



The effects of perceptual cues on visual statistical learning: Evidence from children and adults

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Abstract

In visual statistical learning, one can extract the statistical regularities of target locations in an incidental manner. The current study examined the impact of salient perceptual cues on one type of visual statistical learning: probability cueing effects. In a visual search task, the target appeared more often in one quadrant (i.e., rich) than the other quadrants (i.e., sparse). Then, the screen was rotated by 90° and the targets appeared in the four quadrants with equal probabilities. In Experiment 1 without the addition of salient perceptual cues, adults showed significant probability cueing effects, but did not show a persistent attentional bias in the testing phase. In Experiments 2, 3, and 4, salient perceptual cues were added to the rich or the sparse quadrants. Adults showed significant probability cueing effects but no persistent attentional bias. In Experiment 5, younger children, older children, and adults showed significant probability cueing effects. All three groups also showed an attentional gradient phenomenon: reaction times were slower when the targets were in the sparse quadrant diagonal to, rather than adjacent to, the rich quadrant. Furthermore, both children groups showed a persistent egocentric attentional bias in the testing phase. These findings indicated that salient perceptual cues enhanced but did not reduce probability cueing effects, children and adults shared similar basic attentional mechanisms in probability cueing effects, and children and adults showed differences in the persistence of attentional bias.

Keywords Visual statistical learning · Saliency · Perceptual cues · Probability cueing · Children

Introduction

Our visual environment is full of statistical regularities. In visual statistical learning (e.g., Fiser & Aslin, 2002; Jiang, Swallow, Rosenbaum, & Herzig, 2013), one extracts and utilizes the statistical probabilities of targets' locations and other aspects of the environment to facilitate visual search and target identification. The current study examined the role of perceptual cues on one form of visual statistical learning, probability cueing.

Probability cueing – a visual statistical learning paradigm

One paradigm of visual statistical learning (VSL) is the probability cueing paradigm (Jiang & Swallow, 2013). In visual search displays, targets can consistently appear more often in one quadrant (i.e., rich) relative to the other (i.e., sparse) quadrants. Participants are not told about the statistical probabilities of target locations. Yet, over time they respond faster when targets appear in the rich quadrant than in the sparse quadrants, showing the probability cueing effects. This form of learning is generally considered incidental, rather than intentional. Large-scale studies have also found subsequent explicit awareness about the rich quadrant after participants acquire probability cueing effects (Giménez-Fernández et al., 2020; Jiang, Li, & Sisk, 2018; Vadillo, Linssen, Orgaz, Parsons, & Shanks, 2020), although it is less common to find significant levels of explicit awareness in smaller studies due to insufficient power (e.g., Jiang & Swallow, 2013; Jiang, Swallow, & Rosenbaum, 2013).

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One mechanism thought to be responsible for probability cueing is that one develops attentional guidance towards the rich quadrant. Search slopes were reduced when the targets were in the rich, rather than the sparse, quadrants (Jiang, Swallow, & Rosenbaum, 2013). Therefore, one important reason to study probability cueing is that it provides a means to probe how one can acquire statistical regularities in the environment incidentally, through experience, and in a seemingly bottom-up fashion, and guide attention towards the target in a seemingly top-down fashion. Through the study of probability cueing, we may gain a better understanding of the “cognitive architecture of attention” (Jiang, Swallow, & Rosenbaum, 2013, p. 285). Towards this effort, it is essential to understand the attention characteristics of the probability cueing effects. Here we focus on three: persistence, frame of reference, and spatial distribution of the attentional bias.

One issue concerning the attentional bias towards the rich quadrant is whether or not it persists over time. Jiang, Swallow, Rosenbaum, and Herzog (2013) found that attentional bias can persist longer than a week and last for several hundred trials even when the targets are evenly redistributed across the displays in the testing phase. However, this claim has been challenged by Giménez-Fernández, Luque, Shanks, and Vadillo (2020), who recently conducted two preregistered large studies (about 160 participants each) of the probability cueing effects. They found that the attentional persistence towards the previous rich quadrant was significantly attenuated, although still existed, in the testing phase where target locations were evenly distributed. However, because they presented only 12 blocks in the testing phase, the authors hinted that with more trials, the attentional bias might eventually disappear. Hence, Giménez-Fernández et al. (2020) has cast some doubt on whether the attentional bias is inflexible, and suggests it can be “unlearned.”

The second characteristic of attentional bias towards the rich quadrant that requires additional research is that it may be encoded in an egocentric (relative to the observer), rather than an allocentric (relative to the environment) fashion (Jiang, Swallow, & Capistrano, 2016; Jiang, Swallow, & Sun, 2014; Jiang & Won, 2015). Jiang and Swallow (2013) presented targets more often in the rich quadrant than in the sparse quadrants during the learning phase. In the test phase, the targets were distributed evenly among the four quadrants. Importantly, participants also physically moved to a new position while the display stayed in the same location. As a result, one quadrant preserved the same spatial relation relative to the observer (e.g., the front left side of the participant) and hence was the egocentric-rich quadrant. One quadrant preserved the same spatial relation relative to the display (e.g., top left corner of the display) and hence was the allocentric-rich

quadrant. Adults responded faster when the targets appeared in the egocentric-rich quadrant than in the other quadrants. Reaction times (RTs) in the allocentric-rich quadrant were no different from those in the sparse quadrants. They replicated the study and found the same results when the display was rotated (Jiang, Swallow, & Sun, 2014), rather than having the participants physically move. It hence showed the persistence of egocentric bias, regardless of spatial updating.

The third feature of attentional bias towards the rich quadrant is that the spread of attention from the rich quadrant may be graded, reducing with increasing distance from the rich quadrant. It hence reflects the attentional gradient phenomenon (LaBerge & Brown, 1989). Jiang, Li, and Sisk (2018) re-examined previously published data of over 400 participants who searched for Ts among Ls in the classic probability cueing tasks. RTs were slower in the sparse quadrant diagonal to the rich quadrant than in the two sparse quadrants adjacent to the rich quadrants. Different mechanisms may account for this result. For instance, eye movements may shift to adjacent quadrants rather than to the diagonal quadrants more quickly after initially selecting items in the rich quadrant. It is also possible that attention is distributed in a gradient fashion in the visual field. Therefore, targets that are closer to the attended rich quadrant were processed better than those that are further away.

Effects of perceptual cues on probability cueing effects

During probability cueing, the attentional bias towards high-probability target locations has to be acquired via experience and learning. In contrast, perceptual cues, like a distinctly colored background, can be very salient and noticed by participants immediately (e.g., Theeuwes, 2010; Yantis & Egeth, 1999). Research has also shown that salient perceptual cues can guide attention (Wolfe, 2007). So, how does one acquire and guide attention towards high-probability target locations in the presence of both salient perceptual cues and seemingly less-salient location cues? Ultimately, studying how salient perceptual cues impact probability cueing helps to understand how we perceive, evaluate, balance, and select different cues that are probabilistically available, being perceptual or spatial, to facilitate our interactions with the visual world.

To date, research has suggested that the impact of perceptual cues may be limited (Jiang et al., 2016; Jiang, Swallow, & Sun, 2014; Jiang & Won, 2015). For instance, Jiang and colleagues found that perceptual cues failed to alter adults' persistent egocentric attentional bias in probability cueing. Their perceptual manipulations

included highlighting one edge of the search display (e.g., red wall) (Jiang, & Swallow, 2013); using a real-life photo as the background (Jiang, Swallow, & Sun, 2014); and highlighting the rich quadrant using a blue outline every 96 trials (Jiang, Swallow, & Sun, 2014). Participants did not exhibit a difference between the allocentric-rich and the sparse quadrants after the display rotated in the test phase of these studies. This hence suggested a stronger role of location cues (e.g., top right quadrant) over perceptual cues in biasing attention in probability cueing effects. It also indicated that the egocentric attentional bias towards the rich quadrant may have been encoded spontaneously.

The current study aimed to examine the role of perceptual cues on several attention features of probability cueing effects. Here, we refer to the attention features as the acquisition, persistence, frame of reference, and spatial distribution of the attentional bias developed in probability cueing effects. Different from previous studies (e.g., Jiang, Swallow, & Sun, 2014), we colored the entire quadrants of the displays red or grey to make the perceptual cues stronger and more salient. We had three specific goals. First, we evaluated whether perceptual cues would facilitate or impede the acquisition of attentional bias in probability cueing effects. Second, we examined how persistent the attentional bias was in probability cueing effects once acquired and whether perceptual cues would alter it. Third, we examined whether features of the attentional bias in probability cueing effects would differ between children and adults and whether perceptual cues would modulate them.

The effect of perceptual cues in children and adults

In addition to testing adults, the current study was also interested in the effect of perceptual cues on probability cueing effects in children. Studying children helps to answer general questions regarding the developmental course of VSL, such as: does VSL become more automatic, incidental, and implicit over age, or can children already acquire VSL at a young age? Pertaining to perceptual cues, studying children helps to understand whether the effects of perceptual cues on VSL may vary as a function of age due to children's different sensitivity to perceptual information. Jiang, Capistrano, Esler, and Swallow (2013) found that typically developing children (5–13 years old) were able to show significant probability cueing effects. When the probabilities were evenly redistributed *without* a change of perspective, children showed an attentional bias towards the previous rich quadrant for one block. Nevertheless, attentional guidance

quickly dissipated over the next three blocks, with participants showing no difference between previous rich and sparse quadrants. However, they did not include an adult group, did not manipulate perceptual cues, and did not change the perspective in the testing phase.

It is reasonable to think that children may be more susceptible to the influence of perceptual cues than adults. Previous research has found that children are more easily distracted by salient perceptual features and are less adequate at top-down attentional control than adults (e.g., Cavallina, Puccio, Capurso, Bremner, & Santangelo, 2018; Gaspelin, Margett-Jordan, & Ruthruff, 2015; Hommel, Li, & Li, 2004; Lookadoo, Yang, & Merrill, 2017; Yang & Merrill, 2014; Yang, & Merrill, 2015b). Yang and Merrill (2014) found that relative to adults, children are more influenced by perceptual cues such as distracter-target similarities in the contextual cueing paradigm¹ of VSL. Similarly, using modified artificial grammar learning paradigms of VSL, Witt and Vinter (2012) found that 5- to 8-year-old children's learning was predominantly based on salient perceptual features rather than abstract relation rules. Therefore, it is likely that children may be impacted by perceptual cues to a larger degree than adults are in probability cueing effects.

Our lab (Yang & Song, 2020) recently investigated the role of overall perceptual cues on probability cueing effects in children (6–13 years old) and adults. Each of the four quadrants in the display had a unique background color (i.e., red, blue, green, and yellow) and was, hence, associated with unique perceptual cues. All participants showed probability cueing effects and the attentional gradient phenomenon to a similar extent. Moreover, all age groups showed persistent attentional biases based on egocentric and allocentric perspectives in the testing phase. However, because all four quadrants were colored, each quadrant should have attracted a similar amount of attention initially. Perceptual cues distinguished four quadrants from each other but did not highlight one quadrant more than the others. In the current study, we only colored one quadrant. Therefore, the colored quadrant should attract stronger attention initially than the other quadrants that were not colored. Perceptual cues in the current study would distinguish the colored quadrant and make it perceptually salient, hence different from Yang and Song (2020). Therefore, this study addressed the role of salient perceptual cues, rather than overall perceptual cues, on probability cueing.

¹ Both contextual cueing and probability cueing have been considered forms of statistical learning (e.g., Goujon, Didierjean, & Thorpe, 2015; Goschy, Bakos, Müller, & Zehetleitner, 2014). However, contextual cueing and probability cueing rely on different neural mechanisms (e.g., Goldfarb, Chun & Phelps, 2016).

The current study

The overarching goal of the current study was to investigate the impact of salient perceptual cues on VSL via the probability cueing paradigm. In the learning phase of each experiment, one quadrant (i.e., rich) was associated with high probabilities. During the testing phase, the screen was rotated, and the targets were evenly distributed among the four quadrants. Hence, this experiment setup afforded the opportunity to examine the acquisition, persistence, frames of reference, and spatial distribution of the attentional bias towards high probability regions in probability cueing effects all in one setting. We then systematically manipulated perceptual cues to examine their role in these different features of probability cueing effects. Experiment 1 served as a baseline condition where there were no salient perceptual cues highlighting any of the quadrants. In Experiments 2 and 3, we placed salient perceptual cues (e.g., red background color) in the rich quadrants. Hence, perceptual cues overlapped with location cues in indicating high-probability target regions. In Experiment 4, we placed salient perceptual cues in the diagonal sparse quadrant. Hence, perceptual cues did not overlap with location cues in indicating high-probability target regions. Experiments 1–4 only included adult participants to examine the robustness of the general effects. In Experiment 5, children as well as adults participated.

Experiment 1 (baseline)

Method

Participants Twenty college students (18–26 years old) were recruited from Sun Yat-sen University, China. Each adult participant received \$1 for their participation. In this and the following experiments, all participants were tested individually in a quiet room. All the recruitment and testing procedures followed the ethical guidelines of Sun Yat-sen University.

Power analyses Experiments 1–4 were mainly interested in the probability cueing effects acquired in the learning phase and the persistence of the attentional bias in the testing phase. Using effect sizes (Cohen's $d_z = 1.66$ and 1.4) calculated from previous research (Jiang, Swallow, & Sun, 2014) and the software G*Power 3.1.9.4, our power analyses have shown that 20 participants per experiment afforded more than enough power ($>.80$) to detect evidence of both probability cueing effects (i.e., rich vs. sparse) in the learning phase and persistent attentional bias (i.e., egocentric-rich vs. sparse) in the testing phase at .05 alpha level (either one- or two-tailed).

Of lesser interest in Experiments 1–4 was the attentional gradient phenomenon (i.e., diagonal sparse vs. adjacent sparse) and explicit awareness. Our sample sizes were at the cusp of affording adequate power ($.76 \sim .80$) to detect significant attentional gradient phenomenon at .05 alpha level (one-tailed) based on effect sizes reported previously (Cohen's $d_z = .56 \sim .59$, calculated from Jiang et al., 2018). We reported analyses of the attentional gradient phenomenon to provide additional evidence for this effect, which was rarely studied other than in Jiang et al. (2018). Our sample sizes in Experiments 1–4 were fewer than the 64 participants (two-tailed) or 51 participants (one-tailed) calculated by Vadillo et al. (2020) to detect significant explicit awareness with an effect size of Cohen's $h=.35$, an alpha level of .05, and a power of .80. We reported analyses of explicit awareness to be consistent with research protocol in the field, which routinely probes explicit awareness.

Materials Each search display (900×600 pixels) contained 12 black and white characters (all 40×44 pixels): either a Mickey or Minnie Mouse (target), and 11 teddy bears (distracters). The grey search display was placed on a white background of the computer screen (see Fig. 1). There were 25 possible locations (five horizontal \times five vertical) within each quadrant of the search display for a total of 100 possible locations. There were three randomly selected locations in each quadrant of the display. The characters were random in their orientations (i.e., upright, upside-down, leftward, or rightward).

Procedures Participants performed ten practice trials, in which the targets' quadrants were randomly selected. Then participants completed the learning phase consisting of eight blocks of 24 trials each. Trials within each block were randomized. The targets appeared in the "rich" quadrant on 50% of the trials (96 trials), and in each sparse quadrant on 16.7% (32 trials) of the trials. The location of the rich quadrant was randomly determined for each participant. After the learning phase, participants were asked to rotate the screen either clockwise or counterclockwise, counterbalanced between participants (see Fig. 2). Participants then completed the testing phase consisting of four blocks of 24 trials each. The target was evenly distributed in each quadrant (25%) during the test phase. Participants completed a total of 298 trials, including the practice trials. A break was provided after every two blocks. There was a recognition test at the end of the experiment. Participants were first asked whether the target was more likely to appear in one quadrant than the other quadrants. Then they needed to indicate or guess which quadrant contained the target most often.

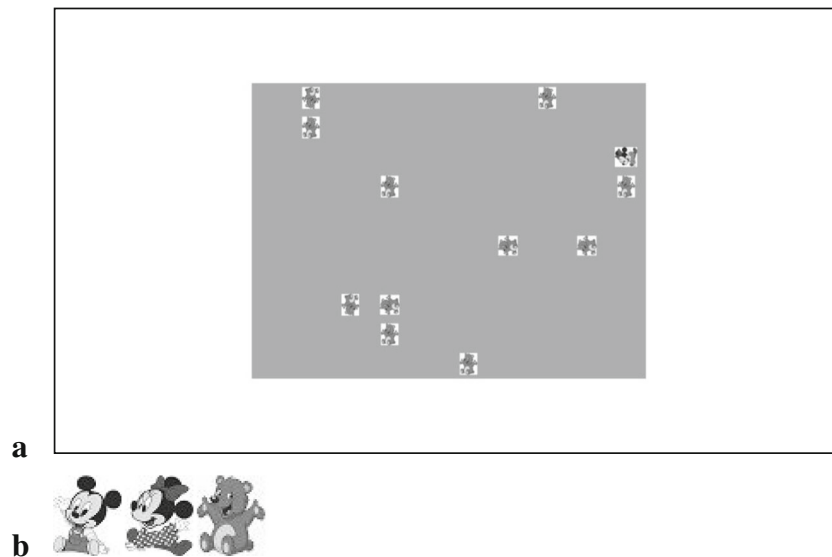


Fig. 1 Experimental Materials. **A** An example of the display. **B** The two possible targets (Mickey Mouse, Minnie Mouse) and the distracter (teddy bear)

The visual search task was presented on a rectangular Microsoft Surface 2 Tablet (10.6 in., 1,366 × 768 pixels), laid flat on a rectangular table. Participants responded via a keyboard on their lap. The placement of the screen during the learning phase (e.g., width side up or length side up) was counterbalanced between participants. The experiment was programmed in Psychtoolbox and implemented in MATLAB. Each trial started with a fixation cross for 750 ms followed by the search display, which appeared on the screen until the participant made a response. Participants pressed “F” for Minnie Mouse and “J” for Mickey Mouse. An error message (i.e., a crying face cartoon) was displayed for wrong responses. Both speed and accuracy were emphasized.

We combined every two blocks into one epoch for later data analysis. There were four epochs in the learning phase. Within each epoch, there were 24 rich trials (i.e., targets in the rich quadrant), eight diagonal sparse trials (i.e., targets in the sparse quadrant diagonal to the rich quadrant), and 16 adjacent sparse trials (i.e., targets in the sparse quadrants adjacent to the rich quadrant). There were two epochs in the testing phase. Within each epoch, there were 12 allocentric-rich trials, 12 egocentric-rich trials, and 24 sparse trials. More specifically, in the allocentric-rich trials, the target appeared in the allocentric-rich quadrant, which preserved the same spatial relation relative to the display as the rich quadrant in

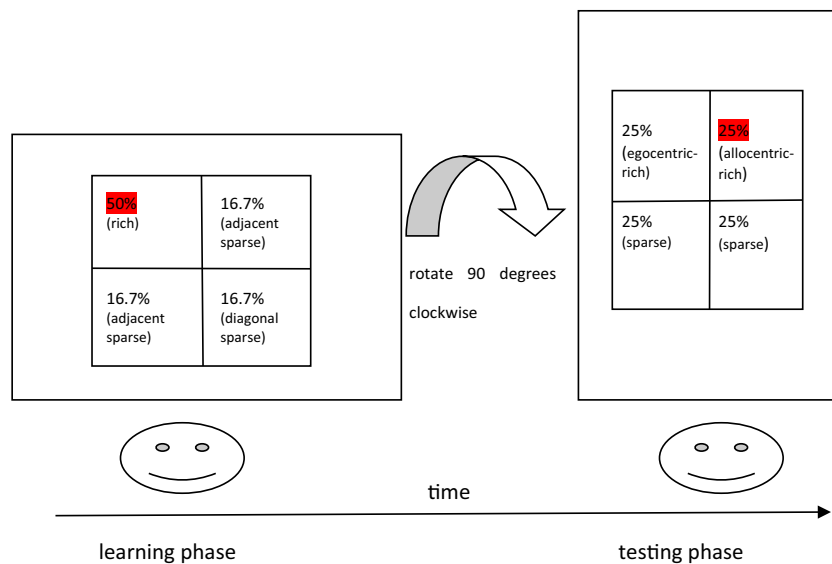


Fig. 2 Experimental design and procedures. The smiley face indicates where participants sit relative to the display. The outlines correspond to the screen and the inner lines correspond to the search display. We

highlighted the rich quadrant in red to show the consistency from the learning phase to the testing phase

the learning phase. For instance, if the rich quadrant was top left during the learning phase and the display was rotated 90° clockwise, then the allocentric-rich quadrant would be top right from the perspective of the participant (see Fig. 2). The egocentric-rich quadrant is the quadrant that preserves the same spatial relation relative to the viewer as the rich quadrant in the learning phase. In the same example, it would be top left.

Results

Whenever sphericity was not met, the Greenhouse-Geisser method was used. For post hoc comparisons, we reported uncorrected p -values and compared them with Bonferroni-corrected alphas. Only significant and theoretically important null results are discussed. We removed incorrect responses and responses outside three standard deviations of the mean. As a result, 1.6% of the total data were removed. We obtained average RTs for each condition in each epoch. For detailed analyses of error rates in this and the following experiments, please see the Appendix.

Learning phase The probabilities of all three sparse quadrants were equal (i.e., 16.7%). Hence, any difference between the diagonal sparse quadrant and the adjacent sparse quadrants would not be due to probability differences, but rather to differences in geometric distance from the rich quadrant. We conducted a 4 (Epoch) \times 3 (Condition: rich, diagonal sparse, adjacent sparse) within-subjects ANOVA on RTs. The main effect of epoch was significant, $F(3, 57) = 4.54$, $p = .006$, $\eta^2_p = .193$, with faster RTs over blocks. The main effect of condition was also significant, $F(1.52, 28.84) = 21.89$, $p < .001$, $\eta^2_p = .535$. Targets were found faster in the rich quadrant (M

= 958 ms) than both the diagonal sparse ($M = 1,060$ ms) and the adjacent sparse conditions ($M = 1,033$ ms), $ps < .001$. Comparing the diagonal sparse and the adjacent sparse conditions yielded $p = .059$, indicating a marginal significance. The interaction was not significant, $F(6, 114) = .90$, $p = .496$ (see Fig. 3).

Testing phase A 2 (Epoch) \times 3 (Condition: allocentric-rich, egocentric-rich, sparse) within-subjects ANOVA on RTs revealed no significant effects. The main effect of condition was not significant, $F(2, 38) = 2.0$, $p = .149$. The sparse condition ($M = 981$ ms) did not differ from either the allocentric-rich quadrant ($M = 966$ ms) or the egocentric-rich quadrant ($M = 1,004$ ms), $ps > .65$. The main effect of epoch was not significant, $F(1, 19) = 3.36$, $p = .082$. The interaction was not significant, $F(2, 38) = 1.31$, $p = .282$ (see Fig. 4).

Recognition Due to technical difficulties, one participant failed to answer both questions and another participant failed to answer the second question. For the remaining participants, 10 out of 19 (52.6%) agreed with the statement that the targets appeared in one quadrant more often than in the other quadrants. For the second question, six (33.3%), five (27.7%), and seven (38.8%) out of 18 participants indicated the allocentric-rich, the egocentric-rich, and the sparse quadrants as the quadrant where the targets appeared most often, respectively. Fisher's exact test of independence indicated no significant difference from chance level (i.e., 25%, 25%, and 50%), $p = .680$.

Experiment 2

Experiment 1 found significant probability cueing effects, consistent with previous research. However, there was no

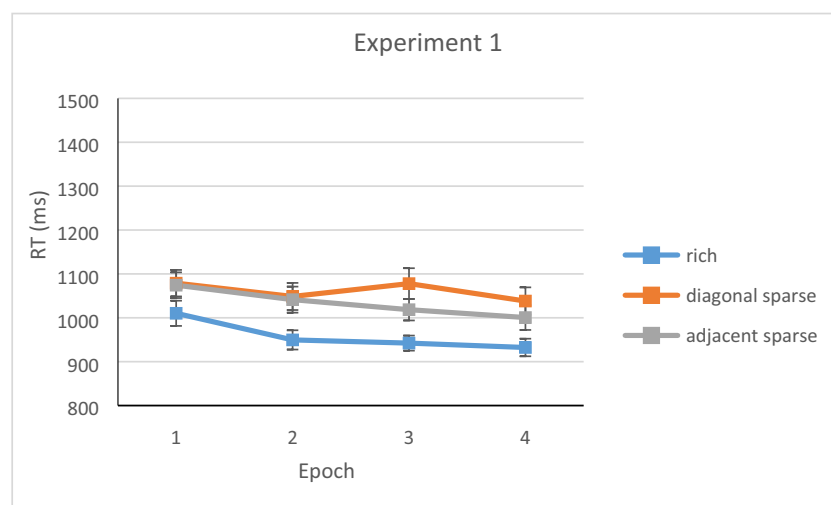


Fig. 3 Reaction times (RTs) (standard errors are shown as error bars) in the learning phase of Experiment 1

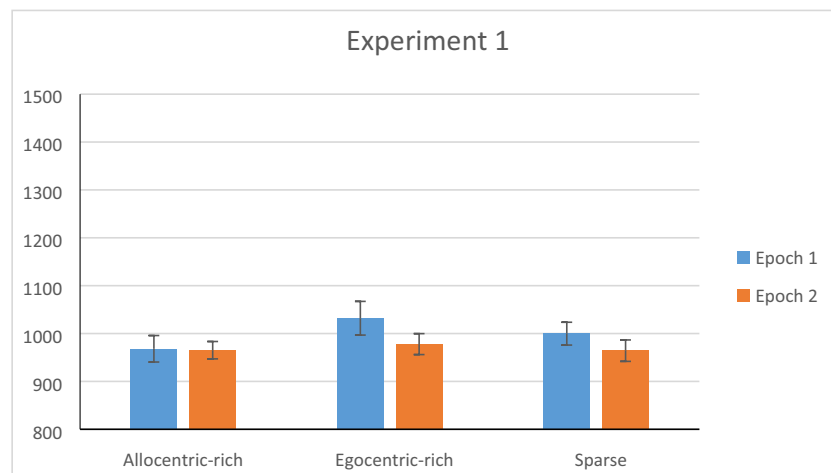


Fig. 4 Reaction times (RTs) (standard errors are shown as error bars) in the testing phase of Experiment 1

persistent attentional bias in the testing phase, contrary to previous studies (e.g., Jiang et al., 2013). This is discussed later. In Experiment 2, we colored the rich quadrant red, providing a salient feature to identify the rich quadrant. In addition to attracting attention, the rich quadrant was now associated with two types of statistical cues: a specific spatial relation relative to the observer (e.g., top left quadrant) and a salient feature (e.g., the red quadrant). Hence, Experiment 2 examined whether providing perceptual cues in addition to location cues would elicit probability cueing effects and whether it would elicit persistent attentional bias in the testing phase.

Method

Participants Twenty new college students participated.

Materials/procedures The materials and procedures were the same as those in Experiment 1 except for the following: The location of the rich quadrant was again randomly

determined for each participant. However, the rich quadrant was now colored red (see Fig. 5). In the testing phase, participants still rotated the screen 90° clockwise or counterclockwise. The red quadrant remained red and did not change its position relative to the screen. Hence, the red quadrant was the rich quadrant in the learning phase and was the allocentric-rich quadrant in the testing phase.

Results

We removed all the incorrect responses and responses outside three standard deviations of the mean. A total of 2.0% of data were removed.

Learning phase We conducted a 4 (Epoch) × 3 (Condition: rich/red, diagonal sparse, adjacent sparse) ANOVA. The main effect of epoch was significant, $F(2.05, 39.02) = 7.71, p < .001, \eta^2_p = .289$, with faster RTs over blocks. The main effect

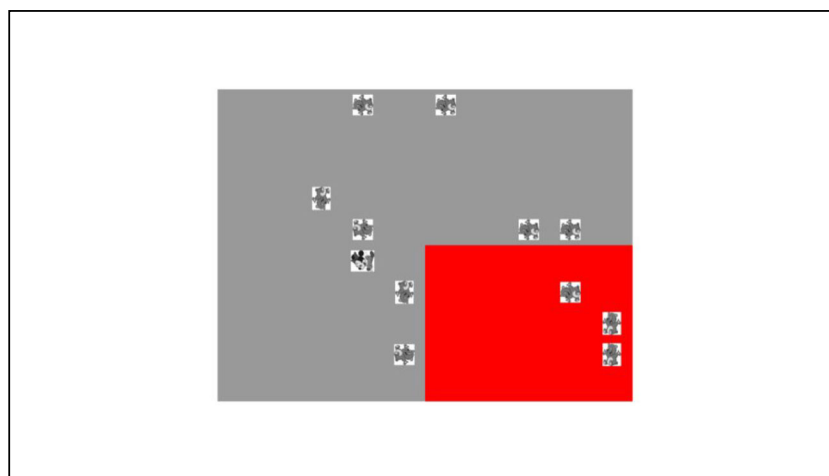


Fig. 5 Experimental materials in Experiment 2. The red quadrant was the rich quadrant. This was a sparse trial where the target was in the adjacent sparse quadrant

of condition was also significant, $F(1.23, 23.39) = 18.51, p < .001, \eta^2_p = .493$. Targets were found faster in the rich quadrant ($M = 1057$ ms) than both the diagonal sparse ($M = 1,290$ ms) and the adjacent sparse conditions ($M = 1,182$ ms), $ps < .001$. More importantly, the diagonal sparse was significantly slower than the adjacent sparse conditions, $p = .006$ (see Fig. 6). The interaction was not significant, $F(2.83, 53.75) = .43, p = .723$.

Testing phase A 2 (Epoch) \times 3 (Condition: allocentric-rich/red, egocentric-rich, sparse) ANOVA revealed no significant effects. The main effect of condition was not significant, $F(2, 38) = 1.07, p = .353$. The sparse condition ($M = 1,108$ ms) did not differ from either the allocentric-rich quadrant ($M = 1,093$ ms) or the egocentric-rich quadrant ($M = 1,076$ ms), $ps > .17$. The main effect of epoch was not significant, $F(1, 19) = 3.76, p = .067$. The interaction was not significant, $F(1.36, 25.79) = 1.45, p = .248$.

Recognition For the first question, 15 out of 20 (75%) agreed that the targets appeared in one quadrant more often than in the other quadrants. For the second question, 13 (65%), one (5%), and six (30%) out of 20 participants indicated the allocentric-rich, the egocentric-rich, and the sparse quadrants as the quadrant where the targets appeared most often, respectively. A Chi-square test of independence suggested a significant difference from the chance level, $\chi^2(2) = 17.6, p < .001$. Participants were more likely to choose the allocentric-rich quadrant.

Cross-experiment analysis We compared results from Experiments 1 and 2, focusing on the learning phase. After collapsing trials over epochs and combining the diagonal

sparse and the adjacent sparse conditions, we conducted a 2 (Experiments: 1 vs. 2) \times 2 (Condition: Rich vs. Sparse) mixed ANOVA. Of major interest, the interaction effect was significant, $F(1, 38) = 4.96, p = .032, \eta^2_p = .115$, with larger probability cueing effects in Experiment 2 (MD = 161) than in Experiment 1 (MD = 84). The main effect of condition was significant, $F(1, 38) = 50.11, p < .001, \eta^2_p = .569$. The main effect of experiment was not significant, $F(1, 38) = 3.27, p = .079$.

Experiment 3 (lines)

Experiment 2 found significant probability cueing effects that were greater in magnitude than those in Experiment 1. This suggested that salient perceptual cues may enhance attention guidance to the rich quadrant when they are consistent with location cues. However, no persistent attentional bias was found in the testing phase again. The goal of Experiment 3 was to examine whether we would again find a lack of persistent attentional bias using even more salient perceptual cues. In Experiment 3, we delineated the entire search region into four quadrants using a cross, in addition to coloring the rich quadrant red. As a result, the physical division of the four quadrants was more apparent.

Method

Participants Twenty new college students participated.

Materials/procedures Materials and procedures were identical to Experiment 2 except that we delineated the screen into four quadrants using black lines (see Fig. 7). The red quadrant was

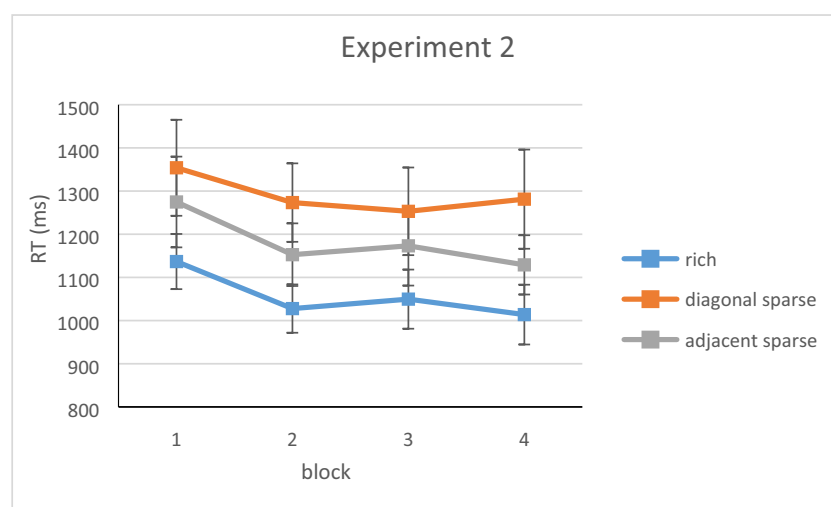


Fig. 6 Reaction times (RTs) in the learning phase of Experiment 2

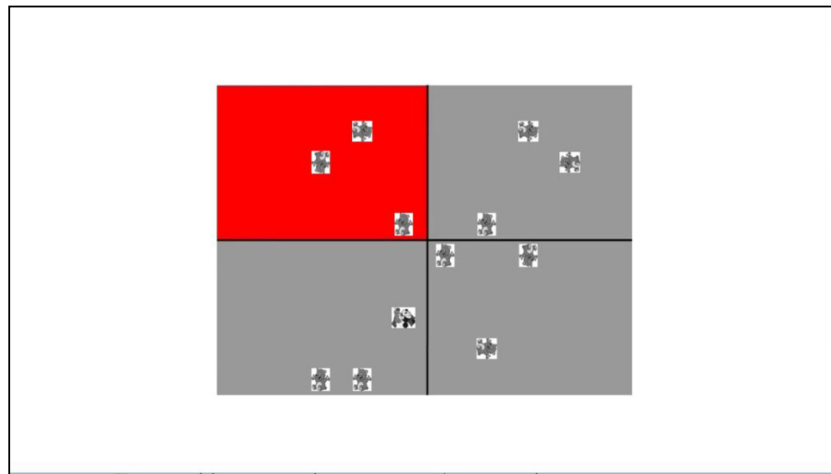


Fig. 7 Example of the search display in Experiment 3. The red quadrant was the rich quadrant

the rich quadrant in the learning phase and was the allocentric-rich quadrant in the testing phase.

Results

Of the data, 2.8% were removed due to incorrect responses and responses outside three standard deviations of the mean.

Learning phase We conducted a 4 (Epoch) × 3 (Condition: rich/red, diagonal sparse, adjacent sparse) ANOVA. The main effect of epoch was significant, $F(2.09, 39.71) = 8.61, p = .001, \eta^2_p = .312$, with faster RTs over time. The main effect of condition was also significant, $F(1.11, 20.99) = 21.03, p < .001, \eta^2_p = .525$. The rich condition ($M = 913$ ms) was faster than both the diagonal

sparse ($M = 1,099$ ms) and the adjacent sparse conditions ($M = 982$ ms), $ps < .001$. The diagonal sparse condition was also slower than the adjacent sparse condition, $p = .003$ (see Fig. 8). The interaction was not significant, $F(3.66, 69.53) = .92, p = .481$.

Testing phase We conducted a 2 (Epoch) × 3 (Condition: allocentric-rich/red, egocentric-rich, sparse) ANOVA. None of the effects were significant. The main effect of epoch was not significant, $F(1,19) = 1.48, p = .239$. The main effect of condition was not significant, $F(2,38) = 1.20, p = .313$. The interaction was not significant, $F(2,38) = 1.05, p = .361$. The sparse conditions ($M = 959$ ms) did not differ from either the environment-rich ($M = 957$ ms) or the egocentric-rich conditions ($M = 930$ ms), $ps > .15$.

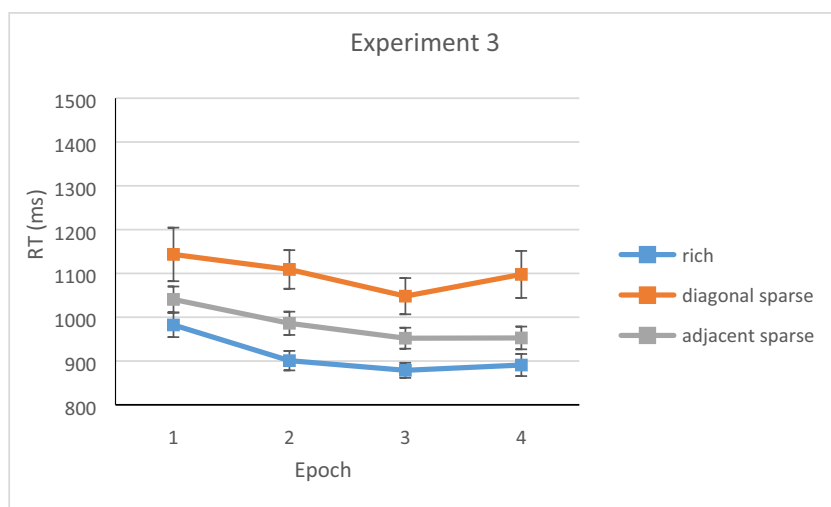


Fig. 8 Reaction times (RTs) in the learning phase of Experiment 3

Recognition For the first question, 50% of participants agreed that the targets appeared in one quadrant more often than in the other quadrants. For the second question, four (20%), five (25%), and 11 (55%) participants indicated the allocentric-rich, the egocentric-rich, and the sparse quadrant as having the most frequent target appearances, respectively. A Chi-square test of independence suggested that the results did not differ from chance level, $\chi^2(2) = .30$, $p = .861$.

Experiment 4 (sparse red)

Experiment 3 replicated results from Experiment 2 in finding significant probability cueing effects in the learning phase but no persistent attentional bias in the testing phase. In both Experiments 2 and 3, the rich quadrant was associated with both higher statistical probabilities and higher perceptual saliency. In Experiment 4, we colored the diagonal sparse quadrant red to examine whether highlighting the sparse quadrant would disrupt probability cueing effects. If perceptual cues only facilitated attentional bias when they were consistent with location cues and perceptual cues were prioritized over location cues, probability cueing effects should be reduced or eliminated in Experiment 4. However, if location cues play a stronger role than perceptual cues and/or if one can flexibly use perceptual cues to direct attention, we should still observe probability cueing effects in Experiment 4. Experiment 4 also afforded another opportunity to examine whether the attentional bias was persistent in the testing phase.

Method

Participants Twenty new college students took part.

Materials/procedures Everything was the same as in Experiment 2, except that the diagonal sparse quadrant, rather than the rich quadrant, was colored red. Hence, the red quadrant was the diagonal sparse quadrant in the learning phase and was a sparse quadrant (diagonal to the allocentric-rich quadrant) in the testing phase.

Results

Of the data, 4.5% were removed due to incorrect responses and responses outside three standard deviations of the mean.

Learning phase We conducted a 4 (Epoch) \times 3 (Condition: rich, diagonal sparse/red, adjacent sparse) ANOVA. The main effect of epoch was significant, $F(3,57) = 16.24$, $p < .001$, $\eta^2_p = .461$, with faster RTs over time. The main effect of condition was significant, $F(1.51, 28.77) = 21.69$, $p < .001$, $\eta^2_p = .533$. The rich condition ($M = 910$ ms) was faster than both the diagonal sparse ($M = 1,046$ ms) and adjacent sparse conditions ($M = 978$ ms), $p < .001$ and $p = .011$, respectively. More importantly, the diagonal sparse condition was again slower than the adjacent sparse condition, $p = .001$ (see Fig. 9). The interaction was not significant, $F(3.99, 75.72) = 1.46$, $p = .222$.

Testing phase We conducted a 2 (Epoch) \times 3 (Condition: allocentric-rich, egocentric-rich, sparse) ANOVA. One of the two sparse quadrants was red. The main effect of condition was significant, $F(2, 38) = 4.70$, $p = .015$, $\eta^2_p = .198$.

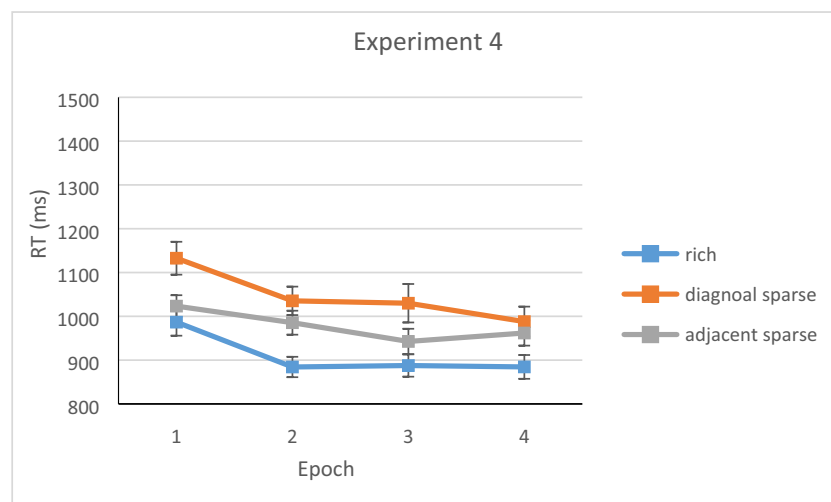


Fig. 9 Reaction times (RTs) in the learning phase of Experiment 4

However, post hoc tests suggested that the sparse condition ($M = 958$ ms) was not significantly different from either the allocentric-rich quadrant ($M = 933$ ms), $p = .43$, or the egocentric-rich quadrant ($M = 908$ ms), $p = .021$ (compared with $.05/3 = .017$), despite trending. The main effect of epoch was not significant, $F(1,19) = 1.25$, $p = .278$. The interaction was not significant, $F(2,38) = 2.42$, $p = .103$.

Recognition Due to technical difficulties, one participant failed to answer the first question and two other participants failed to answer the second question. For the first question, six (31.6%) out of 19 participants agreed that the targets appeared in one quadrant more often than in the other quadrants. For the second question, two (11%), seven (39%), and nine (50%) out of 18 participants indicated the allocentric-rich, the egocentric-rich, and the sparse quadrants as the quadrant associated with the most frequent target appearances, respectively. Fisher's exact test of independence was not significant, $p = .245$, indicating that the recognition did not differ from chance.

Cross-experiment analysis We compared results from Experiments 1 and 4, focusing on the learning phase. We conducted a 2 (Experiments: 1 vs. 4) \times 2 (Condition: rich vs. sparse) mixed ANOVA after collapsing the diagonal sparse and the adjacent sparse conditions. Of major interest, the interaction effect was not significant, $F(1, 38) = .057$, $p = .813$, with similar probability cueing effects in Experiment 4 ($MD = 90$) and in Experiment 1 ($MD = 84$). The main effect of experiment was not significant, $F(1,38) = 2.29$, $p = .138$. The main effect of condition was significant, $F(1,38) = 46.18$, $p < .001$, $\eta^2_p = .549$.

Experiment 5

Results from Experiment 4 were consistent with Experiments 2 and 3 in finding significant probability cueing effects in the

learning phase but no persistent attentional bias in the testing phase. Additionally, while probability cueing effects were greater in Experiment 2 than in Experiment 1, no difference was found comparing Experiments 4 and 1. Together, the results suggested that perceptual cues can facilitate attention guidance towards high-probability regions when consistent with location cues. Meanwhile, perceptual cues were not prioritized over location cues. In Experiment 5, we examined probability cueing effects in children and adults using the methods from Experiment 2.

Method

We recruited children from a local primary school in Hebei, China. Each child participant received a small gift (e.g., pencil). We tested ten additional college students in addition to using the data from Experiment 2. In the final sample of Experiment 5, there were 32 first and second graders (age: $M = 7.87$, $SD = 0.88$, range: 6–9 years old; 17 females); 31 third and fourth graders (age $M = 10.32$ years, $SD = 0.54$, range: 10–11 years old; 15 females); and 30 adults (age $M = 21$, $SD = 0.98$, range: 18–23 years old; 11 females).

Power analyses using G*Power 3.1.9.4 suggested that we had sufficient power ($>.80$) to detect significant probability cueing effects (i.e., rich vs. sparse conditions), persistent attentional bias in the testing phase (i.e., egocentric-rich vs. sparse conditions), and the attentional gradient phenomenon (i.e., diagonal sparse vs. adjacent sparse conditions) in each age group with .05 alpha level (either one- or two-tailed) and a power of .8 (also see *Participants* section of Experiment 1). Moreover, we had sufficient power ($>.80$) to detect significant within-between interactions between group and probability cueing effects, between group and persistent attentional bias in the testing phase, and between group and the attentional gradient phenomenon with a medium effect size (Cohen's $f = .25$), an alpha of .05 (two-tailed) and a power of .8.

All the child participants were tested individually in a quiet room of their school. All the adult participants were tested

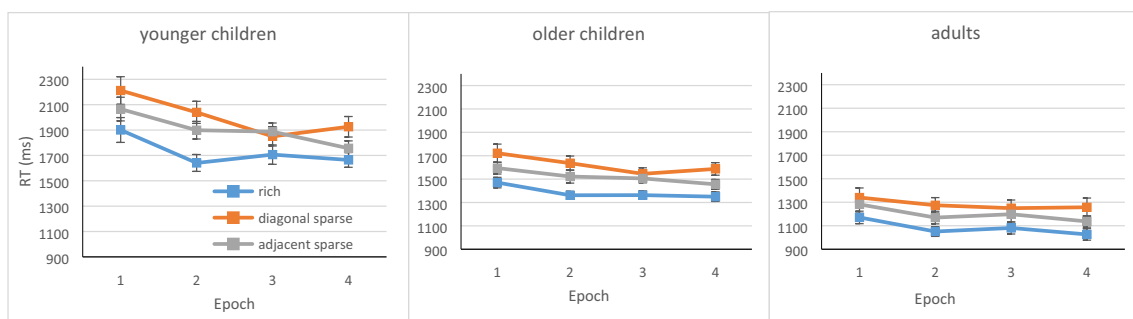


Fig. 10 Reaction times (RTs) in the learning phase of Experiment 5

individually in the research lab of the university. Identical instructions were given to children and adults. The experimenter made sure that the participant understood the task before starting the experiment. Most children had no problems. However, one first grader could not understand the task as he pressed the same key for all responses, and his data were not included.

Results

We removed 2.3%, 2.6%, and 2.0% of the data for younger children, older children, and adults, respectively, due to incorrect responses and RTs outside three standard deviations of the mean.

Learning phase We performed a 3 (Group: younger children, older children, adults) \times 4 (Epoch) \times 3 (Condition: rich/red, diagonal sparse, adjacent sparse) mixed ANOVA. The main effect of group was significant, $F(2,89) = 40.09, p < .001, \eta^2_p = .474$, with faster RTs for adults ($M = 1,186$ ms) than for older children ($M = 1,509$ ms), who were in turn faster than younger children ($M = 1,879$ ms), $ps < .01$. The main effect of epoch was significant, $F(2.09, 185.72) = 29.12, p < .001, \eta^2_p = .247$, with faster RTs over time. The main effect of condition was significant, $F(1.35, 120.30) = 67.65, p < .001, \eta^2_p = .432$, with faster RTs in the rich ($M = 1,398$ ms) than in both the diagonal sparse ($M = 1,636$ ms) and the adjacent sparse condition ($M = 1,539$ ms), $ps < .001$. Importantly, the diagonal sparse condition was slower than the adjacent sparse condition, $p < .001$ (see Fig. 10).

The interaction between group and epoch was significant, $F(4.17, 185.72) = 2.57, p = .037, \eta^2_p = .055$, with greater reductions in RT over epochs for younger children than for older children and adults. This is not surprising given young children's larger RT baselines, which offered more room for speed improvement. The interaction between epoch and condition was also significant, $F(4.97, 441.86) = 4.44, p = .001, \eta^2_p = .048$. The rich condition was significantly faster than both the diagonal sparse and the adjacent sparse conditions across all four epochs, $ps < .001$. The diagonal sparse condition was significantly slower than the adjacent sparse condition in the first, second, and fourth epochs, $ps < .001$, but not in the third epoch, $p = .507$. The lack of a significant difference in the third epoch seems to be an aberration and is not discussed further. No other effects (i.e., the two-way interaction between group and condition, and the three-way interaction) were significant. The two-way interaction between group and condition was not significant, $F(2.70, 120.30) = .71, p = .587$, and the three-way interaction was not significant, $F(9.93, 441.86) = 1.10, p = .360$.

Testing phase We conducted a 3 (Group) \times 2 (Epoch) \times 3 (Condition: allocentric-rich/red, egocentric-rich, sparse) ANOVA. The main effect of group was significant, $F(2, 89) = 42.40, p < .001, \eta^2_p = .488$, with faster RTs in adults ($M = 1,092$ ms) than older children ($M = 1,482$ ms), who were in turn faster than younger children ($M = 1,851$ ms), $ps < .01$. The main effect of epoch was significant, $F(1, 89) = 6.29, p = .014, \eta^2_p = .066$, with faster RTs over time. The main effect of condition was significant, $F(1.85, 164.26) = 14.94, p < .001, \eta^2_p = .144$. The sparse condition ($M = 1,479$ ms) was significantly slower than the egocentric-rich condition ($M = 1,412$ ms), $p < .001$, but not different from the allocentric-rich condition ($M = 1,535$ ms), $p = .026$ (compared with $.05/3 = .017$).

Nevertheless, the main effects were qualified by a significant interaction between age and condition, $F(3.69, 164.26) = 3.79, p = .007, \eta^2_p = .079$. For adults, none of the three conditions differed from each other. However, the egocentric-rich condition was faster than the sparse condition for younger children, $p = .017$, and for older children, $p = .016$, and faster than the allocentric-rich condition for both children groups, $ps < .001$. Hence, both children groups showed a persistent egocentric attentional bias. The allocentric-rich condition was slower than the sparse condition for older children, $p = .004$, but not for younger children, $p = .14$ (see Table 1 and Fig. 11). No other effects were significant. The interaction between epoch and group was not significant, $F(2,89) = .10, p = .906$. The interaction between epoch and condition was not significant, $F(1.62, 144.34) = 1.80, p = .176$. The three-way interaction was not significant, $F(3.24, 144.34) = .751, p = .533$.

Recognition For the first question, 74.2% of younger children, 64.5% of older children, and 73.3% adults agreed that the targets appeared in one quadrant more often than in the other quadrants. A Chi-square test of independence suggested no difference between groups, $\chi^2(2) = .85$. See Table 2 for the second question regarding where the target appeared most often. For each age group, we conducted Chi-square goodness of fit tests to examine whether performance differed from chance. The test was not significant for either younger children, $\chi^2(2) = .29$, or older children, $\chi^2(2) = 4.16, p = .12$. However, it was significant for adults, $\chi^2(2) = 24.07, p < .001$.

Table 1 Reaction times (RTs; standard error in parentheses) in the testing phase of Experiment 5

	Allocentric-rich	Egocentric-rich	Sparse
Younger children	1,959 (90)	1,739 (65)	1,858 (72)
Older children	1,554 (59)	1,415 (56)	1,478 (59)
Adults	1,092 (51)	1,083 (43)	1,103 (48)

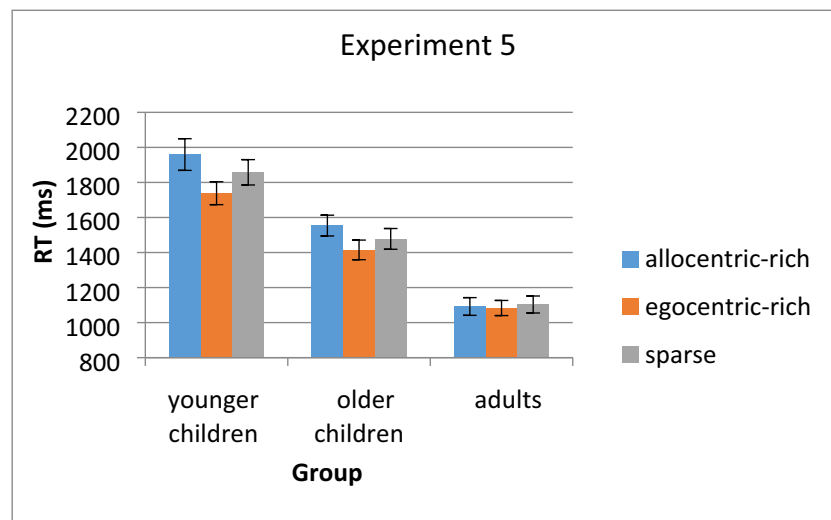


Fig. 11 Reaction times (RTs) (standard errors are shown as as error bars) in the testing phase of Experiment 5

.001. Furthermore, a Chi-square test of independence suggested that the three groups differed in their selections of the rich quadrant, $\chi^2(4) = 11.25, p = .024$. Adults were more likely to choose the allocentric-rich quadrant than the other two types of quadrants and this tendency was stronger for adults than for younger and older children.

Discussion

We found that 6- to 11-year-old children demonstrated significant probability cueing effects and attentional gradient phenomenon similar to adults. The testing phase revealed a developmental difference. Whereas adults did not show persistent attentional biases towards any quadrant, both younger children and older children showed a persistent egocentric attentional bias. Furthermore, older children also unexpectedly showed significantly slower RTs in the allocentric-rich than the sparse quadrants.

General discussion

In a series of experiments, we examined the role of salient perceptual cues on probability cueing effects and the development of probability cueing effects. We found that salient perceptual cues placed on the rich quadrant enhanced the acquisition of attentional bias (i.e., probability cueing effects), but did not eliminate them when placed on the diagonal sparse quadrant. In contrast to previous research, our results found that attentional bias towards the rich quadrant was not as persistent when the targets were redistributed evenly. Furthermore, children and adults showed differences in the persistence of attentional biases in the testing phase, but not in the acquisition and the spatial distribution (i.e., the attentional gradient

phenomenon) of the attentional bias. Together, our study suggested that perceptual cues affect the attentional processes in VSL for different developmental groups.

The impact of salient perceptual cues

Our study found that salient perceptual cues indeed can impact the acquisition of the probability cueing effects. In Experiment 2, participants benefited from the salient perceptual cues and the cross-experiment analyses showed larger probability cueing effects in Experiment 2 than in Experiment 1. In Experiment 4, where salient perceptual cues were in direct conflict with location cues, participants still demonstrated significant probability cueing, although it did not differ from that in Experiment 1. Jiang, Swallow, and Rosenbaum (2013) found that probability cueing was largely eliminated in the presence of endogenous cueing, such as a central arrow predicting the target’s location. In our study, the salient cues (e.g., perceptual) did not block the learning of the less salient cues (e.g., location) (Kamin, 1969). Our studies are consistent with other VSL paradigms that background contexts are encoded in visual search, and participants can use background contexts to establish the associations between

Table 2 Number of participants choosing a quadrant in the recognition test of Experiment 5

	Allocentric-rich	Egocentric-rich	Sparse	Total
Adults	19	2	9	30
Older children	12	4	15	31
Younger children	7	7	17	31

target locations and the contexts (Brockmole & Henderson, 2006a, b; Rosenbaum & Jiang, 2013).

In both Experiment 2 and Experiment 4, salient perceptual cues may attract bottom-up attention towards the salient quadrant, at least at the beginning (Cutsuridis, 2009; Itti & Koch, 2000, 2001). However, over time, participants may develop top-down attention control towards the rich quadrant, driven by VSL (Henderson, Brockmole, Castelhana, & Mack, 2007; Melloni, van Leeuwen, Alink, & Müller, 2012; Wykowska & Schubö, 2010). Therefore, salient perceptual cues may play a rather auxiliary role in probability cueing effects relative to location cues. In Experiment 2, salient perceptual cues may serve as a beacon where attention was guided directly to the salient quadrant, which in turn enhanced probability cueing effects. In Experiment 4, perceptual cues may serve as a landmark, rather than a direct beacon (O’keefe & Nadel, 1978). Therefore, one might learn to guide attention to the quadrant diagonal to the salient red quadrant. In both conditions, perceptual cues were relevant and functional to attention guidance in VSL.

Together, the results showed that salient perceptual cues can enhance attention guidance towards high probability regions when they coincide with predictive location cues. At the same time, location cues take precedence over perceptual cues. In a broader context of human attention and learning, our study shows that the human cognitive system is flexible in selecting the most informative statistical cues and is adept at integrating cues from different sources to facilitate behavior.

How persistent is attentional bias developed in probability cueing

Contrary to previous studies (e.g., Jiang, Swallow, Rosenbaum, et al., 2013), we did not find a persistent attentional bias for adults in the five experiments. RTs to targets in the egocentric-rich quadrants did not differ from RTs to targets in the sparse quadrants during the testing phase. One may rightfully question whether our studies were underpowered. In Jiang, Swallow, and Sun (2014), there was significant persistent attentional bias in the testing phase after screen rotation, and the effect size comparing the egocentric-rich and sparse conditions was large, Cohen’s $d_z = 1.4$. Based on G*Power 3.1.9.4, to obtain such a large effect size at .05 level (two-tailed), a .8 power requires a mere total of seven participants for a paired-sample t-test. Our sample sizes of 20 participants clearly had enough power. Moreover, our sample sizes (i.e., 20) in Experiments 1–4 were actually higher than those (i.e., 12 or 16) typically employed in Jiang and colleagues (e.g., Jiang, Swallow, & Rosenbaum, 2013; Jiang, Swallow, Capistrano, 2013; Jiang, Swallow, &

Sun, 2014). Further, this lack of attentional persistence was found in not one but all five experimental conditions for adults. Hence, the systematic results may not be explained by a simple lack of power.

Some material and procedural differences are apparent between our study and earlier studies. First, due to material differences, RTs were faster (about 1,000 ms) in our study compared with Jiang et al. (1,500 ms above). However, despite the possibility of ceiling performance, we still observed robust and significant probability cueing effects. Hence, it seems unlikely that there was no room to improve speed. Second, we presented 196 learning trials and 92 testing trials, whereas Jiang’s studies usually used twice the number of the trials, which may have led to stronger associations being formed. However, probability learning occurred as early as the first learning block and the preference towards the rich quadrant usually remained for hundreds of trials after an even redistribution of target locations (e.g., Jiang & Swallow, 2013; Jiang, Swallow, Rosenbaum, & Herzig, 2013). Third, we used cartoon characters, whereas Jiang and colleagues have used Ts and Ls. It is noteworthy that using cartoon fish, Jiang and colleagues (Jiang, Capistrano, Esler, & Swallow, 2013) also found a quick dissipation of the cueing effects among typically developing children (5–13 years old) and children with autism spectrum disorder. However, other VSL paradigms such as contextual cueing effects are not impacted by these stimuli differences (e.g., Chun & Jiang, 1999, 2003; Yang & Merrill, 2014, 2018). If the materials/procedural differences contributed to the observed difference between our study and earlier studies, it is not clear how or by what mechanisms they impacted performance.

Nevertheless, one important conclusion is that in situations afforded by our materials and procedures, attentional bias towards the previous rich quadrant disappeared quickly when there were no longer discrepancies in the probabilities of target distributions. We suspect that adults may be able to adjust to the new probabilities of targets’ locations quickly. From an evolutionary perspective, this seems to make more sense. For instance, finding water in one area of the desert should be rewarding. However, if water is no longer found in the same area or water can now be found everywhere, then one should adapt to the new situation, discontinue the preference for the previous area, and adopt other strategies that may be more cost-effective. Very recently, Giménez-Fernández and colleagues (2020) also found that the attentional bias was not as persistent and strong as previously suggested (Jiang, Swallow, Rosenbaum, & Herzig, 2013) once the target locations were evenly distributed in the testing phase. In Giménez-Fernández et al. (2020), there was no change of perspective from the learning to the testing

phase. Does changing perspectives, as in our study, accelerate the attenuation of attentional persistence? Future studies should continue to examine what situations can lead to the dissipation of incidentally acquired attentional bias in probability cueing effects.

Probability cueing in children and adults

We did not find evidence for developmental differences in the acquisition of probability cueing effects because there was no significant interaction between group and probability cueing effects in the learning phase of Experiment 5, which further attests to the robustness of probability cueing effects (Jiang, Capistrano, et al., 2013; Yang & Song, 2020). Similarly, we found no evidence for developmental differences in attentional gradient effects (Yang & Song, 2020). Attention may be drawn to the rich quadrant, attracting more initial eye fixations, and causing more frequent saccades in the rich quadrant (Jiang, Won, et al., 2014). The diagonal sparse quadrant is further away from the focus of attention and hence associated with fewer eye movements and slower responses. The attentional gradient phenomenon found in adults across Experiments 1–5 corroborated the existence of the attentional gradient phenomenon (Jiang, Li, & Sisk, 2018) and its robustness. One important feature of the attentional gradient phenomenon is that it provides some insights into how attention is allocated spatially around the focus point of attention. Overall, the results suggested that after being exposed to visual stimuli of statistical probabilities, children share a similar attention mechanism to adults in acquiring the statistical regularities about high probability regions and in spatially distributing attention around such high probability regions.

We did observe developmental differences in the persistence of the attentional bias effect and the frame of reference used in different age groups. Although adults did not show any persistent attentional bias, the two children groups showed persistent and strong egocentric attentional bias. Relative to adults, children might be less adept at adjusting their responses based on varying probabilities. Just focusing on children, the results were also consistent with the stance that probability cueing effects are encoded via egocentric, rather than allocentric, reference frames (Jiang et al., 2014). Our study is in contrast to Yang and Song (2020), where adults and two children groups showed persistent egocentric and allocentric attentional bias. Our study hence suggests that salient perceptual cues per se may not be enough to elicit persistent attentional bias for adults and to elicit allocentric attentional bias in general.

One somewhat surprising result is that older children showed a suppression, rather than facilitation, towards the allocentric-rich quadrant in Experiment 5. Although uncommon, response cost has also been found in other VSL paradigms (e.g., Yang & Merrill, 2015a). While prioritizing the egocentric-rich quadrant, the older children might have suppressed attention towards the other quadrants. Due to its saliency (i.e., being red), the allocentric-rich quadrant may have been easier to suppress compared with the other sparse but non-salient quadrants. Additionally, the probability of the salient quadrant (i.e., allocentric-rich/red) also reduced from 50% in the testing phase to 25% in the learning phase. As a result, older children may have “over-corrected” and therefore responded slower when the targets were in the allocentric-rich quadrant relative to the sparse quadrant ($MD = 76ms$). Although not significant ($p = .14$), the numerical difference ($MD = 101ms$) between the allocentric-rich and sparse conditions was even larger and in the same direction for the younger children. It is possible that younger children were less effective in suppressing the salient quadrant. This would be consistent with the developmental literature indicating that attention control functions develop with age (Howard, Johnson, & Pascual-Leone, 2014). Adults did not show this suppression, possibly because they have adapted to the new probabilities without being biased by perceptual features. Because we didn’t have a direct measure of attention allocation, we don’t have a definitive answer for why the suppression towards the allocentric-rich quadrant occurred. Future studies should further explore this issue and possibly employ eye-tracking techniques to illuminate the possible mechanisms of this effect.

Conclusions

Faced with countless environmental regularities in the visual world, humans are good at finding, extracting, and using these regularities. By focusing on perceptual cues and development, the current study revealed several characteristics of VSL. First, VSL is flexible and can use salient perceptual cues as either beacons or landmarks to direct attention to locations with high probabilities. Second, VSL is adaptable and adults can re-adjust their responses once probabilistic cues are no longer valid. Third, VSL may develop early in childhood yet be sensitive to the influence of perceptual features. Children may be impacted by perceptual cues to a larger degree than adults during VSL. We encourage future research to continue to explore how other perceptual, cognitive, and individual factors may contribute to VSL.

Appendix (error-rate analysis)

For each condition, we obtained the error rates by dividing the number of incorrect responses by the number of total responses.

Experiment 1

Learning phase. We conducted a 4 (Epoch) \times 3 (Condition: rich, adjacent sparse, diagonal sparse) repeated ANOVA on error rates. The only significant effect was the main effect of epoch, $F(3,57) = 3.38$, $p = .024$, $\eta^2_p = .151$, with smaller errors over time. See Table 3 for the descriptive of error rates.

Table 3 Error rates (SDs in parentheses) in the learning phase of Experiment 1

	Epoch 1	Epoch 2	Epoch 3	Epoch 4
Rich	0.013 (0.02)	0.015 (0.024)	0.017 (0.021)	0.006 (0.02)
Adjacent Sparse	0.022 (0.037)	0.025 (0.043)	0.019 (0.036)	0.006 (0.019)
Diagonal Sparse	0.044 (0.061)	0.013 (0.038)	0.013 (0.038)	0.013 (0.038)

Testing phase. We conducted a 2 (Epoch) \times 3 (Condition: allocentric-rich, egocentric-rich, sparse) ANOVA on error rates. None of the effects was significant. See Table 4 for the descriptive of error rates.

Table 4 Error rates (SDs in parentheses) in the testing phase of Experiment 1

	Epoch 1	Epoch 2
Allocentric-Rich	0.021 (0.037)	0.021 (0.037)
Egocentric-Rich	0.017 (0.034)	0.021 (0.046)
Sparse	0.013 (0.02)	0.01 (0.023)

Experiment 2

Learning phase: We conducted a 4 (Epoch) \times 3 (Condition: rich, adjacent sparse, diagonal sparse) repeated ANOVA on error rates and found none of the effects to be significant. See Table 5 for the descriptive of error rates.

Table 5 Error rates (SDs in parentheses) in the learning phase of Experiment 2

	Epoch 1	Epoch 2	Epoch 3	Epoch 4
Rich	0.025 (0.034)	0.025 (0.031)	0.015 (0.024)	0.017 (0.021)
Adjacent Sparse	0.022 (0.042)	0.016 (0.034)	0.022 (0.031)	0.006 (0.019)
Diagonal Sparse	0.031 (0.08)	0.013 (0.038)	0.025 (0.051)	0.031 (0.069)

Testing phase. We conducted a 2 (Epoch) × 3 (Condition: allocentric-rich, egocentric-rich, sparse) ANOVA on error rates. None of the effects was significant. See Table 6 for the descriptive of error rates.

Table 6 Error rates (SDs in parentheses) in the testing phase of Experiment 2

	Epoch 1	Epoch 2
Allocentric-Rich	0.017 (0.044)	0.029 (0.041)
Egocentric-Rich	0.008 (0.037)	0.021 (0.037)
Sparse	0.023 (0.034)	0.013 (0.024)

Experiment 3

Learning phase We conducted a 4 (Epoch) × 3 (Condition: rich, adjacent sparse, diagonal sparse) repeated ANOVA on error rates. The only significant effect was the main effect of condition, $F(2,38) = 3.39, p = .044, \eta^2_p = .152$. However, post hoc tests suggested none of the comparisons reach significance, $ps > .10$. See Table 7 for the descriptive of error rates.

Table 7 Error rates (SDs in parentheses) in the learning phase of Experiment 3

	Epoch 1	Epoch 2	Epoch 3	Epoch 4
Rich	0.023 (0.032)	0.021 (0.032)	0.033 (0.055)	0.029 (0.038)
Adjacent Sparse	0.025 (0.047)	0.025 (0.037)	0.041 (0.058)	0.028 (0.043)
Diagonal Sparse	0 (0)	0.031 (0.069)	0.006 (0.028)	0.019 (0.046)

Testing phase. We conducted a 2 (Epoch) × 3 (Condition: allocentric-rich, egocentric-rich, sparse) ANOVA on error rates. None of the effects was significant. See Table 8 for the descriptive of error rates.

Table 8 Error rates (SDs in parentheses) in testing phase of Experiment 3

	Epoch 1	Epoch 2
Allocentric-Rich	0.021 (0.046)	0.008 (0.037)
Egocentric-Rich	0.033 (0.068)	0.013 (0.031)
Sparse	0.025 (0.058)	0.044 (0.044)

Experiment 4

Learning phase. We conducted a 4 (Epoch) × 3 (Condition: rich, adjacent sparse, diagonal sparse) repeated ANOVA on error rates. None of the effects were significant. See Table 9 for the descriptive of error rates.

Table 9 Error rates (SDs in parentheses) in the learning phase of Experiment 4

	Epoch 1	Epoch 2	Epoch 3	Epoch 4
Rich	0.023 (0.037)	0.021 (0.032)	0.017 (0.025)	0.015 (0.024)
Adjacent Sparse	0.022 (0.031)	0.009 (0.023)	0.022 (0.037)	0.006 (0.019)
Diagonal Sparse	0.019 (0.046)	0.006 (0.028)	0.013 (0.038)	0 (0)

Testing phase. We conducted a 2 (Epoch) \times 3 (Condition: allocentric-rich, egocentric-rich, sparse) ANOVA on error rates. The main effect of epoch was significant, $F(1,19) = 6.74$, $p = .018$, $\eta^2_p = .262$. The error rate was higher in Epoch 2 ($M = .026$) than in Epoch 1 ($M = .010$). The interaction between epoch and condition was also significant, $F(1.53, 29.11) = 3.86$, $p = .043$, $\eta^2_p = .169$. Post hoc tests suggested higher error rates in the sparse than in the allocentric-rich and egocentric-rich conditions in the first epoch, $ps = .042$. However, in Epoch 2, the difference was no longer significant although there was a trend for smaller error rates in the sparse than in the egocentric-rich condition, $p = .069$, but not in the allocentric-rich condition, $p = .18$. The main effect of condition was not significant. See Table 10 for the descriptive of error rates.

Table 10 Error rates (SDs in parentheses) in the testing phase of Experiment 4

	Epoch 1	Epoch 2
Allocentric-Rich	0.004 (0.019)	0.033 (0.068)
Egocentric-Rich	0.004 (0.019)	0.033 (0.05)
Sparse	0.021 (0.025)	0.01 (0.019)

Experiment 5

Learning phase. We conducted a 3 (Group: younger children, older children, adults) \times 4 (Epoch) \times 3 (Condition: rich, adjacent sparse, diagonal sparse) mixed ANOVA on error rates. None of the effects were significant. See Table 11 for the descriptive of error rates.

Table 11 Error rates (SDs in parentheses) in the learning phase of Experiment 5

		Epoch 1	Epoch 2	Epoch 3	Epoch 4
Younger children	Rich	0.034 (0.055)	0.034 (0.048)	0.023 (0.033)	0.021 (0.03)
	Adjacent sparse	0.021 (0.049)	0.035 (0.061)	0.023 (0.041)	0.014 (0.05)
	Diagonal sparse	0.035 (0.073)	0.047 (0.099)	0.031 (0.064)	0.023 (0.074)
Older children	Rich	0.032 (0.038)	0.03 (0.038)	0.035 (0.032)	0.02 (0.028)
	Adjacent sparse	0.038 (0.048)	0.032 (0.051)	0.026 (0.045)	0.028 (0.035)
	Diagonal sparse	0.048 (0.077)	0.032 (0.064)	0.02 (0.057)	0.032 (0.056)
Adults	Rich	0.025 (0.032)	0.029 (0.04)	0.018 (0.024)	0.019 (0.024)
	Adjacent sparse	0.025 (0.042)	0.017 (0.033)	0.025 (0.035)	0.01 (0.024)
	Diagonal sparse	0.021 (0.066)	0.008 (0.032)	0.021 (0.047)	0.033 (0.086)

Testing phase. We conducted a 3 (Group: younger children, older children, adults) \times 2 Epoch \times 3 (Condition: allocentric-rich, egocentric-rich, sparse) mixed ANOVA on error rates. None of the effects were significant. See Table 12 for descriptive of error rates.

Table 12 Error rates (SDs in parentheses) in the testing phase of Experiment 5

	Allocentric-rich (Epoch 1)	Allocentric-rich (Epoch 2)	Egocentric-rich (Epoch 1)	Egocentric-rich (Epoch 2)	Sparse (Epoch 1)	Sparse (Epoch 2)
Younger Children	0.026 (0.054)	0.031 (0.051)	0.013 (0.031)	0.021 (0.052)	0.031 (0.05)	0.029 (0.057)
Older Children	0.013 (0.038)	0.016 (0.045)	0.024 (0.049)	0.011 (0.028)	0.022 (0.024)	0.013 (0.027)
Adults	0.017 (0.04)	0.025 (0.039)	0.019 (0.068)	0.019 (0.036)	0.022 (0.03)	0.014 (0.023)

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