Attention, Perception, & Psychophysics (2024) 86:1974–1988
https://doi.org/10.3758/s13414-024-02926-2

Invariant contexts reduce response time variability in visual search in an age-specific way: A comparison of children, teenagers, and adults

Chengyu Fan[1,2,3,4] · Artyom Zinchenko[4] · Lihan Chen[5,6] · Jiao Wu[4] · Yeke Qian[1,2,3] · Xuelian Zang[1,2,3]

Accepted: 15 June 2024 / Published online: 11 July 2024
© The Psychonomic Society, Inc. 2024

Abstract

Contextual cueing is a phenomenon in which repeatedly encountered arrays of items can enhance the visual search for a target item. This is widely attributed to attentional guidance driven by contextual memory acquired during visual search. Some studies suggest that children may have an immature ability to use contextual cues compared to adults, while others argue that contextual learning capacity is similar across ages. To test the development of context-guided attention, this study compared contextual cueing effects among three age groups: adults (aged 18–33 years, $N = 32$), teenagers (aged 15–17 years, $N = 41$), and younger children (aged 8–9 years, $N = 43$). Moreover, this study introduced a measure of response time variability that tracks fluctuations in response time throughout the experiment, in addition to the conventional analysis of response times. The results showed that all age groups demonstrated significantly faster responses in repeated than non-repeated search contexts. Notably, adults and teenagers exhibited smaller response time variability in repeated contexts than in non-repeated ones, while younger children did not. This implies that children are less efficient at consolidating contextual information into a stable memory representation, which may lead to less stable attentional guidance during visual search.

Keywords Contextual cueing · Learning · Visual search · Response time variability · Development

Introduction

The regularities present in the environment can influence attention and improve visual search. Research has demonstrated that repeated contexts can be retained in long-term memory and direct visual attention (Chun & Jiang, 1998, 2003). For example, a person would easily be able to locate the recycle bin icon on their own computer because they have learned the overall layout of icons through daily use. However, the same search task would likely be slower on someone else's computer, where the icon arrangement is not familiar to them (as shown in Shi et al., 2013). This phenomenon of facilitated visual search under the familiar arrangement of search items was first examined in an experiment by Chun and Jiang (1998), who asked participants to locate a target letter "T" among distractor letters "L"s. In their study, half of the trials across the experimental blocks featured repeated spatial configurations of the target and distractor items, while the other half featured randomly generated configurations (non-repeated contexts). The results showed significantly faster mean response times (RTs) in the repeated contexts compared to the non-repeated contexts. A subsequent unexpected recognition test revealed that participants were unable to distinguish between repeated and non-repeated contexts, suggesting that context learning may be an implicit process (though see Kroell et al., 2019). In summary, the study demonstrated that participants

✉ Xuelian Zang
zangxuelian@gmail.com

1 Center for Cognition and Brain Disorders, Affiliated Hospital of Hangzhou Normal University, Hangzhou 310015, China

2 Zhejiang Key Laboratory for Research in Assessment of Cognitive Impairments, Hangzhou 310015, China

3 Zhejiang Philosophy and Social Science Laboratory for Research in Early Development and Childcare, Hangzhou Normal University, Hangzhou 311121, China

4 Department Psychologie, Ludwig-Maximilians-Universität München, 80802 Munich, Germany

5 School of Psychological and Cognitive Sciences and Beijing Key Laboratory of Behavior and Mental Health, Peking University, Beijing 100871, China

6 National Engineering Laboratory for Big Data Analysis and Applications, Peking University, Beijing 100871, China

can inadvertently learn repeated spatial configurations and become faster at searching for targets within those contexts, an effect known as contextual cueing.

One of the unanswered questions in the literature is whether children can extract and learn repeated contexts as effectively as adults do. Previous research using the standard contextual cueing paradigm, where participants search for a "T" among "L"s, found that adults exhibited significant contextual cueing facilitation while children aged 6–13 years did not (Vaidya et al., 2007). However, later studies using child-friendlier stimuli have observed contextual cueing effects in children (e.g., Dixon et al., 2010). Although both adults and children were able to learn invariant associations, contextual learning in children was less mature and more susceptible to experimental manipulations, such as distractor-target similarity (Yang & Merrill, 2014), signal-to-noise (SN) ratio (Yang & Merrill, 2015), and joint search (Sakata et al., 2023). For example, Yang and Merrill (2015) found that while adults demonstrated a significant contextual cueing effect regardless of the SN ratio, children aged 6–12 years only showed a reliable contextual cueing effect with a high or medium SN ratio but not a low SN ratio. Moreover, when conducting a joint search with a co-actor, adults learned not only their own context but also their co-actor's context (Zang et al., 2022). On the other hand, Sakata et al. (2023) found no such shared learning in 5-year-olds, whose contextual learning was significantly hindered in the joint-task condition.

While some research claims that children may have difficulty learning repeated contexts, other studies have revealed that children and adults perform similarly in contextual learning. For example, using the standard contextual cueing paradigm, which required participants to search for a "T"-shape target among a group of "L"-shape distractors (cf. Chun & Jiang, 1998; Vaidya et al., 2007), several studies observed reliable contextual cueing in children aged 7–14 years (Barnes et al., 2008, 2010; Weigard & Huang-Pollock, 2014). Contrary to the initial finding of Vaidya et al. (2007), these findings indicated that children's ability to learn contexts may be as sufficient as that of adults. Furthermore, in a study by Merrill et al. (2013), participants from three different age groups (children, young adults, and older adults) were asked to perform a search task with cartoon pictures as search items. The researchers found that all three groups demonstrated reliable contextual cueing and that the magnitude of their cueing effects was comparable, indicating a similar ability to use repeated contexts to guide their search behavior despite their age difference (6.3 years for children, 19.8 years for young adults, and 72.17 years for older adults).

The previous studies, taken together, have produced inconsistent results regarding age-related differences in contextual learning. This inconsistency might stem from the limited sensitivity of the traditional mean response time (RT) measure to detect differences across age groups. Although the mean RT measure has proven to be a valid indicator and is widely used by contextual cueing studies (Chun & Jiang, 1998; Conci et al., 2013; Conci & von Mühlenen, 2011; Jiang & Chun, 2001; Zhao et al., 2017), it fails to capture other critical information, such as variability. The variability of RTs in contextual cueing tasks may serve as a proxy measure of the stability at one or several stages of cognitive processes, including stimuli perception, target search, and response. If the stability of the processing is indeed susceptible to context repetition, RT variability may be a more sensitive and valid indicator, especially for children who exhibit extensive response variability. Therefore, analyzing the RT variability may offer greater insight into developmental differences in context-guided behavior and contribute to a better understanding of the cognitive mechanisms underlying contextual cueing.

To the best of our knowledge, RT variability, as measured by the standard deviation (SD) and coefficient of variation (CV) of RT, has not yet been examined in contextual cueing research, but it has been demonstrated to be a useful measure in other cognitive studies (Kofler et al., 2013; Stuss et al., 1994). For instance, several studies have repeatedly documented the RT variability in individuals with attention deficits. Attention deficit/hyperactivity disorder (ADHD) and traumatic brain injury (TBI) are two conditions that can lead to an increased intra-individual RT variability when performing different cognitive tasks such as go/no-go, stop signal, visual discrimination, working memory, motor speed, and executive function tasks (Alderson et al., 2007; Buzy et al., 2009; Gómez-Guerrero et al., 2011; Klein et al., 2006; Stuss et al., 1994). The results from these studies manifest that people with ADHD or TBI may struggle more than healthy controls to complete tasks accurately due to their decreased ability for sustained focus on the task. It has also been shown that the behavior of individuals with ADHD and healthy controls can be discriminated best by RT variability, which has the largest effect size compared to the analysis of mean RT and error rate (Klein et al. 2006). There is also evidence that the intra-individual RT variability varies with age. A "U"-shaped curve has been shown to represent the relationship between intra-individual RT variability and age over the lifespan (Williams et al., 2005, 2007). According to the research using a stop-signal task (Williams et al., 2005) and a spatial Stroop task (Williams et al., 2007), the RT variability specifically decreases continuously during childhood and adolescence, remains largely stable during early and middle adulthood, and increases in later adulthood. In other words, individuals' response stability improves before maturity and declines with ageing. Consequently, the response stability (measured by RT variability) may be useful to identify the different contextual cueing patterns across individuals of various ages.

Given the existing gaps in research, it is imperative to establish whether contextual cueing enhances response stability in adults before using this method to assess cross-age differences. Therefore, we reanalyzed the data from one of our previous studies (Zang et al., 2022), in which young adults (i.e., college students) searched for the target among contexts consisting of task-relevant and -irrelevant search items. Task-relevant items shared the same color feature as the target, while task-irrelevant items were in a different color. It has been found that adults can learn the repeated and task-relevant contexts but not the repeated-irrelevant contexts using this variant of the conventional contextual cueing paradigm (Jiang & Chun, 2001; Vadillo et al., 2020; Zang et al., 2021, Experiment 2; Zang et al., 2022, Experiments 1 and 3). To preview our results, we found that among adult participants, both the RT and RT variability were reduced in the repeated (and relevant) contexts compared to the non-repeated ones (see our Experiment 1 for more details). These results support our hypothesis that contextual learning could enhance not only response speed but also response stability.

Despite the reanalysis revealing that contextual learning increased both response speed and response stability, it is important to note that this was only a post hoc analysis. Stronger evidence is still necessary to confirm the improvement in response stability. Therefore, we conducted Experiments 2A and 2B with a similar design to Experiment 1 but across different age groups to confirm context-based enhancement on response stability and explore whether RT variability is a more sensitive measure of context learning across a wider age range. Given that individuals' capacity for selectively attending to task-relevant input and resisting the interference of irrelevant items continues to develop from young childhood (3 years of age) until late adolescence (17 years of age) (Enns & Akhtar, 1989; Gaspelin et al., 2015; Pastò & Burack, 1997; Ridderinkhoff & van der Stelt, 2000; Wong-Kee-You et al., 2019), a secondary aim of the current study is to capture whether the sensitive periods for the development of selective attention/inhibition also apply to contextual cueing (or attentional guidance), that is, whether younger individuals could learn the repeated but task-irrelevant contexts. Therefore, Experiments 2A and 2B involved teenagers aged 15–17 years and younger children aged 8–9 years and tested their performance in the search task where the search displays consisted of both task-relevant and -irrelevant contexts.

E e i e 1

In Experiment 1, we investigated whether contextual learning could enhance adult participants' response stability. To achieve this, we aimed to utilize the data from our previous study to analyze RT variability in context-guided visual search tasks. Given our secondary objective of investigating whether teenagers and children can selectively filter task-irrelevant items in visual search, as outlined in the *Introduction*, we selected data from a study that utilized search displays containing both task-relevant and -irrelevant items (Zang et al., 2022, Experiments 1 and 3). This selection facilitates a comparison of contextual learning behavior among adults, teenagers, and children. In the reanalysis of the current Experiment 1, a total of 32 adults were included (27 females, age: 18–33 years, mean ± SD: 23.41 ± 4.04 years). We describe the most crucial pieces of experimental design in the following *Methods* section; for more information, please refer to our prior publication (Zang et al., 2022).

Methods

Stimuli and design

There were 20 items per search display, divided evenly into two subsets: the task-relevant and -irrelevant subsets, based on the items' color (black or white). Each subset consisted of one "T"-shaped target oriented to the left or the right and nine "L"-shaped distractors oriented at 0°, 90°, 180°, or 270°. In the experiment, participants were randomly assigned to search for either the black target or the white target via a text cue of "Black" or "White" at the beginning of each trial, and were required to respond as quickly and accurately as possible according to the orientation of the assigned target. Note that the task-relevant context was defined by the items in the color matching the assigned target, whereas the task-irrelevant context consisted of items whose color differed from the assigned target. The task-relevant color was balanced within each experimental block.

The experiment comprised a 25-block learning session and a five-block transfer session, each containing 24 trials. Within each block, half of the trials featured repeated search displays, while the other half featured non-repeated displays. The repeated displays were consistently presented once in every block with identical item configurations, except for the orientation of targets, which varied to prevent potential learning of target orientation. Conversely, the spatial layouts of non-repeated displays were randomly regenerated for each block, except that the target positions remained constant to eliminate the impact of position learning.

During the transfer session following the learning session, unknown to participants, the text cues indicating the task-relevant color for repeated displays were switched from "White" to "Black" and vice versa, while the spatial layout remained unchanged. This adjustment aimed to assess whether participants had learned the task-irrelevant item configurations during the learning session.

Statistical analysis

Given that participants' mean RTs vary greatly, for instance, children's RTs are substantially slower than those of adults (e.g., Merrill et al., 2013; Sakata et al., 2023; Yang & Merrill, 2014, 2015, 2018), and that the values of means and SDs are often correlated (Wagenmakers & Brown, 2007), the CV (i.e., SD/mean) rather than the SD was employed to test for response stability in the current study to rule out (or at least decrease) any potential influences on RT variability from the mean of RTs.[1] To simplify the analysis and increase the statistical power, every five successive blocks were collapsed into one epoch, yielding five epochs. To determine the response stability, we first calculated the mean and SD of RT for each individual display (i.e., each repeated display and each non-repeated display with the same target location) in the five blocks within each epoch. We then normalized the SD by the mean, producing 12 CVs for repeated displays and 12 CVs for non-repeated displays in each epoch. Next, we averaged the 12 CVs for repeated displays and the other 12 CVs for non-repeated displays separately and obtained two mean CV values in each epoch, which were used to measure the response stability for the two display types. A smaller value of the CV indicates more stable responses.

Note that we adopted the above approach to calculate CV scores (rather than first computing the CV across all repeated and all non-repeated displays within each block) because it allows us to assess the RT variability of each individual repeated display as well as the RT variability of the non-repeated displays with the same target location across five consecutive blocks. Consequently, the disparity in RT variability between repeated and non-repeated displays can be attributed to the learning of target-distractor contexts. By contrast, given that the spatial configurations of the 12 repeated displays in each block are entirely distinct from one another, initially computing the CV for all repeated and all non-repeated displays could introduce noise to the CV of repeated displays and potentially obscure differences in RT variability deriving from contextual learning. Therefore, to obtain the CV scores, we opted to first calculate the CV for each display in each epoch rather than the CV for all repeated and all non-repeated displays collectively.

We used IBM SPSS Statistics 25 (IBM, Armonk, NY, USA) for repeated-measures ANOVAs and *t*-tests. For the non-significant findings, we also provided the Bayes factors (BF_{10}) obtained using JASP software (Wagenmakers et al., 2018). A BF_{10} score greater than 3 provides substantial evidence for the alternative hypothesis while a value less than 1/3 indicates substantial evidence for the null hypothesis (Wetzels et al., 2011).

[1] Given that the SD/mean correction to variability only operates effectively when means and SDs are linearly related, we investigated the correlation between means and SDs for all experiments in the current study. We observed strong linear correlations in all age groups, with Pearson's coefficient *r* of approximately 0.9 (refer to Fig. S1 in the Online Supplementary Materials (OSM) for correlation plots and *r* values).

Results

RTs less than 200 ms or exceeding 2.5 SDs from the individual mean were considered outliers. Outlier and error trials were excluded from the following analysis. The average outlier and error rates were low (1.39% and 4.20%, respectively). The analysis of the Balanced Integration Score (BIS), a measure of task performance combining RT and accuracy (Liesefeld et al., 2015; Liesefeld & Janczyk, 2019, 2022), indicated that participants' task performance was not influenced by the speed-accuracy tradeoff (see Online Supplementary Materials (OSM) for BIS analysis).

Learning session

Figure 1A and B show the group means of RTs and CVs, respectively, as a function of Epoch. The RTs and CVs were analyzed by repeated-measures ANOVAs, with Context (repeated vs. non-repeated) and Epoch (1–5) as factors. For the mean RTs, the repeated-measures ANOVA revealed significant effects of Context, Epoch, and the Context × Epoch interaction: Context, $F(1, 31) = 20.855$, $p < 0.001$, $\eta_p^2 = 0.402$, with the mean RTs of 83 ms shorter for the repeated than the non-repeated contexts, confirming a contextual cueing effect in terms of RT (abbr. CC_{RT}); Epoch: $F(2.508, 77.742) = 45.025$, $p < 0.001$, $\eta_p^2 = 0.592$, with the RT decreasing by 190 ms from Epoch 1 to Epoch 5 [linear effect: $t(124) = 12.881$, $p < 0.001$], indicating a procedural learning effect; Context × Epoch interaction: $F(4, 124) = 6.444$, $p < 0.001$, $\eta_p^2 = 0.172$, mainly due to the CC_{RT} being non-significant in Epoch 1 [$t(31) = 0.848$, $p = 0.403$, Cohen's $d = 0.150$, $BF_{10} = 0.263$] but significant from Epoch 2 onward (all *t*s > 3.292, all *p*s < 0.002).

For the mean CVs, the main effect of Context but not of Epoch was significant: Context, $F(1, 31) = 62.461$, $p < 0.001$, $\eta_p^2 = 0.669$, with a mean CV difference between non-repeated and repeated contexts (abbr. CC_{CV}) of 0.048, demonstrating that the contextual cueing effect could also be expressed through the reduced CV in repeated contexts; Epoch, $F(4, 124) = 0.673$, $p = 0.612$, $\eta_p^2 = 0.021$, $BF_{10} = 0.032$, indicating no decrease in the CVs across epochs. The Context × Epoch interaction was not significant, $F(4, 124) = 1.233$, $p = 0.300$, $\eta_p^2 = 0.038$, $BF_{10} = 0.151$. Together, these findings point to a strong context-based reduction of participants' RT variability (i.e., contextual enhancement of participants' response stability).

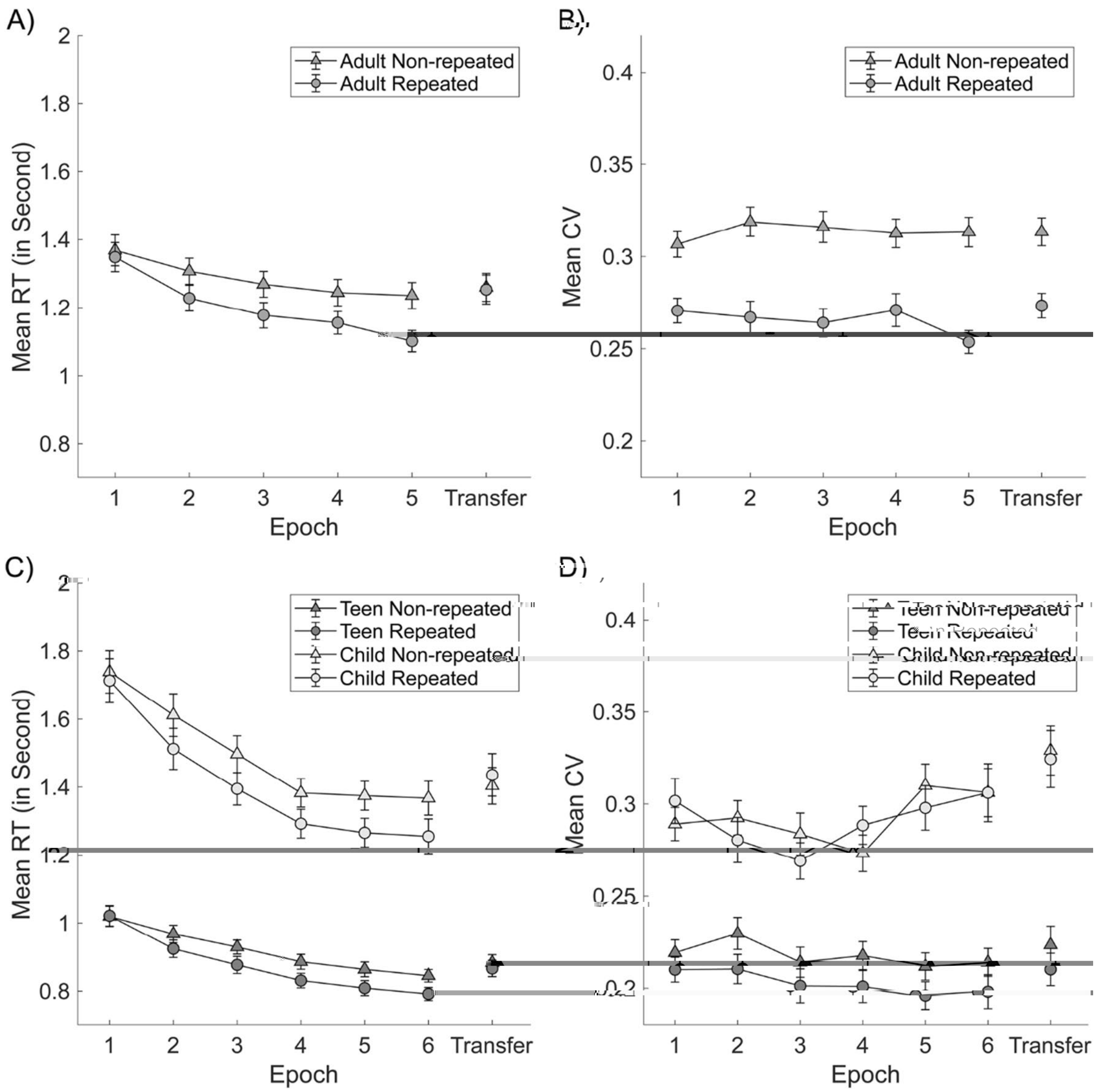

Fig. 1 Results of Experiments 1 (the upper panel) and 2 (the lower panel). (**A**) and (**B**) depict the group means of response times (RTs) and coefficients of variation (CVs), respectively, as a function of Epoch in Experiment 1 (with adult participants, 18–33 years old). (**C**) and (**D**) depict the group means of RTs and CVs, respectively, as a function of Epoch in Experiment 2, where the lines with darker markers represent Experiment 2A (with teenage participants, 15–17 years old) and the lines with lighter markers represent Experiment 2B (with younger child participants, 8–9 years old). The error bars represent the standard error (SE) of the mean

Transfer session

Mean RTs and CVs were separately compared between the two types of contexts (non-repeated vs. repeated) with paired *t*-tests. The difference in RTs for non-repeated and repeated contexts was non-significant, $t(31) = 0.345$, $p = 0.732$, Cohen's $d = 0.061$, $BF_{10} = 0.200$, with mean RTs of 1,259 ms and 1,253 ms for non-repeated and repeated contexts, respectively. However, a significant context-related reduction in CV was observed, $t(31) = 4.806$, $p < 0.001$, Cohen's $d = 0.850$, with mean CVs of 0.313 and 0.273 for non-repeated and repeated contexts, respectively. This might be due to potential learning of the repeated but task-irrelevant contexts.

Interim discussion

Our hypothesis that contextual learning reduces RT variability is supported by Experiment 1. This implies that, in addition to the conventional response speed as an indicator of contextual learning, RT variability may also be a useful metric. In addition, the context-related decrease in CV (but not RT) was also observed in the transfer session. This might reflect potential learning of the repeated but previously irrelevant contexts, but the learning was not detected with the RT measure. This indicates that the context-driven decrease in CV might be prior to RT reduction among adults and highlights the sensitivity of the CV measure as a detector of contextual cueing. In the subsequent Experiment 2, we looked more closely at the contextual learning behavior in teenagers and younger children to determine whether RT variability could serve as a more reliable measurement for age-related differences in contextual learning behavior.

E e i e 2

Experiment 2 aimed to examine context-guided visual search in teenagers (Experiment 2A) and younger children (Experiment 2B). To ensure comparability to the findings of Experiment 1 in adults, a similar visual search task was employed, which included search displays with both task-relevant and -irrelevant contexts. However, considering the possibility that the adult task may be too challenging for the youngest participants (Vaidya et al., 2007), we streamlined the study by reducing the number of displayed search items from 20 in Experiment 1 to 16 in Experiment 2.

Methods

Participants

The sample sizes of Experiments 2A and 2B were computed a priori with the G*Power calculator (Faul et al., 2007) and based on the Context × Epoch interaction. Given that the primary focus of the current study centered on the basic contextual cueing effect, the f(U) effect size was set at 0.33 ($\eta_p^2 = 0.1$, an intermediate value between the medium and larger effect sizes). Similar previous studies have often reported effect sizes for the factor Context exceeding this value (see, e.g., Luque et al., 2021; Vicente-Conesa et al., 2022; Zang et al., 2021; Zinchenko et al., 2020). The number of groups was two, indicating two within-subject variables, and the number of measurements was 12, indicating 12 conditions in total. The non-sphericity correction was set at 1, which means no correction is assumed (Faul et al., 2007), given that the sphericity of Context × Epoch interaction was not violated ($p > 0.05$) in Experiment 1. With 95% power and an alpha level of 0.05, it was found that a sample of 24 participants was required for each experiment. Note, however, that participant recruitment was done *en masse* based on the class, in order to be fair to all children who wished to participate in the experiment. On this ground, the experiment randomly selected one class from the eleventh grade (43 teenage participants, aged 15–17 years) and one from the third grade (60 child participants, aged 8–9 years) at Dingyuan No. 2 Middle School and Dingyuan Construction Primary School, respectively, in Anhui Province, China. Among these participants, nine (one teenager and eight children) were excluded due to a computer crash (with data not being saved), and ten (one teenager and nine children) were excluded because of misinterpretation of the experiment instructions. Finally, data from 41 teenagers (17 females, age: 15–17 years, mean ± SD: 16.15 ± 0.69 years) and 43 children (25 females, age: 8–9 years, mean ± SD: 8.60 ± 0.58 years) were included in Experiments 2A and 2B, respectively.

All participants had normal or corrected-to-normal visual acuity. Written informed consents were given and permission from the homeroom teachers and the school administrators was obtained before the experiment. The experiment was regarded as extra-curricular activity in the self-study class and lasted approximately 30 min. After completing the task, participants were given small gifts (a notebook and a pen) as compensation for their participation. The study was approved by the Center for Cognition and Brain Disorders ethics committee at the Affiliated Hospital of Hangzhou Normal University.

Apparatus and stimuli

Experimental scripts were programmed on MATLAB 2010A software and Psychtoolbox 3 (Brainard, 1997; Pelli, 1997). The experiment was conducted in two computer classrooms (one in the senior high school and the other in the primary school) with light illumination from ceiling lamps. Participants viewed the visual stimuli on 19-in. LCD monitors positioned in front of them at a viewing distance of roughly 57 cm.

Each search display contained 16 search items that were equally distributed into two subsets of white and black colors, each of which contained a "T"-shaped target item and seven "L"-shaped distractor items (each item subtended 0.8° × 0.8° in visual angle). The items were all displayed on a gray background. The luminance contrast between the white items to the background and the background to the black items were comparable in both Experiment 2A (0.52 and 0.59, respectively) and Experiment 2B (0.69 and 0.71, respectively), with the contrast being measured by the Michelson contrast, $(L_1 - L_2)/(L_1 +$ L 22

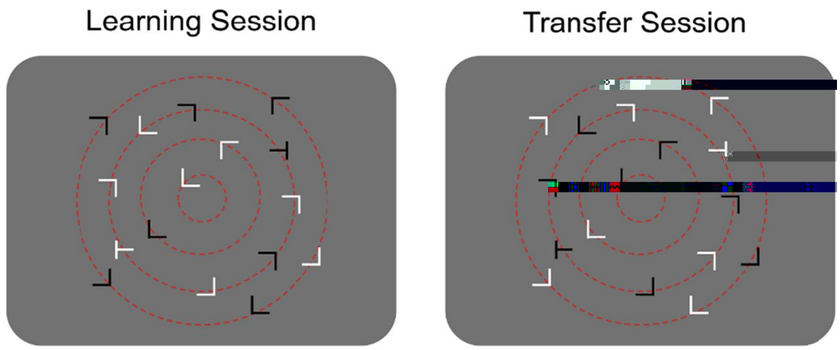

Fig. 2 Schematic representation of a search display presented in the learning session and the transfer session, respectively. The colors of all items (in repeated displays) from the learning session were reversed in the transfer session. The red dashed circles were simply used to illustrate potential item positions; they were absent in the actual experiment

were randomly chosen in the positions on the outer three circles, and they were always placed on the opposing sides of a display (left vs. right hemifield).

Design and procedure

Prior to the experiment, participants were randomly assigned to search for either the white or the black target, and this color assignment remained constant throughout the experiment. Once participants found the target "T", they were instructed to immediately press the left- or the right-arrow key on the keyboard, according to the orientation of the target. Participants were required to respond as quickly and accurately as possible.

The experiment consisted of three sessions: a 30-block learning session, a five-block transfer session, and finally, a one-block recognition session. Each block contained six trials of the repeated displays and six trials of the non-repeated displays, all trials being randomly mixed throughout the block. In the repeated displays, the locations of all search items and the orientations of all "L"-shaped distractors (of both color subsets) were maintained constant, and these displays were presented in every block (once per block). However, the orientations of the two "T"-shaped items in the repeated displays were randomly defined so as to avoid a potential response bias on the target orientation. In the non-repeated displays, all "L"-shaped distractor locations and the orientations of all search items (of both subsets) were randomly renewed, and the displays were presented once throughout the experiment. As in the repeated displays, the target locations in each non-repeated display were also kept constant across blocks. By this manipulation, the pure learning of the target location in the progress of the contextual learning could be excluded, and thus any RT difference between the non-repeated and repeated displays could be attributed to the learning of the target-distractor spatial contexts rather than the target location itself.

In the *learning session*, each trial began with a central fixation cross, which the participants were instructed to fixate for a random duration between 800 and 1,000 ms. After that, the search display was shown until participants made a response. A 1,000- to 1,200-ms inter-trial interval was presented before the start of the next trial. In the *transfer session*, the procedure was identical to that in the learning session. Nevertheless, unknown to the participants, the colors of all search items (both targets and distractors) in the repeated displays were swapped. To be specific, in repeated displays, the white subset of items in the previous learning session would turn black in the transfer session and the previously black subsets would turn white, while the spatial layouts of the displays were maintained the same as the learning session (Fig. 2). This color switch was not employed in non-repeated displays, recalling that all distractor locations in non-repeated displays were renewed throughout the experiment (see previous text). Through this manipulation, we aimed to detect the potential learning of the repeated but task-irrelevant subsets of item configurations. Following the transfer session, a surprising *recognition session* (containing the six repeated displays and six newly generated non-repeated displays) was conducted. The item color settings were the same as those in the learning session. Participants were asked to press the left- or right-arrow key on the keyboard if they believed the displays had been shown in previous search sessions or not, in order to examine whether they had explicitly remembered the repeated displays in the previous search task (see Chun & Jiang, 1998).

Preceding the formal experiment, one practice block of 16 trials was conducted to familiarize participants with the search task. When the accuracy in the practice block reached 85%, participants were allowed to begin the formal experiment; otherwise, they had to repeat the practice block (see also Chen et al., 2021). No participant repeated the exercise more than five times. All of the display configurations in the practice block were produced at random and were not shown during the official experiment.

Results

Analogous to Experiment 1, trials with RT outliers or with wrong responses in the search sessions were excluded from further analysis in learning and transfer sessions. Both the average outlier rate (2.12% and 2.34% in Experiments 2A and 2B, respectively) and average error rate (0.66% and 1.53%, respectively) were low. BIS analysis showed that participants' performance was not influenced by speed-accuracy tradeoff (see OSM). The calculation of the CVs of RTs was also similar to that in Experiment 1.

Learning session

As depicted in Fig. 1C and D, participants' mean RTs and mean CVs are plotted according to Epoch and Context, and they were applied to repeated-measures ANOVAs with Context (repeated vs. non-repeated) and Epoch (1–6) as factors.

In *Experiment 2A*, teenagers exhibited similar patterns of contextual learning to adults in Experiment 1, with both mean RT and mean CV significantly reduced in the repeated contexts relative to the non-repeated ones. For the mean RTs, the effects of Context, Epoch, and the Context × Epoch interaction were all significant: Context, $F(1, 40) = 8.245$, $p = 0.007$, $\eta_p^2 = 0.171$, $CC_{RT} = 43$ ms; Epoch: $F(2.693, 107.732) = 88.335$, $p < 0.001$, $\eta_p^2 = 0.688$, with the RT decreasing by 202 ms from Epoch 1 to Epoch 6 [linear effect: $t(200) = 20.405$, $p < 0.001$], indicating a procedural learning effect; Context × Epoch interaction: $F(5, 200) = 5.241$, $p < 0.001$, $\eta_p^2 = 0.116$, mainly due to the CC_{RT} being non-significant in Epoch 1 [$t(40) = 0.125$, $p = 0.909$, Cohen's $d = 0.018$, $BF_{10} = 0.170$] but significant from Epoch 2 to Epoch 6 (all ts > 2.72, all ps < 0.01).

For the mean CVs, the effect of Context but not of Epoch or Context × Epoch interaction was significant: Context, $F(1, 40) = 9.058$, $p = 0.005$, $\eta_p^2 = 0.185$, $CC_{CV} = 0.015$, indicating the existence of contextual cueing in terms of CV in the teenage participants; Epoch, $F(5, 200) = 1.961$, $p = 0.086$, $\eta_p^2 = 0.047$, $BF_{10} = 0.113$; Context × Epoch, $F(5, 200) = 0.207$, $p = 0.959$, $\eta_p^2 = 0.005$, $BF_{10} = 0.010$.

In *Experiment 2B*, however, different contextual learning patterns were observed among child participants as compared with teenager and adult participants. Children only showed contextual facilitation in terms of RT, but not CV.

For the mean RTs, the effects of Context and Epoch but not the Context × Epoch interaction were significant: Context, $F(1, 42) = 31.838$, $p < 0.001$, $\eta_p^2 = 0.431$, $CC_{RT} = 90$ ms, demonstrating a cueing effect in terms of RT among children; Epoch, $F(2.511, 105.449) = 44.107$, $p < 0.001$, $\eta_p^2 = 0.512$, with the mean RT decreasing by 415 ms from Epoch 1 to Epoch 6 [linear effect: $t(210) = 13.919$, $p < 0.001$], confirming a procedural learning effect; Context × Epoch, $F(5, 210) = 1.919$, $p = 0.093$, $\eta_p^2 = 0.044$, $BF_{10} = 0.021$.

For the mean CV, no effect (of interest) reached significance: Context, F

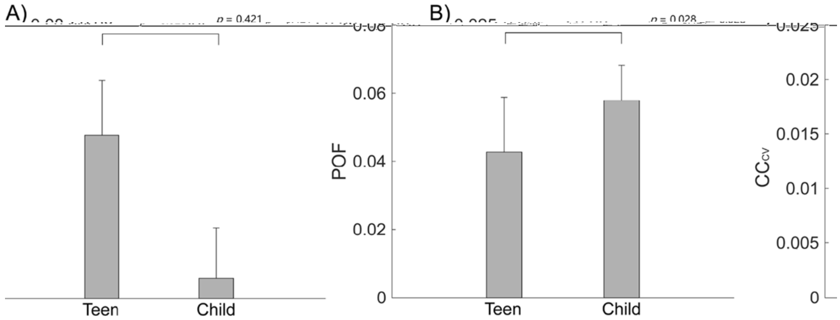

Fig. 3 The magnitude of contextual cueing in the learning session of Experiments 2A (teenagers) and 2B (younger children). (**A**) and (**B**) depict the mean POF (percentage of facilitation in terms of response time (RT)) and the mean CC_{CV}, respectively. The error bars represent the standard error (SE) of the mean

Transfer session

Mean RTs and CVs were analyzed by paired *t*-tests with context as a factor, and the results showed a similar pattern between teenagers and younger children: No contextual cueing transfer effect was observed for either RTs or CVs.

For teenagers (Experiment 2A): RT, $t(40) = 1.271$, $p = 0.211$, Cohen's $d = 0.199$, $BF_{10} = 0.356$, with mean RTs of 883 ms and 866 ms for non-repeated and repeated contexts, respectively; CV, $t(40) = 1.581$, $p = 0.122$, Cohen's $d = 0.247$, $BF_{10} = 0.530$, with mean CVs of 0.224 and 0.210 for non-repeated and repeated contexts respectively.

For younger children (Experiment 2B): RT, $t(42) = -0.962$, $p = 0.342$, Cohen's $d = -0.147$, $BF_{10} = 0.254$, with mean RTs of 1,404 ms (for non-repeated contexts) and 1,436 ms (for repeated contexts); CV, $t(42) = 0.363$, $p = 0.719$, Cohen's $d = 0.055$, $BF_{10} = 0.176$, with mean CVs of 0.329 for non-repeated and 0.324 for repeated contexts.

Recognition session

We examined the hit rates (i.e., repeated contexts were correctly identified as repeated) and false alarm rates (i.e., non-repeated contexts were incorrectly identified as repeated) in the final recognition session by a paired *t*-test to see whether participants had explicit memory of the repeated spatial contexts. In Experiment 2A with teens, the mean hit and false alarm rates were 47.97% and 50.81%, respectively [$t(40) = 0.612$, $p = 0.544$, Cohen's $d = 0.096$, $BF_{10} = 0.201$], and in Experiment 2B with children, they were 52.71% and 50.00%, respectively [$t(42) = 0.622$, $p = 0.538$, Cohen's $d = 0.095$, $BF_{10} = 0.198$]. Thus, the recognition session provides no evidence supporting explicit memory of the repeated contexts in either teenagers or children (see also Merrill et al., 2013; Yang & Merrill, 2014, 2015). This result, however, should be taken cautiously and we refrain from making any inferences regarding it because the recognition test has been shown to be underpowered (Vadillo et al. 2016).

Interim discussion

Experiment 2 aimed to investigate contextual cueing effects in teenagers and younger children. The results demonstrated appreciable contextual cueing effects in terms of both RT and RT variability among teenagers. Together with the comparable findings from adult participants in Experiment 1, we can conclude that RT variability (measured by the coefficient of variation of RT) is a reliable indicator of contextual cueing effects, which was repeatedly supported by Experiments 1 and 2A. In other words, participants can improve both the speed and the stability of responses through repeated exposure to spatial contexts.

It is worth noting that we observed a context-driven decrease only in RT but not in RT variability among 8- to 9-year-old children. Rather than casting doubt on the efficacy of RT variability as a cueing indicator due to the absence of cueing facilitation in children, we propose that it is a more sensitive indicator than mean search speed for identifying contextual learning patterns across individuals of different ages. On one hand, our findings confirm that children can learn repeatedly encountered contexts and exhibit contextual cueing effects, as reported in prior studies (e.g., Barnes et al., 2008, 2010; Merrill et al., 2013; Weigard & Huang-Pollock, 2014). On the other hand, we also concur with previous research (e.g., Yang & Merrill, 2014, 2015, 2018; Sakata et al., 2023) that children's contextual learning ability is not as strong as that of adults, as they were unable to increase response stability. This may be attributed to children's developing cognition and brain functions related to contextual learning.

General discussion

In this study, we employed the measure of RT variability – the coefficient of variation (CV) of RT – in addition to the conventional measure of mean RT, to investigate age-related differences in contextual learning patterns among adults (aged 18–33 years), teenagers (aged 15–17 years), and younger children (aged 8–9 years). The results yielded both similar and different observations across these three age groups concerning search behavior and contextual learning. For the similarity, a significant contextual cueing effect was observed in terms of mean RT across all three age groups during the initial learning phase. For the disparate observations among age groups, significant contextual facilitation in terms of RT variability was observed in teenagers and adults but not in children. Meanwhile, the search speed was slower and less stable in children than in the other two groups. These results offer a valuable contribution to the understanding of both the mechanisms behind contextual cueing and the age-related differences in contextual learning. For instance, the similar contextual facilitation in terms of mean RT and the different cueing in terms of RT variability among the three groups of participants pointed to the conclusion that the latter relative to the former measure can be used as an additional, potentially more sensitive measure to detect age-related differences in contextual learning.

The finding that children displayed overall greater RT variability is not surprising since similar observations have been reported in a number of previous studies (e.g., Li et al., 2004; Williams et al., 2005, 2007). Williams et al. (2005) examined the RT of participants aged 6–81 years in a two-choice task and discovered a “U”-shaped association between age and RT variability (termed “inconsistency” in their study). Their findings revealed that individuals within the age range of 6–8 years and 60–81 years exhibited greater intra-individual standard deviation of RTs compared to those aged 9–59 years (see also Williams et al., 2007). Similarly, Li et al. (2004) reported higher RT variability in younger children and older adults in multiple basic cognitive tasks, such as visual search, response competition, long-term and short-term memory search, and choice reactions. In addition to the previous research, the current study provides a novel finding that RT variability in younger children remained consistently high throughout the visual search task, despite being presented with invariant display configurations. This underscores the significance of the current work, which reveals an additional layer of information beyond what was previously known about cognitive variability in different age groups.

In the context of our findings, the RT variability (CV) serves as a critical indicator of the efficiency and consistency of psychological processes during contextual learning across different developmental stages. While our results demonstrated that all age groups could learn and benefit from contextual cueing, as evidenced by faster mean RTs in repeated contexts, the differential patterns of CV across age groups shed light on the age-related difference in underlying mechanisms at play. In adults and teenagers, the context-driven reduction in CV hints at a mature ability to consistently apply the learned contextual associations to guide attention and facilitate search efficiency. This consistency indicates not only successful learning but also efficient retrieval and application of contextual memories with minimal variability in performance. Such a pattern reflects a stable attentional guidance mechanism and a robust memory representation that can be reliably accessed across trials. In contrast, the lack of context-related reduction in CV among younger children, despite learning contextual cues, points to a different psychological process. This suggests that while children can form contextual associations and use them to some extent (as shown by faster response speed), their cognitive systems exhibit greater variability in applying these associations consistently across trials.

This age-related difference in the contextual facilitation of RT variability could be attributed to the development of several interrelated psychophysiological and cognitive mechanisms. It has been shown that the high variability in children may be influenced by the high neural noise generated by the catecholaminergic system, which is believed to play a crucial role in regulating the signal-to-noise ratio of neurons by increasing their sensitivity to other incoming signals or distractors (Li & Lindenberger, 1999; Williams et al., 2005). Meanwhile, the core cognitive mechanisms, such as cognitive flexibility, and planning, were also weaker in younger children (Zinchenko, Chen et al., 2019a), which may be related to high response variability. For instance, it was shown that weaker cognitive control is associated with higher RT variability in children with ADHD when they performed tasks of executive control and the Eriksen Flanker task (Gómez-Guerrero et al., 2011). The developing state of children’s psychophysiological mechanisms and their cognitive mechanisms may result in increased neural and behavioral noise, thereby constraining the potential for improving response consistency through short-term training approaches. This is because neither the catecholaminergic system nor the core cognitive abilities could be adjusted within a short period. Thus, it is not surprising to observe no variation reduction through contextual learning in our study for younger children aged 8–9 years.

The observed result that RT variability was not reduced during contextual learning in children may be linked to their strategic flexibility during visual search (Hultsch et al., 2008; McDaniel et al., 2008). Children’s higher CV may reflect a greater propensity for strategic shifts across trials. While such flexibility is beneficial for exploring different strategies, it may also lead to greater intra-individual variability in task performance, especially in tasks requiring the consistent application of learned cues. Siegler (1994) conducted a review of studies on cognitive development in young children. The studies reviewed by Siegler (1994) covered a wide range of tasks, including math problems, spatial reasoning tasks, and other cognitive tasks. In these studies, researchers observed children as they performed the task and looked for patterns in their behavior and thinking. Siegler (1994) analyzed the results of these studies and proposed that young children tend to discover new cognitive strategies in various cognitive tasks and that this discovery is often accompanied by more pronounced behavioral variability (e.g., Church & Goldin-Meadow, 1986; Siegler & Jenkins, 2014). Similarly, young children may frequently change their search strategies during the context-guided search task (e.g., prioritizing target detection vs. distractor suppression). Frequent alterations of search strategies can generate extra variability in the form of "changing" noise, which could lead to increased variability in RT. The variability caused by frequent strategic shifts in children may "overwhelm" the benefit of the repetition of contexts, resulting in comparable levels of variability in the repeated and non-repeated contexts.

The findings concerning RT variability in children may be also related to their still-developing attention control: Children are still refining their ability to maintain focus and exert attentional regulation during tasks (Gaspelin et al., 2015; Trick & Enns, 1998). The high CV might reflect fluctuations in their ability to consistently apply attentional resources in a focused manner, leading to variability in how effectively they can use contextual information. Additionally, our finding may be related to memory retrieval and stability: Although children can encode contextual cues, the memory traces may be less stable, and the retrieval of these memories may be less efficient compared to teenagers and adults (Fynes-Clinton et al., 2019). This could be caused by ongoing developmental changes in children's memory systems, affecting the consistency with which contextual information is applied during visual search. Therefore, the variability measure reveals critical insights into the maturation of psychological processes essential for efficient and consistent visual search guided by context. It underscores the importance of considering not only the acquisition and application of contextual knowledge but also the developmental trajectory of the cognitive mechanisms that enable this knowledge to be applied consistently and efficiently.

It is possible that there are age-specific developmental differences in the neural mechanisms underlying contextual cueing. Previous research has shown that brain regions involved in attention and memory, such as the prefrontal cortex, parietal cortex, and hippocampus, undergo significant developmental changes during childhood and adolescence (Giedd et al., 1999; Gogtay et al. 2004; MacDonald et al. 2006; Pfefferbaum et al., 1994; Reiss et al., 1996; Sowell et al., 2001). For instance, previous research has found a connection between the slower pace of frontal lobe development in children and their higher RT variability. In a study conducted by Simmonds et al. (2007) in children aged 8–12 years, RT variability was correlated with prefrontal cortex activation during both Go and No-go events in a Go/No-go task. Similarly, Stuss et al. (2003) found that adults with frontal lesions had greater RT variability in four different RT tasks compared to a control group. Given the evidence that prefrontal circuits are related to behavioral response variability and since the prefrontal cortex was also linked to context learning (Zinchenko, Conci et al., 2019b), it is possible that prolonged development time of the prefrontal cortex in younger children could be responsible for the observed higher RT variability in the contextual cueing task in the current work. Accordingly, age-specific developmental changes may lead to differences in the way that older and younger children process and learn from repeated contexts in the contextual cueing task, which could impact the variability of RTs.

Although the analysis of intra-individual RT variation revealed age-related differences in contextual learning, children are able to learn and use the repeated spatial contextual memory, as demonstrated by comparable context-driven facilitation in RT between the children and teenagers in the current study. This supports the previous research demonstrating the contextual cueing effect in children aged 7–14 years (Barnes et al., 2008, 2010; Weigard & Huang-Pollock, 2014), and in contrast to other studies that found no such evidence in children aged 6–13 years (Couperus et al., 2011; Vaidya et al., 2007). Hence, our study provides further evidence to support the idea that children are capable of learning and utilizing repeated spatial contextual memory.

Note that in a study with a similar design to the current work, Couperus et al. (2011) did not observe the contextual cueing effect in children (mean age of 10 years) when the search displays contained an equal number of task-relevant and -irrelevant items. The conflicting results could be due to the complexity of their experimental design, which included four types of search displays (both-repeated, relevant-repeated, irrelevant-repeated, and both-non-repeated), potentially leading to a decrease in the SN ratio and a lower probability of contextual learning (see also Yang & Merrill, 2015; Zang et al., 2018; Zinchenko et al., 2018). In contrast, our current study used a less complex design with only two conditions (both-repeated and both-non-repeated displays), which resulted in an overall faster mean RT (around 1,400 ms, see Fig. 1C) relative to what was reported by Couperus et al. (2011, around 3,000 ms), although both studies tested comparable age groups of 8- to 9-year-old children. Consistent with this idea, several child studies have reported reliable contextual cueing using more child-friendly search displays (e.g., cartoon pictures as search items in Dixon et al., 2010; Merrill et al., 2013; Yang & Merrill, 2014, 2015, 2018). These findings suggest that the ability to learn repeated spatial context may develop early on (see also Jiang et al., 2019), albeit with different learning patterns across ages.

Another finding worth noting in the current study was the impairment of the contextual cueing effect when the task-relevant and task-irrelevant contexts were switched (by swapping the color of the search items) in teenagers and younger children. In more detail, the visual search displays in the current study included both task-relevant and task-irrelevant subsets, distinguished by the color of the items. During the transfer session following the initial learning session, unbeknownst to the participants, we reversed the task relevance of the two subsets of contexts. As a result, the contextual facilitation effect was not maintained after the reversal in teenagers and younger children, as evidenced by the non-significant difference in both RT and CV measures between repeated and non-repeated contexts in the transfer session. This indicates that task-irrelevant contexts did not provide any behavioral benefits. This decline of contextual cueing can be attributed to selective attention: Participants tend to selectively focus on the task-relevant contexts while disregarding the task-irrelevant context when forming contextual memory, leading to the lack of learning of repeated but task-irrelevant information. Our study adds to the growing body of evidence that children as young as 8–9 years old are capable of selectively attending to task-relevant items while filtering out irrelevant items based on task demands (see also Pritchard & Neumann, 2004, 2009; Tipper et al., 1989; Tipper & McLaren, 1990). However, it is notable that among adults, a significant context-related reduction in CV (but not RT) was observed in the transfer session. This might indicate that the repeated but previously task-irrelevant contexts were more or less learned during the initial learning session, but the learning was not detected with the RT measure. Alternatively, it is also possible that the previously irrelevant contexts were learned in the transfer session (namely, after the task relevance of search items was swapped). Both possibilities could suggest that the context-driven reduction in CV, reflecting an improvement in response consistency, might precede the enhancement of response speed in adults. This assumption is in line with our finding of reliable contextual cueing in terms of CV but not RT in the first epoch among adults (Fig. 1A and B). The precedence of CV reduction (over the decrease in RT) might be because adults' search behavior among the same search context could be easily modulated and tuned by the learning of context repetition, which leads to more consistent responses (i.e., smaller CV). By contrast, the average search speed might improve gradually with the repetition of search contexts. These speculations, nevertheless, need to be further clarified in future research.

In conclusion, the current study used traditional RT analysis to demonstrate that both teenagers aged 15–17 years and younger children aged 8–9 years can acquire knowledge of repeated contexts consisting of task-relevant and -irrelevant displays, leading to context-related improvement in response speed. However, by incorporating the analysis of intra-individual RT variability, this study found that the teenagers exhibited significant improvement in RT variability, while the younger children did not. These findings suggest that age-related differences exist in contextual cueing mechanisms, and future research could consider both response speed and RT variability to further understand this phenomenon.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.3758/s13414-024-02926-2.

Acknowledgements The authors gratefully acknowledge Prof. Dr. Yu-Feng Zang for his invaluable inspiration for the data analysis, which greatly refined the current study.

Funding This research was supported by the National Natural Science Foundation of China (NSFC 32071042) and the Starting Research Fund from Hangzhou Normal University (2021YN2021107) to X.Z. The funding bodies played no role in the study design, data collection, data analysis, decision to publish, or preparation of the manuscript.

Availability of data and codes The data and data processing codes (based on MATLAB) for the experiments are available via the Open Science Framework at: https://osf.io/9ub7w/. The codes for presenting the experimental stimuli are available upon request. None of the experiments was preregistered.

Declarations

Conflicts of interest The authors have no conflicts of interest to declare.

Ethics approval Ethics approval was obtained from the Center for Cognition and Brain Disorders ethics committee at the Affiliated Hospital of Hangzhou Normal University.

Consent to participation and publication Informed consent to participation and publication of the anonymized data was obtained from all participants. Experiments conducted in the high school and primary school were regarded as extra-curricular activities, and permission was obtained from the homeroom teachers and school administrators.

References

Alderson, R. M., Rapport, M. D., & Kofler, M. J. (2007). Attention-deficit/hyperactivity disorder and behavioral inhibition: A meta-analytic review of the stop-signal paradigm. *Journal of Abnormal Child Psychology, 35*(5), 745–758. https://doi.org/10.1007/s10802-007-9131-6

Barnes, K. A., Howard, J. H., Jr., Howard, D. V., Gilotty, L., Kenworthy, L., Gaillard, W. D., & Vaidya, C. J. (2008). Intact implicit learning of spatial context and temporal sequences in childhood autism spectrum disorder. *Neuropsychology, 22*(5), 563–570. https://doi.org/10.1037/0894-4105.22.5.563

Barnes, K. A., Howard, J. H., Howard, D. V., Kenealy, L., & Vaidya, C. J. (2010). Two forms of implicit Learning in childhood ADHD. *Developmental Neuropsychology, 35*(5), 494–505. https://doi.org/10.1080/87565641.2010494750

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10*(4), 433–436. https://doi.org/10.1163/156856897X00357

Buzy, W. M., Medoff, D. R., & Schweitzer, J. B. (2009). Intra-individual variability among children with ADHD on a working memory task: An ex-Gaussian approach. *Child Neuropsychology, 15*(5), 441–459. https://doi.org/10.1080/09297040802646991

Chen, S., Shi, Z., Müller, H. J., & Geyer, T. (2021). When visual dis-

Journal of Genetic Psychology: Research and Theory on Human Development, 174(4), 387–402. https://doi.org/10.1080/00221325.2012.694919

Pastò, L., & Burack, J. A. (1997). A developmental study of visual attention: Issue of filtering efficiency and focus. *Cognitive Development, 12*(4), 523–535. https://doi.org/10.1016/S0885-2014(97)90021-6

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*(4), 437–442. https://doi.org/10.1163/156856897x00366

Pfefferbaum, A., Mathalon, D. H., & Sullivan, E. V. (1994). A quantitative magnetic resonance imaging study of changes in brain morphology from infancy to late adulthood. *Archives of Neurology, 51*(9), 874–887. https://doi.org/10.1001/archneur.1994.00540210046012

Pritchard, V. E., & Neumann, E. (2004). Negative priming effects in children engaged in nonspatial tasks: Evidence for early development of an intact inhibitory mechanism. *Developmental Psychology, 40*(2), 191–203. https://doi.org/10.1037/0012-1649.40.2.191

Pritchard, V. E., & Neumann, E. (2009). Avoiding the potential pitfalls of using negative priming tasks in developmental studies: Assessing inhibitory control in children, adolescents, and adults. *Developmental Psychology, 45*(1), 272–283. https://doi.org/10.1037/a0014168

Reiss, A. L., Abrams, M. T., Singer, H. S., Ross, J. L., & Denckla, M. B. (1996). Brain development, gender and IQ in children. *Brain, 119*(5), 1763–1774. https://doi.org/10.1093/brain/119.5.1763

Ridderinkhoff, R. K., & van der Stelt, O. (2000). Attention and selection in the growing child: Views derived from developmental psychophysiology. *Biological Psychology, 54*(1–3), 55–106. https://doi.org/10.1016/S0301-0511(00)00053-3

Sakata, C., Ueda, Y., & Moriguchi, Y. (2023). The contextual cueing effect disappears during joint search in preschool children. *J Exp Child Psychol, 227*, 105592. https://doi.org/10.1016/j.jecp.2022.105592

Shi, Z., Zang, X., Jia, L., Geyer, T., & Muller, H. J. (2013). Transfer of contextual cueing in full-icon display remapping. *Journal of Vision, 13*(3), 1–10. https://doi.org/10.1167/13.3.2

Siegler, R. S. (1994). Cognitive variability: A key to understanding cognitive development. *Current Directions in Psychological Science, 3*(1), 1–5. https://doi.org/10.1111/1467-8721.ep10769817

Siegler, R. S., & Jenkins, E. A. (2014). *How children discover new strategies*. Psychology Press.

Simmonds, D. J., Fotedar, S. G., Suskauer, S. J., Pekar, J. J., Denckla, M. B., & Mostofsky, S. H. (2007). Functional brain correlates of response time variability in children. *Neuropsychologia, 45*(9), 2147–2157. https://doi.org/10.1016/j.neuropsychologia.2007.01.013

Sowell, E. R., Thompson, P. M., Tessner, K. D., & Toga, A. W. (2001). Mapping continued brain growth and gray matter density reduction in dorsal frontal cortex: Inverse relationships during postadolescent brain maturation. *Journal of Neuroscience, 21*(22), 8819–8829. https://doi.org/10.1523/JNEUROSCI.21-22-08819.2001

Stuss, D. T., Pogue, J., Buckle, L., & Bondar, J. (1994). Characterization of stability of performance in patients with traumatic brain injury: Variability and consistency on reaction time tests. *Neuropsychology, 8*(3), 316–324. https://doi.org/10.1037/0894-4105.8.3.316

Stuss, D. T., Murphy, K. J., Binns, M. A., & Alexander, M. P. (2003). Staying on the job: The frontal lobes control individual performance variability. *Brain, 126*(11), 2363–2380. https://doi.org/10.1093/brain/awg237

Tipper, S. P., & McLaren, J. (1990). Chapter 10 Evidence for efficient visual selectivity in children. In *Advances in Psychology* (Vol. 69, pp. 197–210). https://doi.org/10.1016/s0166-4115(08)60457-4

Tipper, S. P., Bourque, T. A., & Anderson, S. H. (1989). Mechanisms of attention: A developmental study. *Journal of Experimental Child Psychology, 48*(3), 353–378. https://doi.org/10.1016/0022-0965(89)90047-7

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

Vadillo, M. A., Konstantinidis, E., & Shanks, D. R. (2016). Underpowered samples, false negatives, and unconscious learning. *Psychonomic Bulletin & Review, 23*, 87–102. https://doi.org/10.3758/s13423-015-0892-6

Vadillo, M. A., Gimenez-Fernandez, T., Aivar, M. P., & Cubillas, C. P. (2020). Ignored visual context does not induce latent learning. *Psychonomic Bulletin & Review, 27f [(Jour)-16(nal of Exper)-8( )Tj [(().5(3).* tps:// org/
13.7586/s13423-203-0722-x6

Vaidsya, C. J.,Hunger, M.,H(o)22(r)28(ar)2.1(d,D., V)100(., &H(o)22(r)28(ar)1(d,JD. H
opsychology, 31(4), 497–5106. https://doi.org/10.1037/0894-

Psychology, 167, 162–179. https://doi.org/10.1016/j.jecp.2017.10.015
Zang, X., Zinchenko, A., Jia, L., Assumpcao, L., & Li, H. (2018). Global repetition influences contextual cueing. *Frontiers in Psychology, 9*, 402. https://doi.org/10.3389/fpsyg.2018.00402
Zang, X., Huang, L., Zhu, X., Muller, H. J., & Shi, Z. (2020). Influences of luminance contrast and ambient lighting on visual context learning and retrieval. *Attention, Perception, & Psychophysics, 82*(8), 4007–4024. https://doi.org/10.3758/s13414-020-02106-y
Zang, X., Assumpcao, L., Wu, J., Xie, X., & Zinchenko, A. (2021). Task-irrelevant context learned under rapid display presentation: Selective attention in associative blocking. *Frontiers in Psychology, 12*, 675848. https://doi.org/10.3389/fpsyg.2021.675848
Zang, X., Zinchenko, A., Wu, J., Zhu, X., Fang, F., & Shi, Z. (2022). Contextual cueing in co-active visual search: Joint action allows acquisition of task-irrelevant context. *Attention, Perception, & Psychophysics, 84*(4), 1114–1129. https://doi.org/10.3758/s13414-022-02470-x
Zhao, G., Zhuang, Q., Ma, J., Tu, S., Liu, Q., & Sun, H. J. (2017). Contextual cueing effect in spatial layout defined by binocular disparity. *Frontiers in Psychology, 8*, 1472. https://doi.org/10.3389/fpsyg.2017.01472
Zinchenko, A., Conci, M., Müller, H. J., & Geyer, T. (2018). Predictive visual search: Role of environmental regularities in the learning of context cues. *Attention, Perception, & Psychophysics, 80*(5), 1096–1109. https://doi.org/10.3758/s13414-018-1500-4
Zinchenko, A., Chen, S., & Zhou, R. (2019). Affective modulation of executive control in early childhood: Evidence from ERPs and a Go/Nogo task. *Biological Psychology, 144*, 54–63. https://doi.org/10.1016/j.biopsycho.2019.03.016
Zinchenko, A., Conci, M., Taylor, P. C. J., Muller, H. J., & Geyer, T. (2019). Taking attention out of context: Frontopolar transcranial magnetic stimulation abolishes the formation of new context memories in visual search. *Journal of Cognitive Neuroscience, 31*(3), 442–452. https://doi.org/10.1162/jocn_a_01358
Zinchenko, A., Conci, M., Töllner, T., Müller, H. J., & Geyer, T. (2020). Automatic guidance (and misguidance) of visuospatial attention by acquired scene memory: Evidence from an N1pc polarity reversal. *Psychological Science, 31*(12), 1531–1543. https://doi.org/10.1177/0956797620954815

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.