interval [CI] with 5000 bootstrap resamples from 0.50 to 1.53) and a partial between-person variability in the within-person trajectories of accuracy over trials (variance = 0.02, SD = 0.13, 95% CI = [0.08, 0.19]), suggesting that learning trajectories differed across participants.

Although a significant person-to-person variability was observed, in line with our hypotheses, results showed that participants' accuracy improved across trials, with the oldest children showing better performance overall.

Test phase

We fitted a generalized linear model on binomial data to test whether the familiar configurations were more likely to be selected than the unfamiliar ones (accuracy). The three types of trials (control, color, and spatial trials) and participants' age were modeled as predictors. Participants were added as a random intercept. Results showed a main effect of trial type, Wald $\chi^2(2) = 172.78$, $p < .001$, a main effect of age, Wald $\chi^2(1) = 9.30$, $p = .002$, a significant interaction between trial type and age, Wald $\chi^2(1) = 7.55$, $p = .02$, and significant between-person variability in the intercepts of accuracy (variance = 1.18, SD= 0.42, with a 95% CI from 0.026 to 0.53). (Regression coefficients were extracted using the *Anova* function from the R "car" package. Refer to Table 2 in the supplementary material for comprehensive information regarding the model.)

Preplanned contrasts showed better performance in the control trials compared with the color and spatial trials (z = 11.79, b = 7.09, p < .001), suggesting that children relied more on the color of the bushes than on their location to find the target position in the learning phase (Fig. 3). No difference in accuracy was found between the color and spatial trials.

Marginal effects were then inspected to get a better understanding of the effect of age on accuracy. The R package "ggeffects" (Lüdecke, 2018) was used to extract the predicted probabilities of the slope of accuracy across age and trial type. Results show that all age groups were above chance level (50%) in the control trials (Table 2A). In contrast, in the spatial and color trials (Tables 2B and 2C), predicted probabilities were above chance level only after 54 months of age (4.5 years), suggesting that the ability to acquire contextual regularities develops over time.

Lastly, we ran the same analysis selecting only the trials in which children selected the familiar configuration and explored whether children were more likely to select the correct bush compared with any other bushes. The R package "ggeffects" was used to extract the predicted probabilities—modeled as a binary variable—of selecting the correct bush within the familiar configuration in the spatial trials. In further support of our findings, results revealed that the probability of selecting the correct bushes increased with age in the spatial trials. In contrast, a similar increase was not observed in the control and color trials when both the color and spatial cues were available (see Tables 3 and 4 in the supplementary material for further details).

Discussion

Experiment 1 was designed to investigate when children can assimilate and further use contextual regularities to guide their behavior. To answer this question, we exposed 3- to 5-year-olds to fixed

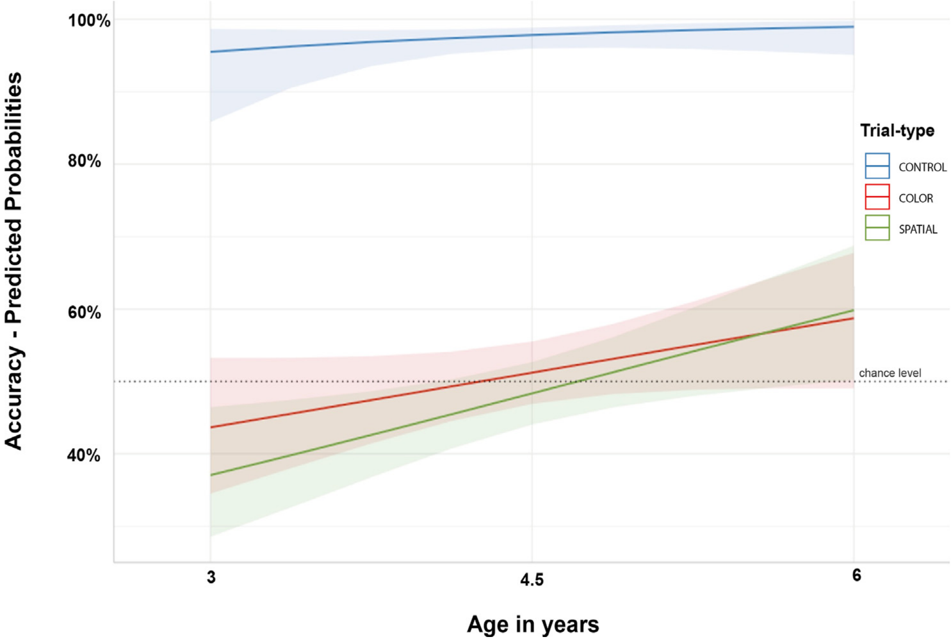

Fig. 3. Predicted probabilities of selecting the familiar configurations by age and trial type. Note that participants' age has been modeled as a continuous variable.

Table 2
Predicted probabilities of selecting the familiar configurations across age in the control trials (A), color trials (B), and spatial trials (C)

(A) Control trials

Age group	*z*-Score age	Predicted	CI low	CI high
36 months	−1.67	0.88	0.78	0.94
42 months	−1.15	0.92	0.87	0.95
47 months	−0.59	0.95	0.93	0.97
54 months	0.03	0.97	0.95	0.98
57 months	0.29	0.98	0.96	0.99
59 months	0.46	0.98	0.96	0.99
75 months	2.04	1	0.98	1

(B) Color trials

Age group	*z*-Score age	Predicted	CI low	CI high
36 months	−1.67	0.45	0.38	0.53
42 months	−1.15	0.47	0.41	0.53
47 months	−0.59	0.49	0.45	0.54
54 months	0.03	0.51	0.47	0.55
57 months	0.29	0.52	0.48	0.56
59 months	0.46	0.53	0.48	0.57
75 months	2.04	0.58	0.49	0.66

(C) Spatial trials

Age group	*z*-Score age	Predicted	CI low	CI high
36 months	−1.67	0.39	0.32	0.46
42 months	−1.15	0.42	0.36	0.47
47 months	−0.59	0.45	0.40	0.49
54 months	0.03	0.48	0.44	0.52
57 months	0.29	0.50	0.45	0.54
59 months	0.46	0.50	0.46	0.55
75 months	2.04	0.59	0.50	0.67

Note. CI, confidence interval. Predicted probabilities were estimated with the R package “ggeffects” (Lüdecke, 2018).

spatial configurations of bushes and asked them to guess behind which bush a monkey was hiding. The location of the hidden monkey was cued by the color of the bushes and their location within each configuration. In line with our hypotheses, results showed good performance overall, with improvement over learning trials, indicating that children understood the task and succeeded in finding the hidden monkey.

We then asked children to perform a preferential choice task to investigate whether they had encoded the color cue and/or the spatial context during the learning task and whether they could use either or both memory cues to guide their behavior. Here again, results showed ceiling performance in the control trials, indicating that children could identify familiar configurations when both cues were available. However, a drop in performance was observed when children were forced to use the spatial context only. Children’s accuracy (i.e., likelihood of selecting the familiar configuration) was above chance level at 5 years of age but not before for both the spatial and color trials. Furthermore, children’s ability to accurately locate the target within spatial configurations when spatial context alone was available increased gradually from 3 to 5 years of age. This is an important finding because it suggests that over this period children improve their ability to use information held in memory to guide spatial attention to precise target locations. This, in turn, indicates an increasingly efficient interplay between memory and spatial attention guidance.

Surprisingly, in contrast to the infant literature (Bogaerts et al., 2022; Jiang et al., 2019; Saffran & Kirkham, 2018), our results did not find evidence of a sensitivity to contextual regularities in 3- and 4-year-old children. This inconsistency might be attributed to differences in the experimental paradigms. Infant studies are usually based on violation of expectations (Bertels et al., 2017; Keen, 2003), whereas the current experiment required participants to assimilate contextual regularities and further use them to make predictions about events. Thus, it is possible that young children did encode the regularities but failed to actively use them to guide behavior in the test phase, leading to contrasting findings. Consistent with this, a recent CC study by Yang and Merrill (2018) compared the ability of 6- and 7-year-olds and 9- and 10-year-olds to differentiate the identity and location of objects in the environment. Unlike their older counterparts, 6- and 7-year-olds showed faster reaction times when both the location and identity of the stimuli in the configuration remained invariant, but not when one of the two was changed, highlighting that the ability to encode and use contextual regularities develops over time, becoming more robust to environmental perturbations.

A second factor contributing to failures by the youngest children might be the relevance of context for the underlying task. It must be recalled that in Tummeltshammer and Amso (2018) contextual regularities constituted central information to succeed in the task. In contrast, in our study the spatial context supported visual search but was not essential for finding the target. Thus, it is possible that the conflicting patterns observed between the infant paradigm and our task concealed the presence of different learning strategies rather than a lack of sensitivity to contextual regularities. Previous studies (Amso & Scerif, 2015; Matusz et al., 2015; Wu et al., 2018) have shown that factors such as past experience with a given stimulus, stimulus familiarity, and the relevance of a stimulus for the underlying task influence attention deployment and, consequently, what information is held in memory and accessible for further tasks. On a related note, classical attention studies (Akhtar & Enns, 1989; Plude et al., 1994; Trick & Enns, 1998) have highlighted that feature bindings and voluntary movement of spatial attention are not fully developed during childhood and follow a pattern of late maturation. Therefore, it is possible that, due to immature attention skills, children focused their attention on the most relevant cue (the color) in the learning phase. This, in turn, might have masked their sensitivity to the spatial context. If this is the case, we reasoned that if spatial context becomes the most important information to solve the task, children would encode it and use it to guide their behavior. To explore this possibility, in Experiment 2 we manipulated the level of information conveyed by the color and fixed configuration of bushes and measured how this affected young children's encoding and use of contextual information to guide behavior.

Experiment 2

Experiment 2 was designed to investigate whether 3- and 4-year-olds can take advantage of spatial regularities if they are relevant for the underlying task.

Based on the literature on statistical learning (Saffran & Kirkham, 2018), we hypothesized that young children are equipped with the ability to encode contextual regularities. In Experiment 1, we found evidence of context sensitivity, but only in children aged 5 years, which is surprising given previous research with infants (Bertels et al., 2017; Tummeltshammer & Amso, 2018). One possible explanation is that younger children may indeed have this ability, but they adopted different learning strategies to solve the task at hand, possibly due to limited cognitive resources.

Gómez (2017) argued that the developmental trajectories of the different memory systems dictate what regularities can be assimilated and learned. Similarly, the development of the attention system may determine the amount of information and the speed at which external stimuli are processed (Frost et al., 2019). Furthermore, the literature on infant development has documented a consistent preference for stimuli of moderate complexity from the first year of life, with infants appearing to strategically allocate their cognitive resources to optimize their learning progress (Kidd et al., 2012; Poli et al., 2020).

Building on this, we hypothesized that, due to the immaturity of their memory and attention systems, the younger children in Experiment 1 focused their cognitive resources on the cue that maximized their chance of succeeding in the task (i.e., color) while discounting spatial regularities. To explore this possibility, we manipulated the color of the fixed configurations in Experiment 1 so that each configuration was composed of four bushes of a unique color (Fig. 1C). Thus, in Experiment 2, the spatial context was the most informative cue for finding the target, whereas color was an additional cue that helped to discriminate the fixed configurations. Everything else remained invariant between the two experiments.

We hypothesized that if the ability to encode contextual regularities is developed early in life, under these conditions 3- and 4-year-olds would succeed in using the spatial context to find the target.

Method

Participants

A total of 29 healthy full-term children aged 3 and 4 years participated in the experiment. Of these children, 26 were recruited from and tested in a nursery in [XXXX] and 3 were recruited via birth records and tested at the [XXXX]. Two participants were excluded from the data analysis because they failed to understand the task instructions or did not want to take part in the study. The final sample consisted of 27 children (17 girls and 10 boys; *M* = 49 months, *SD* = 4.81). The study was approved by the ethical committee of the School of Sciences at [XXXX].

Materials

The experiment was built and hosted using the Gorilla Experiment Builder (www.gorilla.sc; Anwyl-Irvine et al., 2020) and was presented on an Apple 10.2-inch iPad. The stimuli used in Experiment 1 were recolored using Adobe Illustrator (www.adobe.com) such that each fixed configuration of bushes in Experiment 1 had a unique color in Experiment 2 (Fig. 1C). Specifically, each fixed configuration was composed of four bushes of the same color—pink, yellow, or blue (no pink flowered bushes were present). Random configurations were composed of four bushes of the same color. The color of the bushes in the random configurations matched the color of the bushes in the fixed configurations (pink, yellow, or blue) in the spatial trials but differed (brown) in the control trials (Fig. 2B). The location of the bushes in the fixed and random configurations remained invariant across the two experiments.

Design and procedure

Children were tested in a quiet room either within their nursery or at the [XXXX]. At the beginning of the experiment, children were presented with four bushes of different colors and were asked to tap the yellow, pink, blue, and brown bushes, respectively. Children who made more than one mistake were excluded from data analysis because a visual color impairment might have interfered with the ability to complete the task. Experimental instructions and procedures were kept identical between the two experiments. As in Experiment 1 (Fig. 1B), children were presented with fixed configurations of bushes in the learning phase and were asked to guess behind which bush the monkey was hiding. Importantly, the location of the bushes within each fixed configuration was kept invariant between Experiment 1 (Fig. 1A) and Experiment 2 (Fig. 1C). However, the level of information conveyed by the color and location of the bushes changed between the two experiments.

In Experiment 2, all the bushes within one fixed configuration had the same color (Fig. 1C). Thus, differently from Experiment 1, the spatial context acted as the most informative cue to find the target. The color of the bushes aided visual search but was not a determinant for locating the hiding monkey. Participants completed five blocks of 6 trials for a total of 30 trials.

Following the learning phase, participants completed the test phase, which consisted of a preferential choice task. In the spatial trials, the fixed configurations were contrasted against new random configurations in which bushes were randomly located but shared the same color as the fixed configurations (Fig. 2B). In the control trials, the bushes in the fixed and random configurations differed in color and location (Fig. 2B).

The control trials allowed us to test whether children understood the task, whereas the spatial trials allowed us to test whether children could assimilate and take advantage of contextual regularities to guide attention and behavior when they are relevant to a given task.

Table 3
Learning phase (A) and test phase (B) of Experiment 2

(A) Learning phase		Trial number							
N		1	5	10	15	20	25	30	Total
27	Correct bush	2	10	16	15	19	16	19	403
	Wrong bush	25	17	11	12	8	11	8	407
	%	7.41%	37.04%	59.26%	55.56%	70.37%	59.26%	70.37%	49.75%

(B) Test phase		Trial type			
N		Control (6 Trials)		Spatial (12 Trials)	
27	Familiar	115	70.99%	212	65.43%
	Unfamiliar	47		112	
	Correct bush	73	63.48%	133	62.74%
	Wrong bush	42		79	

Note. For the learning phase. participants' correct bush selection and percentage of correct responses across trials are shown. For the test phase, participants' selection of familiar and unfamiliar configurations, correct bush selection within the familiar configurations, and percentage of correct responses in the control and spatial trials are shown. Each familiar configuration is composed of 4 bushes; the probability of selecting the correct bush by chance was 25%.

Results

Learning phase

Children's performance improved across the learning trials, starting with a .07 probability of selecting the correct bush and reaching .70 by the end of the learning phase (Table 3A). To further investigate the robustness of this improvement, multilevel modeling was applied to the data.

Models were built using the "lme4" R package (Bates et al., 2015). First, we fitted a generalized linear model, modeling accuracy as a binomial variable (i.e., likelihood of selecting the correct target location) and adding participant as a random intercept. The ICC of accuracy was .25, indicating substantial person-to-person variance (Nakagawa et al., 2017). We then fitted a generalized linear model on binomial data with trials as predictor variables and participants as a random intercept. Results showed a main effect of the intercept, Wald $\chi^2(1) = -3.64$, $B = -0.99$, $p < .001$, 95% CI obtained by bootstrapping 5000 resamples = [−1.55, −0.44], indicating that accuracy was below chance at the beginning of the experiment. The main effect of trial was significant, Wald $\chi^2(1) = 43.87$, $B = 0.06$, $p < .001$, 95% CI = [0.05, 0.08], suggesting that participants' accuracy improved across trials. (Regression coefficients were extracted using the *Anova* function from the R "car" package [Fox & Weisberg, 2019]. Refer to Table 5 in the supplementary material for comprehensive information regarding the model.)

Test phase

A generalized linear model on binomial data was fitted to test whether the familiar configurations were more likely to be selected than the unfamiliar ones (i.e., accuracy) in the test phase. The two types of trials (control and spatial) were modeled as a predictor variable. Participants were added as a random intercept. Results showed no difference between the two types of trials, Wald $\chi^2(1) = 1.78$, $B = -0.30$, $p = .18$, 95% CI [−0.77, 0.14], and a significant intercept, Wald $\chi^2(1) = 3.967$, $B = 1.09$, $p < .001$, 95% CI [0.56, 1.68], indicating that participants were more likely to select the familiar configurations than the unfamiliar ones regardless of the type of trial. (Regression coefficients were extracted using the *Anova* function from the R "car" package. Refer to Table 6 in the supplementary material for comprehensive information regarding the model.)

We then compared accuracy in Experiments 1 and 2 to test the effect of training on participants' performance. Specifically, we selected participants younger than 5 years from Experiment 1 and compared performance on the spatial trials across both experiments. We fitted a generalized linear model on binomial data with experiment type as a predictor variable and participants as a random intercept (see Table 7 in supplementary material). Results show a main effect of experiment, $\chi^2(1) = 25.81$, *B*

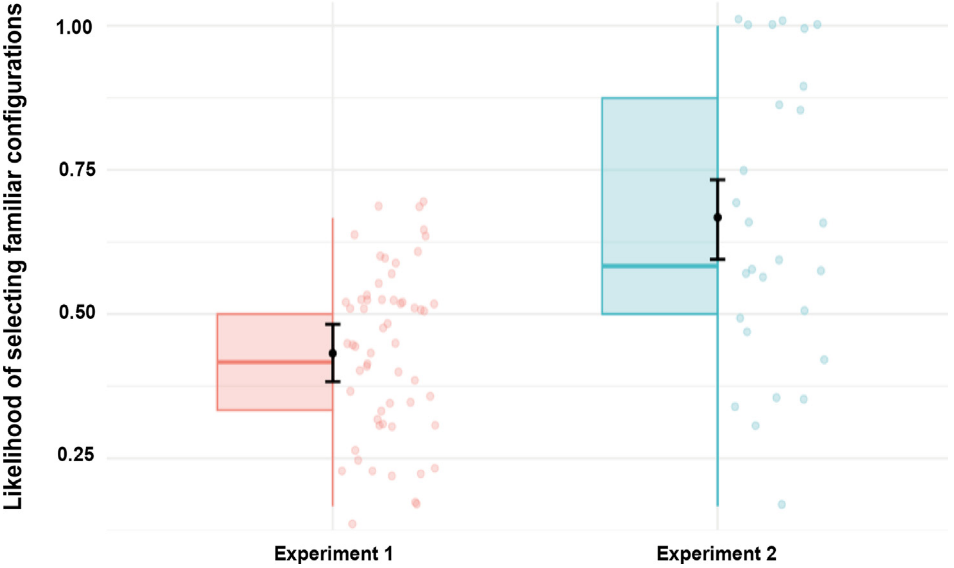

Fig. 4. Predicted probabilities of selecting the familiar configurations in the spatial trials in Experiment 1 and Experiment 2. Only data from participants younger than 5 years were included in the analysis.

= 0.97, $p < .001$, 95% CI [0.60, 1.35], with better performance in Experiment 2 than in Experiment 1 (Fig. 4).

Discussion

Experiment 2 was designed to investigate whether 3- and 4-year-olds can use contextual regularities to guide their behavior when these are relevant to a given task. To answer this question, we presented young children with fixed configurations of bushes and asked them to guess where a cartoon monkey was hiding. Each configuration had a unique color and was composed of four bushes. Unbeknownst to participants, the location of the monkey was fixed within each configuration. Results highlighted an improvement in performance across trials in the learning phase, suggesting the presence of an early sensitivity to spatial regularities. To confirm this hypothesis, we then presented children with familiar (fixed) and unfamiliar (random) configurations of the same colors (spatial trials) or different colors (control trials) and asked them to indicate where the monkey was hiding before. As predicted, children's performance was above chance level in the spatial trials. In addition, no difference was found between the control and spatial trials. In line with the infant statistical learning literature, these findings show that a sensitivity to visuospatial regularities is at play early in life and that young children can use this information to guide their behavior. Furthermore, they reveal that this sensitivity may depend on the information value conveyed by the environmental cues. Indeed, young children took advantage of contextual regularities to guide behavior in Experiment 2 when it was the only cue relevant to solving the task.

General discussion

The current study investigated the developmental trajectory of children's sensitivity to contextual regularities between 3 and 5 years of age. To address this research question, we devised a new contextual learning paradigm and manipulated the relevance of color and spatial cues in two experiments. In Experiment 1, the color served as the most informative cue for the underlying task goal, whereas spatial context supported learning but was not necessary for task success. Children of all age groups performed proficiently when both cues were available. They were able to extract and use these visual cues to guide behavior. However, only 5-year-olds solved the task when the spatial context became the only cue available in the test phase. In contrast, 3- and 4-year-olds did not perform above chance level. Furthermore, the ability to accurately localize targets within configurations increased steadily over the 3- to 5-year period.

Given the nature of our paradigm in Experiment 1, it is difficult to disentangle whether 3- and 4-year-olds simply did not acquire the invariant relationships between the location of the bushes and the fixed configurations in the learning phase or whether they were sensitive to these relationships but failed to use them to guide behavior. Nevertheless, given that previous evidence has reported a robust sensitivity to contextual regularities during infancy (Bogaerts et al., 2022; Saffran & Kirkham, 2018), we argued that young children must be equipped with this same ability, but the degree to which contextual information is processed depends on several factors, among which are the relevance of the context for the underlying task and the amount of competing information. To test our hypothesis, in Experiment 2 we manipulated the information conveyed by the visual cues. In fact, the spatial context became the only cue to succeed in the task, whereas the color of the stimuli supported learning but was not informative in finding the target. Under these conditions, 3- and 4-year-olds were able to solve the task.

Taken together, our results suggest that the ability to encode, store, and use contextual regularities to guide attention and behavior is present in children as young as 3 years. However, as shown by Experiment 1, this ability is not fully mature at this stage and continues to develop throughout childhood. Only around 5 years of age do children naturally begin to integrate contextual regularities to guide their behavior in complex environments, where multiple cues are available, and the spatial context supports but is not essential to the learning process itself. This can be seen as a form of graded representation account of development (Mareschal et al., 2007). Indeed, rather than an "on/off" switch-type mechanism, our results highlight that sensitivity to contextual knowledge develops over time.

Although our study demonstrated that children's sensitivity to contextual information improves between 3 and 5 years of age, it does not identify the mechanisms that promote the emergence of this ability. One possible explanation can be found in the concurrent development of the attention system during this age period (Matusz et al., 2015; Pozuelos et al., 2014; Remington et al., 2014; Shimi et al., 2014; Wu et al., 2018). As highlighted in the existing literature, attentional capacity for perception and awareness is limited (Aly & Turk-Browne, 2017; Chun et al., 2011; Hutchinson & Turk-Browne, 2012) and undergoes developmental changes with age (Matusz et al., 2015; Remington et al., 2014; Shimi et al., 2014; Wu et al., 2018). This capacity is indispensable in daily life because it governs which stimuli are prioritized, leading to better encoding and further recollection of important information. However, it comes with the drawback that unattended stimuli may be missed (e.g., Cherry, 1953; Simons & Chabris, 1999) or remain inaccessible in memory (i.e., Jiang & Chun, 2001). Studies on limited attentional capacity have demonstrated that under high cognitive load, perceptual processing becomes selective, filtering out task-irrelevant information (Bruckmaier et al., 2020; Forster & Lavie, 2016; Lavie & Dalton, 2014; Lavie et al., 2004; Remington et al., 2014). In line with this account, it is possible that the limited attention capacity hindered the 3-and 4-year-olds' ability to encode both color and spatial cues in Experiment 1, thereby preventing the creation of visuospatial templates for the location of the bushes. Conversely, shifting their attention to the spatial cue in Experiment 2 might have helped to prioritize the spatial context, resulting in improved performance.

Another factor that may explain why children prioritized color information over spatial information in Experiment 1 is the utility of the color cue for the underlying task goal. Previous studies have suggested that environmental variables, such as the level of surprise of a stimulus (Kidd et al., 2012) and the overall predictability of the environment (Poli et al., 2020), determine what information will be attended to. For instance, Kidd et al. (2012) showed that even infants as young as 8 months focus their attention on stimuli with an intermediate level of complexity and avoid allocating their cognitive resources to stimuli that are either too simple or too complex. Similarly, in a recent study, Poli et al. (2020) showed that infants focus their cognitive resources on stimuli that maximize learning progress. Thus, it is possible that in our study children directed their attentional resources to the cue that maximized success in the task, namely the color cue in Experiment 1 and the spatial cue in Experiment 2, while disregarding potential superfluous information. In addition, previous research has shown that differential expertise with the to-be-attended stimuli can influence attention deployment. For example, in Matusz et al. (2019), 6-year-olds, 11-year-olds, and young adults were asked to find a target number while distractor number words or digits were presented peripherally. Unlike older children and young adults, 6-year-olds' RTs were not affected by the presence of distractor number words and audiovisual stimuli, possibly due to their limited experience with these categories. Thus, it is plausible that familiarity-dependent constraints facilitated the encoding of the color cues over the spatial cues in Experiment 1.

The development of memory systems could also contribute to the observed differences in performance. Working memory resources are necessary for encoding visual information, maintaining contextual information available during visual search, and capturing attention by contexts retrieved from memory (Chun, 2011; Manginelli, Baumgartner, et al., 2013). For example, it has been reported that concurrent visual working memory load impairs attentional capture by repeated contexts in CC paradigms (Travis et al., 2013). In addition, evidence showed that working memory plays a significant role in the "expression of learning," specifically in the retrieval of visual information to guide visual search (Manginelli, Langer, et al., 2013; Pollmann, 2019).

Thus, further investigation is required to identify more precisely what factors promote the ability to acquire contextual regularities, helping young children to navigate their environment.

To conclude, this study bridges the gap between the infant and adult literatures, showing that although sensitivity to both color and spatial configurations is present from infancy, the ability to use both to guide behavior emerges around the fifth year of life, when presumably children are equipped with more robust cognitive skills. These findings are in line with recent models of attentional guidance in older children and adults, in which the interplay between cognitive control mechanism and memory representations plays a central role in guiding attention over time and in space (Amso & Scerif, 2015; Chun et al., 2011; Nobre & van Ede, 2023). Furthermore, they shed light on the active role of the learner in sampling information to efficiently navigate the environment, according to the task goals and the limitations originating from the developing memory and attention system (Frost et al., 2019; Mareschal et al., 2007; Munakata, 2001).

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.jecp.2023.105795.

References

Akhtar, N., & Enns, J. T. (1989). Relations between convert orienting and filtering in the development of visual attention. *Journal of Experimental Child Psychology, 48*(2), 315–334. https://doi.org/10.1016/0022-0965(89)90008-8.

Aly, M., & Turk-Browne, N. B. (2017). How hippocampal memory shapes, and is shaped by, attention. In D. E. Hannula & M. C. Duff (Eds.), *The hippocampus from cells to systems* (pp. 369–403). Springer International. https://doi.org/10.1007/978-3-319-50406-3_12.

Amso, D., & Kirkham, N. (2021). A multiple-memory systems framework for examining attention and memory interactions in infancy. *Child Development Perspectives, 15*(2), 132–138. https://doi.org/10.1111/cdep.12410.

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

Anwyl-Irvine, A. L., Massonnié, J., Flitton, A., Kirkham, N., & Evershed, J. K. (2020). Gorilla in our midst: An online behavioral experiment builder. *Behavior Research Methods, 52*(1), 388–407. https://doi.org/10.3758/s13428-019-01237-x.

Aslin, R. N. (2017). Statistical learning: A powerful mechanism that operates by mere exposure. *Wiley Interdisciplinary Reviews Cognitive Science, 8*(1–2). https://doi.org/10.1002/wcs.1373 e1373.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01.

Becker, M. W., & Rasmussen, I. P. (2008). Guidance of attention to objects and locations by long-term memory of natural scenes. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 34*(6), 1325–1338. https://doi.org/10.1037/a0013650.

Bertels, J., San Anton, E., Gebuis, T., & Destrebecqz, A. (2017). Learning the association between a context and a target location in infancy. *Developmental Science, 20*(4). https://doi.org/10.1111/desc.12397 e12397.

Bogaerts, L., Siegelman, N., Christiansen, M. H., & Frost, R. (2022). Is there such a thing as a "good statistical learner"? *Trends in Cognitive Sciences, 26*(1), 25–37. https://doi.org/10.1016/j.tics.2021.10.012.

Bono, R., Alarcón, R., & Blanca, M. J. (2021). Report quality of generalized linear mixed models in psychology: A systematic review. *Frontiers in Psychology, 12*. https://doi.org/10.3389/fpsyg.2021.666182 666182.

Boyle, M. H., & Willms, J. D. (2001). Multilevel modelling of hierarchical data in developmental studies. *Journal of Child Psychology and Psychiatry, 42*(1), 141–162. https://doi.org/10.1111/1469-7610.00706.

Bruckmaier, M., Tachtsidis, I., Phan, P., & Lavie, N. (2020). Attention and capacity limits in perception: A cellular metabolism account. *Journal of Neuroscience, 40*(35), 6801–6811. https://doi.org/10.1523/JNEUROSCI.2368-19.2020.

Castelhano, M. S., & Krzyś, K. (2020). Rethinking space: A review of perception, attention, and memory in scene processing. *Annual Review of Vision Science, 6*(1), 563–586. https://doi.org/10.1146/annurev-vision-121219-081745.

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and with two ears. *Journal of the Acoustical Society of America, 25*, 975–979. https://doi.org/10.1121/1.1907229.

Chun, M. M. (2000). Contextual cueing of visual attention. *Trends in Cognitive Sciences, 4*(5), 170–178. https://doi.org/10.1016/S1364-6613(00)01476-5.

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

Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology, 36*(1), 28–71. https://doi.org/10.1006/cogp.1998.0681.

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

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. Routledge.

Couperus, J. W., Hunt, R. H., Nelson, C. A., & Thomas, K. M. (2011). Visual search and contextual cueing: Differential effects in 10-year-old children and adults. *Attention, Perception, & Psychophysics, 73*(2), 334–348. https://doi.org/10.3758/s13414-010-0021-6.

Dixon, M. L., Zelazo, P. D., & Rosa, E. D. (2010). Evidence for intact memory-guided attention in school-aged children. *Developmental Science, 13*(1), 161–169. https://doi.org/10.1111/j.1467-7687.2009.00875.x.

Field, D. J. (1994). What is the goal of sensory coding? *Neural Computation, 6*(4), 559–601. https://doi.org/10.1162/neco.1994.6.4.559.

Fiser, J., & Aslin, R. N. (2002). Statistical learning of new visual feature combinations by infants. *Proceedings of the National Academy of Sciences of the United States of America, 99*(24), 15822–15826. https://doi.org/10.1073/pnas.232472899.

Forster, S., & Lavie, N. (2016). Establishing the attention–distractibility trait. *Psychological Science, 27*(2), 203–212. https://doi.org/10.1177/0956797615617761.

Fox, J., & Weisberg, S. (2019). *An R companion to applied regression* (3rd ed.). Sage. https://socialsciences.mcmaster.ca/jfox/Books/Companion.

Frost, R., Armstrong, B. C., & Christiansen, M. H. (2019). Statistical learning research: A critical review and possible new directions. *Psychological Bulletin, 145*(12), 1128–1153. https://doi.org/10.1037/bul0000210.

Frost, R., Armstrong, B. C., Siegelman, N., & Christiansen, M. H. (2015). Domain generality versus modality specificity: The paradox of statistical learning. *Trends in Cognitive Sciences, 19*(3), 117–125. https://doi.org/10.1016/j.tics.2014.12.010.

Gómez, R. L. (2017). Do infants retain the statistics of a statistical learning experience? Insights from a developmental cognitive neuroscience perspective. *Philosophical Transactions of the Royal Society B: Biological Sciences, 372*(1711). https://doi.org/10.1098/rstb.2016.0054 20160054.

Hunnius, S., & Bekkering, H. (2014). What are you doing? How active and observational experience shape infants' action understanding. *Philosophical Transactions of the Royal Society B: Biological Sciences, 369*(1644). https://doi.org/10.1098/rstb.2013.0490 20130490.

Hutchinson, J. B., & Turk-Browne, N. B. (2012). Memory-guided attention: Control from multiple memory systems. *Trends in Cognitive Sciences, 16*(12), 576–579. https://doi.org/10.1016/j.tics.2012.10.003.

Jiang, Y., & Chun, M. M. (2001). Selective attention modulates implicit learning. *Quarterly Journal of Experimental Psychology A, 54*(4), 1105–1124. https://doi.org/10.1080/713756001.

Jiang, Y. V., Sisk, C. A., & Toh, Y. N. (2019). Implicit guidance of attention in contextual cueing: Neuropsychological and developmental evidence. *Neuroscience & Biobehavioral Reviews, 105*, 115–125. https://doi.org/10.1016/j.neubiorev.2019.07.002.

Keen, R. (2003). Representation of objects and events: Why do infants look so smart and toddlers look so dumb? *Current Directions in Psychological Science, 12*(3), 79–83. https://doi.org/10.1111/1467-8721.01234.

Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2012). The Goldilocks effect: Human infants allocate attention to visual sequences that are neither too simple nor too complex. *PLoS One, 7*(5). https://doi.org/10.1371/journal.pone.0036399 e36399.

Kirkham, N. Z., Slemmer, J. A., & Johnson, S. P. (2002). Visual statistical learning in infancy: Evidence for a domain general learning mechanism. *Cognition, 83*(2), B35–B42. https://doi.org/10.1016/S0010-0277(02)00004-5.

Kirkham, N. Z., Slemmer, J. A., Richardson, D. C., & Johnson, S. P. (2007). Location, location, location: Development of spatiotemporal sequence learning in infancy. *Child Development, 78*(5), 1559–1571. https://doi.org/10.1111/j.1467-8624.2007.01083.x.

Lavie, N., & Dalton, P. (2014). Load theory of attention and cognitive control. In A. C. Nobre & S. Kastner (Eds.), *The Oxford handbook of attention* (pp. 56–75). Oxford University Press.

Lavie, N., Viding, E., Lavie, N., Hirst, R., Fockert, J. W. D., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General, 133*(3), 339–354. https://doi.org/10.1037/0096-3445.133.3.339.

Lüdecke, D. (2018). ggeffects: Tidy data frames of marginal effects from regression models. *Journal of Open Source Software, 3* (26). https://doi.org/10.21105/joss.00772 772.

Manginelli, A. A., Baumgartner, F., & Pollmann, S. (2013). Dorsal and ventral working memory-related brain areas support distinct processes in contextual cueing. *NeuroImage, 67*, 363–374. https://doi.org/10.1016/j.neuroimage.2012.11.025.

Manginelli, A. A., Langer, N., Klose, D., & Pollmann, S. (2013). Contextual cueing under working memory load: Selective interference of visuospatial load with expression of learning. *Attention, Perception, & Psychophysics, 75*(6), 1103–1117. https://doi.org/10.3758/s13414-013-0466-5.

Mareschal, D., Johnson, M. H., Sirois, S., Spratling, M., Thomas, M. S. C., & Westermann, G. (2007). *Neuroconstructivism, Vol. 1: How the brain constructs cognition*. Oxford University Press.

Matusz, P. J., Broadbent, H., Ferrari, J., Forrest, B., Merkley, R., & Scerif, G. (2015). Multi-modal distraction: Insights from children's limited attention. *Cognition, 136*, 156–165. https://doi.org/10.1016/j.cognition.2014.11.031.

Matusz, P. J., Merkley, R., Faure, M., & Scerif, G. (2019). Expert attention: Attentional allocation depends on the differential development of multisensory number representations. *Cognition, 186*, 171–177. https://doi.org/10.1016/j.cognition.2019.01.013.

Merrill, E. C., Conners, F. A., Roskos, B., Klinger, M. R., & Klinger, L. G. (2013). Contextual cueing effects across the lifespan. *Journal of Genetic Psychology, 174*(4), 387–402. https://doi.org/10.1080/00221325.2012.694919.

Mitchel, A. D., Christiansen, M. H., & Weiss, D. J. (2014). Multimodal integration in statistical learning: Evidence from the McGurk illusion. *Frontiers in Psychology, 5*. https://doi.org/10.3389/fpsyg.2014.00407 407.

Monroy, C. D., Gerson, S. A., & Hunnius, S. (2017). Toddlers' action prediction: Statistical learning of continuous action sequences. *Journal of Experimental Child Psychology, 157*, 14–28. https://doi.org/10.1016/j.jecp.2016.12.004.

Mooij, S. M. M., Raijmakers, M. E. J., Dumontheil, I., Kirkham, N. Z., & Maas, H. L. J. (2021). Error detection through mouse movement in an online adaptive learning environment. *Journal of Computer Assisted Learning, 37*(1), 242–252. https://doi.org/10.1111/jcal.12483.

Munakata, Y. (2001). Graded representations in behavioral dissociations. *Trends in Cognitive Sciences, 5*(7), 309–315. https://doi.org/10.1016/S1364-6613(00)01682-X.

Nakagawa, S., Johnson, P. C. D., & Schielzeth, H. (2017). The coefficient of determination R2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. *Journal of the Royal Society Interface, 14*(134). https://doi.org/10.1098/rsif.2017.0213 20170213.

Nezlek, J. B. (2008). An introduction to multilevel modeling for social and personality psychology: Multilevel analyses. *Social and Personality Psychology Compass, 2*(2), 842–860. https://doi.org/10.1111/j.1751-9004.2007.00059.x.

Nobre, A. C., & van Ede, F. (2023). Attention in flux. *Neuron, 111*(7), 971–986. https://doi.org/10.1016/j.neuron.2023.02.032.

Nussenbaum, K., Scerif, G., & Nobre, A. C. (2019). Differential effects of salient visual events on memory-guided attention in adults and children. *Child Development, 90*(4), 1369–1388. https://doi.org/10.1111/cdev.13149.

Plude, D. J., Enns, J. T., & Brodeur, D. (1994). The development of selective attention: A life-span overview. *Acta Psychologica, 86* (2–3), 227–272. https://doi.org/10.1016/0001-6918(94)90004-3.

Poli, F., Serino, G., Mars, R. B., & Hunnius, S. (2020). Infants tailor their attention to maximize learning. *Science Advances, 6*(39). https://doi.org/10.1126/sciadv.abb5053 eabb5053.

Pollmann, S. (2019). Working memory dependence of spatial contextual cueing for visual search. *British Journal of Psychology, 110*(2), 372–380. https://doi.org/10.1111/bjop.12311.

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. *Developmental Psychology, 50*(10), 2405–2415. https://doi.org/10.1037/a0037469.

Remington, A., Cartwright-Finch, U., & Lavie, N. (2014). I can see clearly now: The effects of age and perceptual load on inattentional blindness. *Frontiers in Human Neuroscience, 8*. https://doi.org/10.3389/fnhum.2014.00229 229.

Romberg, A. R., & Saffran, J. R. (2010). Statistical learning and language acquisition. *Wiley Interdisciplinary Reviews: Cognitive Science, 1*(6), 906–914. https://doi.org/10.1002/wcs.78.

Rosen, M. L., Stern, C. E., & Somers, D. C. (2014). Long-term memory guidance of visuospatial attention in a change-detection paradigm. *Frontiers in Psychology, 5*. https://doi.org/10.3389/fpsyg.2014.00266 266.

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science, 274*(5294), 1926–1928. https://doi.org/10.1126/science.274.5294.1926.

Saffran, J. R., & Kirkham, N. Z. (2018). Infant statistical learning. *Annual Review of Psychology, 69*(1), 181–203. https://doi.org/10.1146/annurev-psych-122216-011805.

Santolin, C., & Saffran, J. R. (2018). Constraints on statistical learning across species. *Trends in Cognitive Sciences, 22*(1), 52–63. https://doi.org/10.1016/j.tics.2017.10.003.

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

Simons, D. J., & Chabris, C. F. (1999). Gorillas in our midst: Sustained inattentional blindness for dynamic events. *Perception, 28* (9), 1059–1074. https://doi.org/10.1068/p2952.

Sisk, C. A., Remington, R. W., & Jiang, Y. V. (2019). Mechanisms of contextual cueing: A tutorial review. *Attention, Perception, & Psychophysics, 81*(8), 2571–2589. https://doi.org/10.3758/s13414-019-01832-2.

Theeuwes, J. (1991). Cross-dimensional perceptual selectivity. *Perception & Psychophysics, 50*(2), 184–193. https://doi.org/10.3758/BF03212219.

Travis, S. L., Mattingley, J. B., & Dux, P. E. (2013). On the role of working memory in spatial contextual cueing. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39*(1), 208–219. https://doi.org/10.1037/a0028644.

Trick, L. M., & Enns, J. T. (1998). Lifespan changes in attention: The visual search task. *Cognitive Development, 13*(3), 369–386. https://doi.org/10.1016/S0885-2014(98)90016-8.

Tummeltshammer, K., & Amso, D. (2018). Top-down contextual knowledge guides visual attention in infancy. *Developmental Science, 21*(4). https://doi.org/10.1111/desc.12599 e12599.

Vaidya, C., Huger, M., Howard, D., & Howard, J. (2007). Developmental differences in implicit learning of spatial context. *Neuropsychology, 21*, 497–506. https://doi.org/10.1037/0894-4105.21.4.497.

van Asselen, M., Sampaio, J., Pina, A., & Castelo-Branco, M. (2011). Object based implicit contextual learning: A study of eye movements. *Attention, Perception, & Psychophysics, 73*(2), 297–302. https://doi.org/10.3758/s13414-010-0047-9.

Wang, B., & Theeuwes, J. (2018a). How to inhibit a distractor location? Statistical learning versus active, top-down suppression. *Attention, Perception, & Psychophysics, 80*(4), 860–870. https://doi.org/10.3758/s13414-018-1493-z.

Wang, B., & Theeuwes, J. (2018b). Statistical regularities modulate attentional capture. *Journal of Experimental Psychology: Human Perception and Performance, 44*(1), 13–17. https://doi.org/10.1037/xhp0000472.

Wang, B., & Theeuwes, J. (2018c). Statistical regularities modulate attentional capture independent of search strategy. *Attention, Perception, & Psychophysics, 80*(7), 1763–1774. https://doi.org/10.3758/s13414-018-1562-3.

Wu, R., Shimi, A., Solis, M., & Scerif, G. (2018). Learning what to attend to: From the lab to the classroom. *Journal of Cognitive Neuroscience, 30*(12), 1749–1756. https://doi.org/10.1162/jocn_a_01316.

Yang, Y., Chen, M., He, W., & Merrill, E. C. (2020). The role of working memory in implicit memory: A developmental perspective. *Cognitive Development, 55*. https://doi.org/10.1016/j.cogdev.2020.100929 100929.

Yang, Y., & Merrill, E. C. (2014). The impact of distracter–target similarity on contextual cueing effects of children and adults. *Journal of Experimental Child Psychology, 121*, 42–62. https://doi.org/10.1016/j.jecp.2013.10.009.

Yang, Y., & Merrill, E. C. (2015). The impact of signal-to-noise ratio on contextual cueing in children and adults. *Journal of Experimental Child Psychology, 132*, 65–83. https://doi.org/10.1016/j.jecp.2014.12.005.

Yang, Y., & Merrill, E. C. (2018). Implicit memory of locations and identities: A developmental study. *Journal of Experimental Child Psychology, 167*, 162–179. https://doi.org/10.1016/j.jecp.2017.10.015.

Zhao, G., Liu, Q., Jiao, J., Zhou, P., Li, H., & Sun, H. (2012). Dual-state modulation of the contextual cueing effect: Evidence from eye movement recordings. *Journal of Vision, 12*(6). https://doi.org/10.1167/12.6.11 11.