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Guidance of Spatial Attention by Incidental Learning and Endogenous Cuing

Yuhong V. Jiang, Khena M. Swallow, and Gail M. Rosenbaum
University of Minnesota

Our visual system is highly sensitive to regularities in the environment. Locations that were important in one's previous experience are often prioritized during search, even though observers may not be aware of the learning. In this study we characterized the guidance of spatial attention by incidental learning of a target's spatial probability, and examined the interaction between endogenous cuing and probability cuing. Participants searched for a target (T) among distractors (Ls). The target was more often located in one region of the screen than in others. We found that search reaction time (RT) was faster when the target appeared in the high-frequency region rather than the low-frequency regions. This difference increased when there were more items on the display, suggesting that probability cuing guides spatial attention. Additional data indicated that on their own, probability cuing and endogenous cuing (e.g., a central arrow that predicted a target's location) were similarly effective at guiding attention. However, when both cues were presented at once, probability cuing was largely eliminated. Thus, although both incidental learning and endogenous cuing can effectively guide attention, endogenous cuing takes precedence over incidental learning.

Keywords: spatial attention, incidental learning, endogenous attention, visual search

Our visual environment is complex yet stable. Places that were important in the past usually remain important in the future, presenting many opportunities for learning where to attend. Previous studies have shown that visual statistical learning influences how people allocate spatial attention (Chun & Jiang, 1998; Jiménez, 2003; Geng & Behrmann, 2002) without any intention to learn (i.e., incidental learning). Although incidental learning of visual statistics helps people report a search target more quickly, previous studies have not conclusively demonstrated whether it does so by guiding attention to a target's likely location or by speeding decisional processes after the target has been found. In this study we ask: Does incidental learning of a target's likely location guide the allocation of spatial attention? If so, how does it interact with endogenous cuing?

When a cue facilitates the speed at which attention is allocated to targets, it is said to guide spatial attention (Wolfe, 1994). A hallmark of attentional guidance is the reduction of visual-search slope, which relates reaction time (RT) to the number of items (set size) on the display. Search slope is an indicator of how quickly spatial attention moves from one item to the next (Wolfe, 1998). Salient visual features or advanced knowledge of the target are effective cues for attentional guidance. When these cues are present, search RT is faster and search slope is shallower (Wolfe, 1994, 2007). Whether incidental learning of visual statistics also guides spatial attention, however, is unresolved (see Kunar, Flusberg, Horowitz, & Wolfe, 2007; Kunar, Flusberg, & Wolfe, 2008 for conflicting results in a contextual cuing paradigm).

Understanding the role of incidental learning in attentional guidance is important for understanding the cognitive architecture of attention. Existing theories of attention suggest that attention is dichotomous, with spatial attention being driven by salient stimuli (bottom-up) or by an observer's goal (top-down). Where incidental learning fits in this dichotomy is difficult to determine. In the most recent version of the guided search model (Wolfe, 2007), contextual cuing, or attentional biases that result from previous experience with a search display, was considered a possible source of top-down attention. The biased competition model of attention, on the other hand, suggested that learning acts in a bottom-up fashion to bias top-down control (Desimone & Duncan, 1995). At present, the field lacks a consensus as to whether experience-driven attention, particularly when learning occurs incidentally, should be categorized as a special case of top-down attention, a special case of bottom-up attention, or a third source of attentional guidance.

To better situate incidental learning in the cognitive architecture of attention, we conducted five experiments that tested the relationship between top-down attention and incidental learning of one type of visual statistic—the spatial distribution of the search target. Participants performed an inefficient visual-search task. On each trial they searched for a T (target) among several Ls (distractors).

Yuhong V. Jiang, Khena M. Swallow, and Gail M. Rosenbaum, Department of Psychology, University of Minnesota.

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Correspondence concerning this article should be addressed to Yuhong V. Jiang or Khena M. Swallow, 75 East River Road, S251 Elliott Hall, Department of Psychology, University of Minnesota, Minneapolis, MN 55455. E-mail: jiang166@umn.edu or swall011@umn.edu

Both incidental learning of a target's probable location (probability cuing) and top-down attention were manipulated. For probability cuing, the target was more likely to appear in one region (rich) of the screen than in other regions (sparse). Previous research on probability cuing has shown that, although unaware of the manipulation, participants are able to use the uneven spatial distribution of targets to speed their search (Druker & Anderson, 2010; Geng & Behrmann, 2002, 2005; Jiang, Swallow, Rosenbaum, & Herzig, in press; Miller, 1988; Walthew & Gilchrist, 2006; Umemoto, Scolari, Vogel, & Awh, 2010). In contrast to probability cuing, an explicit cue manipulated top-down attention on a trial-by-trial basis. A central arrow directed spatial attention to one of the four visual quadrants. Participants were informed that the arrow was predictive of the upcoming target's location. Previous studies have shown that within about 300 ms of seeing the arrow, people effectively orient attention to the cued location (Müller & Rabbit, 1989; Posner, 1980).

In many ways probability cuing is similar to endogenous cuing (Posner, 1980). Like endogenous cuing, location probability learning informs participants of important spatial locations. Unlike endogenous cuing, learning often occurs without intentional prioritization of the high-frequency locations (Geng & Behrmann, 2002). If attentional guidance is facilitated by an intention to deploy spatial attention, then probability cuing should be less effective than endogenous cuing in guiding attention. Alternatively, attentional guidance may depend primarily on how informative an attentional cue is. As long as probability cuing and endogenous cuing provide the same amount of information about the target's spatial location, they may be equally effective at guiding attention.

Our experiments are grouped into two sections that investigated two aspects of the relationship between probability cuing and endogenous cuing. In the first section, we examined attentional guidance by probability cues and endogenous cues in two separate experiments. Probability cuing was the sole source of attentional guidance in Experiment 1, whereas endogenous cuing was the sole source of attentional guidance in Experiment 2. We tested whether probability cuing and endogenous cuing were equally effective at guiding attention when each was the only source of attention.

Section 2 examined the interaction between probability cuing and endogenous cuing when both cues were present during search. These experiments combined location probability learning with a central arrow cue. On any given trial, both cues could be valid, both cues could be invalid, or one cue could be valid and the other cue invalid. At least two possible patterns of interaction exist. First, both probability cuing and endogenous cuing may optimally and equally mobilize the same spatial orienting system. Under these conditions, the presence of a single valid cue of either type should facilitate search performance. However, the addition of a second valid cue would produce little additional benefit, resulting in an underadditive interaction. A second possibility is that one cue may dominate performance on all trials. Associative learning is sensitive to "blocking," where a salient cue that is predictive of a target blocks the learning of a less salient but predictive cue (Kamin, 1969). Experiments 3–5 examined the interaction between endogenous cuing and probability cuing when both cues can potentially guide spatial attention.

Section 1. Probability Cuing and Endogenous Cuing in Isolation

In this section we measured visual-search slope as a function of the number of items on the display. We tested whether the availability of probability cuing (Experiment 1) or endogenous cuing (Experiment 2) reduced visual-search slope. Some insight into whether probability guides attention can be found in a previous study (Geng & Behrmann, 2005). Participants searched briefly presented displays of eight or four items (Ts and Ls) for a single target. In eight-item trials, the target (a T) appeared in a specific location 75% of the time, and in each of the other seven locations 3.6% of the time. Responses were more accurate and faster when the target occurred in the rich location than in the sparse locations. However, the advantage for the rich location was smaller in the four-item trials than in the eight-item trials. These data suggest that probability cuing reduced search slope and is effective at guiding spatial attention.

However, several difficulties render the findings from that study inconclusive. First, the study used two types of four-item trials. Because only one type of four-item trial included the rich location, at least half of the four-item trials presented targets in a sparse location[1]. As a result, the probability manipulation was weaker in four-item trials than in eight-item trials (in which the rich location was always present). This difference alone could explain the weaker effect of probability cuing in four-item trials. Second, the probability manipulation was extreme. In eight-item trials the target appeared in the rich location 21 times more often than in any of the sparse locations. Given the extreme probability manipulation, it is likely that participants became aware of and intentionally used the probability information to direct spatial attention. The strategic allocation of attention may have changed the nature of probability cuing from incidental to intentional.

Here we investigate the effectiveness of probability cuing in guiding spatial attention. Participants searched for a T among Ls. The target was presented in one visual quadrant on 50% of the trials. On the other 50% of the trials it was randomly positioned in any of the remaining three quadrants (16.7% in each quadrant). Each quadrant contained 25 possible locations, reducing the saliency of the manipulation. In addition, the ratio of target frequency in the rich and sparse quadrants was 3:1:1:1. This ratio was less extreme than that in Geng and Behrmann's (2005) study. It was also less than the 4:1 ratio used in another study that demonstrated implicit learning of the target's spatial distribution (Geng & Behrmann, 2002). Consequently, the likelihood that learning was intentional and strategic in Experiment 1 was low.

In Experiment 1, we compared visual-search slope for trials in which the target fell in the rich quadrant to trials in which the target fell in the sparse quadrants. If probability cuing guides spatial attention, then search slope should be significantly shallower in the rich quadrant condition than the sparse quadrant condition. In Experiment 2, we examined whether the efficiency of

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[1] Insufficient details were provided by Geng and Behrmann (2005), so we could not determine the exact probability distribution of the target on Set-Size 4 trials. However, it was clear that the two types of Set-Size 4 trials occurred with equal frequency, and the target was never in the rich location in one of these two types. Consequently, at most, the target could only have appeared in the rich location on 50% of the Set-Size 4 trials.

guidance by probability cuing was comparable to the efficiency of guidance by endogenous cuing. We measured the change in search slope as a result of trial-by-trial endogenous cuing (based on an arrow cue). The change in search slope due to endogenous cuing was compared with that due to probability cuing in Experiment 1. Together, these two experiments allowed us to (a) address the possibility that probability cuing guides spatial attention, and (b) compare probability cuing with endogenous cuing.

Experiment 1

Method.

Participants. Students from the University of Minnesota volunteered in experiments reported in this study in exchange for $10/hour or extra course credits. They were naïve to the purpose of the study. They had normal or corrected-to-normal visual acuity.

Twelve participants, including nine women and three men, completed Experiment 1. Their mean age was 25 years old.

Equipment. Participants were tested individually in a room with normal interior lighting. They sat in front of a 19" CRT monitor (1024 × 768 pixels; 75-Hz refresh rate). Viewing distance was approximately 57 cm but was unconstrained. The experiment was programmed with Psychtoolbox (Brainard, 1997; Pelli, 1997) implemented in MATLAB (MathWorks, Natick, MA).

Materials. In each visual-search trial, participants were shown one rotated T (90° to the left or to the right) and several rotated Ls (0°, 90°, 180°, or 270° rotated). The offset between the two segments of the Ls was five pixels. The items were white presented against a black background. They subtended 1.25° × 1.25° and were placed in randomly selected locations in a 10 × 10 invisible grid (20° × 20°). The total number of items in each set (set size) was 8, 12, or 16 and it varied across trials. In each trial there were an equal number of items in the four quadrants. That is, there were two, three, or four items in each quadrant for the three different set sizes.

Procedure. Participants searched for a T and pressed the left or right arrow key to report the direction of the long stem of the T. They were asked to respond as quickly and as accurately as possible. The display was presented until a response was made. Three pleasant rising tones lasting a total of 300 ms followed a correct response. A buzz (200 ms) and a 2-s blank timeout followed an incorrect response.

To initiate each trial, participants clicked on a small square (0.6° × 0.6°) with a mouse. The square was presented at a random location within the central 3° of the monitor. The mouse click required eye–hand coordination and enforced fixation prior to the next search trial. After the click and a 200-ms blank period, the search display was presented.

Design. Participants completed 10 practice trials, 540 training trials, and 180 testing trials. The target was equally probable in all quadrants during practice and during the testing phase. However, its spatial distribution was uneven during the training phase. One quadrant contained the target in 50% of the trials (rich quadrant). In the remaining trials, the target was equally likely to appear in any of the other three quadrants (sparse quadrants). Location probability was manipulated in orthogonal to set size: there were eight, 12, or 16 items on the display. All trials were randomly intermixed in presentation.

Participants were not informed of the target's spatial distribution, nor were they given any information about the transition from the uneven distribution (the first 540 trials) to the even distribution (the last 180 trials). In the training (uneven) phase, the rich quadrant was counterbalanced across participants, but was held constant for a given participant.

Recognition. At the completion of the experiment, participants answered a recognition question that queried their awareness. The first eight participants answered a 5-choice question. They had to report whether the target was equally likely to appear anywhere on the screen, or whether it had more often appeared in the upper-left, upper-right, lower-left, or lower-right quadrant. To increase the sensitivity of the recognition test to explicit awareness, we modified the recognition task to a sequence of two questions for the last four participants. First they reported whether the target was evenly or unevenly distributed. They were then told that the target's distribution was uneven and were asked to select the quadrant that more frequently contained the target.

Results. Visual-search accuracy was higher than 98% in this and all subsequent experiments. There was no evidence of a speed–accuracy trade-off.[2] This report focuses on RT. We excluded incorrect trials and trials with an RT longer than 10 s (typically less than 0.3% of the trials). Mean RT was calculated for each participant.

Training. The training data were binned into epochs of 180 trials each and plotted in Figure 1.

Search RT decreased as the experiment progressed, resulting in a main effect of epoch, $F(2, 22) = 24.33$, $p < .001$. In addition, RT was faster in the rich quadrant condition than the sparse quadrant condition, $F(1, 11) = 86.75$, $p < .001$, and faster when set size was smaller, $F(2, 22) = 178.11$, $p < .001$. The advantage afforded by probability cuing was greater in later epochs than in earlier ones, resulting in a significant interaction between epoch and target quadrant, $F(2, 22) = 5.90$, $p < .009$. Of note, the search slope was shallower when the target was in the rich rather than the sparse quadrants. Aggregated across the entire training phase, visual-search slope was 106 ms/item when the target was in the rich quadrant, which was 64% of the slope for trials when the target was in a sparse quadrant (166 ms/item). This difference led to a significant interaction between set size and target quadrant, $F(2, 22) = 13.22$, $p < .001$. The other interactions were not significant, all $ps > .30$.

Testing. The learned attentional bias persisted in the final testing epoch, even though the target was evenly distributed. Figure 2 shows data from the testing phase.

Search RT was faster when the target was in the previously rich quadrant rather than the other quadrants, $F(1, 11) = 45.06$, $p < .001$. In addition, visual-search slope was 58% shallower when the target fell in the previously rich quadrant (88 ms/item) than the other quadrants (158 ms/item), resulting in a significant interaction between set size and target quadrant, $F(2, 22) = 14.67$, $p < .001$. The main effect of set size was also significant, $F(2, 22) = 101.37$, $p < .001$.

Recognition. Of the first eight participants who were given a 5-alternative-forced-choice question, six reported that the target

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[2] We would be happy to provide accuracy data to interested readers upon request.

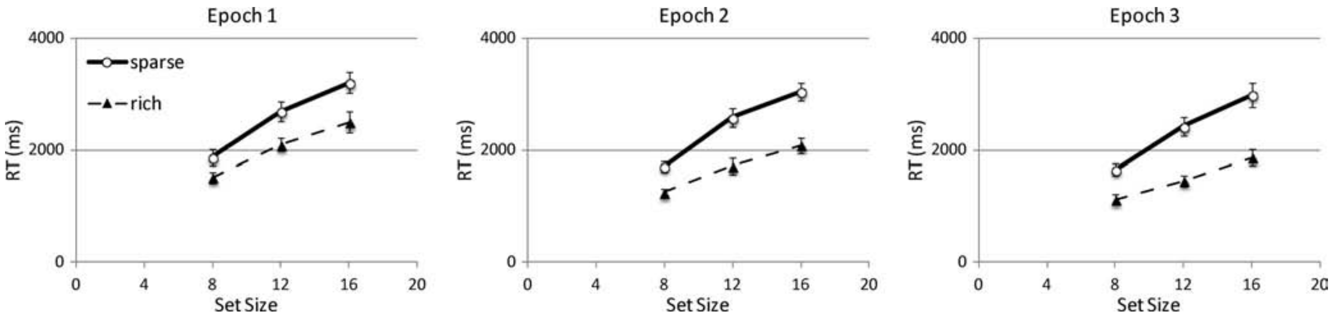


Figure 1. Results from the first three epochs (each epoch had 180 trials) of Experiment 1. The target appeared in a rich quadrant on 50% of the trials and in any of the remaining quadrants on 16.7% of the trials. Error bars show ±1 *SE* of the mean. Some error bars may be too small to see.

was evenly distributed. The other two correctly identified the rich quadrant. Of the last four participants who were given a forced choice of the rich quadrant, one correctly identified the rich quadrant. Altogether three out of the 12 participants correctly identified the rich quadrant (25%), which was not different from chance. Removing the data from those three participants did not change the pattern of results. Recognition performance supports the characterization of learning in this experiment as incidental learning.

Discussion. Experiment 1 showed that incidental learning of a target's likely location led to faster visual-search RT and shallower search slope in the high-frequency regions. The reduction in visual-search slope was consistent with Geng and Behrmann's (2005) finding. However, this result was obtained with a design that equated the target's probability across set sizes. In addition, the uneven distribution used in our study was much less extreme than that used by Geng and Behrmann (2005), reducing the likelihood that learning was intentional. The recognition data further suggested that learning was incidental. Experiment 1, therefore, presents the clearest evidence demonstrating that probability cuing, a form of incidental learning, guides spatial attention.

Unlike many other studies of location-probability learning, the design of Experiment 1 minimized the contribution of transient priming effects. Previous studies have shown that visual search is enhanced if the target on trial N shares the same location as the target on trial N-1 (Maljkovic & Nakayama, 1994). Although transient priming occurs regardless of whether the target is located in the rich or sparse locations (Geng & Behrmann, 2005), the likelihood of a repetition is higher in the rich locations than in the sparse locations. Indeed, one study found no evidence for location-probability learning when the target's location did not repeat in four consecutive trials (Walthew & Gilchrist, 2006). Because items in our study could appear in 100 possible locations, the likelihood that the target's location repeated in consecutive trials was low (see also Druker & Anderson, 2010). In addition, because the target was evenly distributed in the testing phase, it was no more likely to repeat its location in the rich condition than the sparse condition. Continued persistence of an attentional bias toward the previously rich locations during the "even" testing phase provided strong evidence of probability cuing. Experiment 1 extends findings from a previous study (Jiang, et al. in press) by showing that the persistence of the learned bias occurs not only in overall search RT, but also in search slope. The reduction in search slope is strong evidence that probability cuing guides spatial attention.

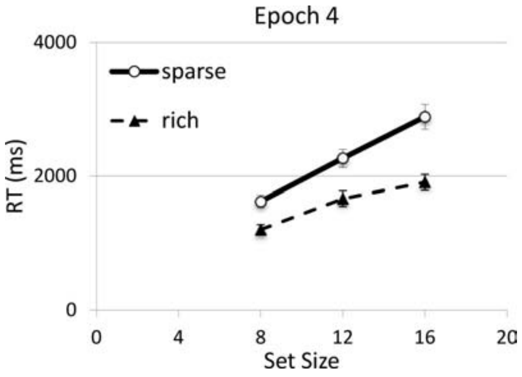


Figure 2. Results from the testing phase of Experiment 1. The target was evenly distributed across the four quadrants. The "rich" or "sparse" quadrants were the quadrant(s) that were rich or sparse during the training phase of the experiment. Error bars show ±1 *SE* of the mean.

Experiment 2

Although location-probability learning facilitated visual search in Experiment 1, the reduction in slope was modest. If participants had always searched the rich quadrant first, then the search slope in that quadrant should have been about 25% of that in the sparse quadrants. In actuality, the slope in the rich quadrant was 64% of that in the sparse quadrants. Does this mean that probability cuing is an inefficient source of attentional guidance? Is guidance stronger if spatial orienting is supported by an explicit endogenous cue rather than by incidental learning?

Experiment 2 assesses the efficiency of attentional guidance by an endogenous cue. The experiment is analogous to Experiment 1 except that the source of the attentional bias changed. On each trial, a centrally presented arrow pointed toward one of the four quadrants. The direction of the arrow was random from trial to trial. Consequently, the target was evenly distributed in space. There was no reason to favor a specific quadrant over others. However, for a given trial, the quadrant cued by the arrow had a higher probability than the others of containing the target. Specifically, the cued quadrant had a 50% probability of containing the target, whereas each of the uncued quadrants had a 16.7% probability of containing the target. The validity of the cued quadrant to the uncued quadrants was 3:1:1:1. The utility of using the endogenous cue was therefore identical to the utility of Experiment 1's probability cuing. However, participants used the endogenous cue intentionally (they were instructed to do so). If endogenous cuing is more effective in guiding spatial attention than probability cuing is, then the reduction in search slope produced by endogenous cuing should exceed that produced by probability cuing in Experiment 1.

Method.

Participants. Twelve college students completed Experiment 2. There were seven women and five men, with a mean age of 20 years.

Procedure and design. Experiment 2 was similar to Experiment 1 except for the following changes: The target was equally probable in any quadrant (25% in each quadrant). In each trial, participants clicked a small fixation square to initiate the trial. Immediately after that, an arrow (1.25° in length) was presented at the center of the screen for 100 ms. The arrow pointed at 45°, 135°, 225°, or 315° angles, chosen at random. After a blank interval of 100 ms the search display was presented. The quadrant cued by the arrow contained the target on 50% of the trials. In the remaining trials, the target was equally likely to appear in any of the other quadrants. Participants were given a faithful description of the cue validity and were encouraged to use the arrow to speed up visual search.

The timing of the arrow—100 ms duration and 100 ms blank—was chosen to prevent eye movements to the cued quadrant before the onset of the search display. This duration was shorter than what was considered optimal timing for endogenous cuing (275–400 ms; Müller & Rabbit, 1989). However, search takes an average of 1–3 s to complete, so there was adequate time for endogenous cuing to develop soon after display onset and influence visual search.

Participants completed 10 practice trials and 720 experimental trials.

Results. Experiment 2 was comparable to the training phase of Experiment 1 except for the source of attentional cuing. Because the training phase of Experiment 1 lasted only 540 trials, we compared the first 540 trials of Experiment 2 with the training phase of Experiment 1. Figure 3 shows data from the first 540 trials, binned into three epochs, as was done in Experiment 1. Results from the last 180 trials were similar and are listed in the Appendix.

We entered epoch (1–3), target quadrant (cued or uncued), and set size (8, 12, or 16) as factors in a repeated-measures ANOVA. All three main effects were significant: RT was faster in later epochs than in earlier ones, $F(2, 22) = 33.79$, $p < .001$, faster when the target was in the validly cued quadrant than in the other quadrants, $F(1, 11) = 15.47$, $p < .002$, and faster with smaller set sizes, $F(2, 22) = 193.24$, $p < .001$.

Endogenous cuing significantly affected visual-search slope. Slope was 123 ms/item in the cued quadrant, which was 77% of the slope in the uncued quadrants (160 ms/item). This difference resulted in a significant interaction between set size and target quadrant, $F(2, 22) = 5.00$, $p < .016$. Unlike Experiment 1, there was no probabilistic information to learn. The interaction between epoch and target quadrant was not significant, $F(2, 22) = 2.38$, $p > .10$. The other interactions were not significant, $p\text{s} > .10$.

Endogenous cuing versus incidental learning. In this analysis we directly compared the impact of incidental learning (Experiment 1) with that of endogenous cuing (Experiment 2). We conducted an ANOVA using experiment as a between-subjects factor, and epoch, target quadrant, and set size as within-subject factors. This analysis showed no interaction between experiment and target quadrant, suggesting that incidental learning and endogenous cuing had comparable effects on overall RT ($p > .20$). In addition, there was no interaction between experiment, target quadrant, and set size, suggesting that the two types of cues were comparable in their effects on search slope ($p > .20$). The only significant interaction involving experiment was a three-way interaction between experiment, target quadrant, and epoch ($p < .003$). This interaction was driven by an increase in probability cuing over time (Experiment 1), in contrast to a constant effect of endogenous cuing over time (Experiment 2). To illustrate the modulation of visual-search slope by probability cuing and endogenous cuing, Figure 4 plots visual-search slope for Experiments 1 and 2 as a function of time in the experiment. While both types of cues reduced search slope, the reduction increased over time with probability cuing, and was stable with endogenous cuing.

Discussion. The first two experiments demonstrate that not only is probability cuing effective in guiding attention, its efficiency in guiding attention is comparable to endogenous cuing. However, there are important differences between the two sources of spatial attention. Endogenous cuing is established immediately. It does not increase as the experiment progresses. In addition, because the cue varies from trial to trial, endogenous cuing guides attention on a trial-by-trial basis. In contrast, probability cuing

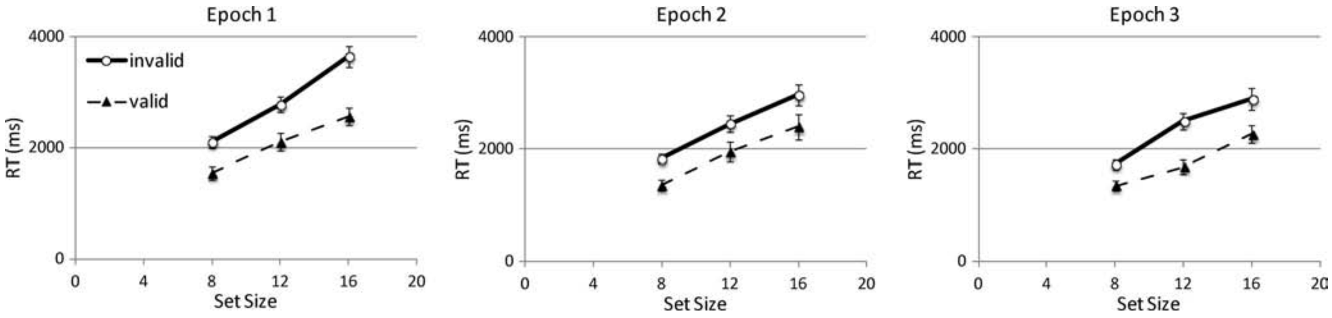


Figure 3. Results from the first three epochs of Experiment 2, plotted comparably to Figure 1. Valid refers to the cued quadrant and invalid refers to the uncued quadrants. Error bars show ±1 *SE* of the mean.

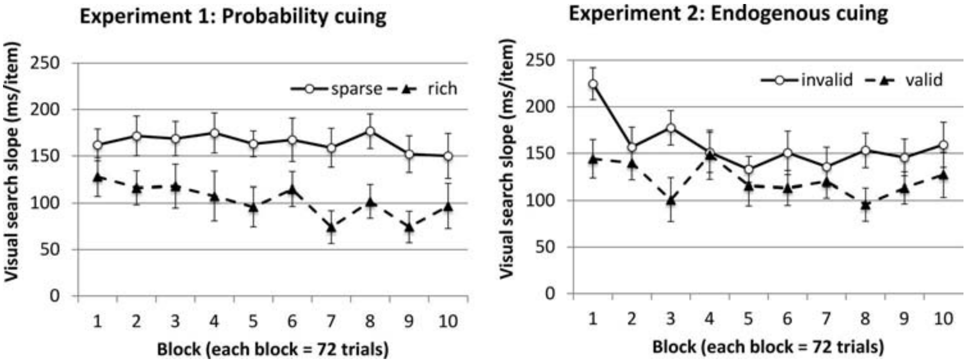


Figure 4. Visual-search slope over the course of an entire experiment, for probability cuing (Experiment 1) and endogenous cuing (Experiment 2). Error bars show ±1 *SE* of the mean.

emerges with time; its strength increases as the experiment progresses. Once acquired, the learned spatial bias persists long after the learning signal has been removed.

Both probability cuing and endogenous cuing produced moderate reductions in visual-search slope. This suggests that the cued quadrant was not always the first quadrant that participants searched. Instead, participants may have probability matched to the likelihood that a cue was valid. Specifically, the probability that the cued quadrant (p) was searched first may match the probability that the cued quadrant contained the target ($p = .50$). In trials when the cued quadrant was searched first, the effective set size would be 25% of the actual set size. In the remaining trials, the effective set size would be 100% of the actual set size. Expected search slope in the cued quadrant should therefore be ($p \times 25\% + (1 - p) \times 100\%$) of that in the uncued quadrants. If participants had probability matched, then p would be .50, resulting in a slope of 62.5% in the cued quadrant compared with the uncued quadrant. The observed slope reductions in Experiments 1 and 2 were statistically indistinguishable from 62.5% (ps $> .10$).

To conclude, Section I showed that (a) incidental learning of a target's spatial distribution can guide attention, and (b) when presented as the sole source of attentional guidance, this form of incidental learning guides spatial attention as effectively as endogenous cuing. The similarity in the utility of the two sources of attention provides some support for the notion that incidental learning is a form of top-down attention. However, Section I also reveals an important distinction between probability cuing and endogenous cuing: their flexibility to changes in search context. Once established, probability cuing persists for several hundred trials after the learned statistics are no longer valid. In contrast, endogenous cuing is established based on a cue that changes from trial-to-trial. The difference in flexibility provides the first hint for the idea that incidentally learned attention may be distinct from top-down attention.

Section II. The Coexistence of Probability Cuing and Endogenous Cuing

So far, we have compared probability cuing and endogenous cuing in situations where each one is the sole source of attentional bias. In daily experience, however, the two types of cues often coexist. How do incidental learning and endogenous cuing interact to guide attention? Would both cues guide spatial orienting to produce underadditive effects (analogous to the underadditivity between endogenous cuing and exogenous cuing, Yantis & Jonides, 1990)? Or would one cue block the use of the other cue?

We are aware of one study that has examined the interaction between probability cuing and endogenous cuing (Geng & Behrmann, 2005). In that study, participants searched for a T that could appear in one of four locations. On some blocks, the T was evenly distributed across the four locations. On other blocks, the T appeared in a single rich location 70% of the time. A second factor varied the presence of an endogenous cue. On some blocks, a neutral cue preceded the display. On other blocks, an arrow pointed to one of the four locations, and the target appeared in that location 70% of the time. Geng and Behrmann (2005) reported that both the endogenous cue and the uneven probability cue enhanced RT. They did not observe an interaction between these two sources of attentional bias.

However, there are difficulties in interpreting these data. First, the statistical analysis included entire blocks in which one of the factors was neutral, potentially obscuring moderate interactive effects. Because the data figures only plotted the main effects of both conditions, it is impossible to estimate whether interactive effects occurred in blocks where both factors existed. Second, additional experiments in the same paper suggest that incidental learning interacted with a cue that participants were told was informative. Although the cue was uninformative, task instructions may have led participants to use it endogenously for some period of time. The apparent inconsistency across experiments makes the findings inconclusive. Finally, as mentioned previously, the use of an extreme probability manipulation (7:1:1:1 for the rich and sparse locations) may have changed the nature of probability cuing from incidental learning to intentional learning.

For these reasons, it is important to further investigate how probability cuing and endogenous cuing interact. Therefore, in the remaining three experiments, both endogenous and probability cues were simultaneously available during parts of the experiment. In Experiments 3 and 4, endogenous cuing was available from the start of the experiment, before probability cuing had developed. In Experiment 5, the endogenous cue was introduced after probability cuing had developed. These experiments examined the possibility that both sources of attentional bias mobilize the same spatial orienting mechanism. They also elucidated the conditions under which incidental learning of the probability cue is blocked.

Experiment 3

Similar to Experiment 1, the first part of Experiment 3 involved an uneven spatial distribution of the target (rich:sparse quadrants 3:1:1:1), and the second part of the experiment involved an even spatial distribution of the target. Of critical note, a central arrow appeared on each trial. The quadrant cued by the arrow was more likely to contain the target than any of the uncued quadrants. The validity of the endogenous cue was also 3:1:1:1. This design therefore combined probability cuing with endogenous cuing. It allowed us to examine how the two sources of attention interact, both in the uneven training phase and in the even testing phase.

This design produced four types of trials (see Figure 5): (a) *Valid arrow, rich*. The arrow pointed at the rich quadrant, and the target appeared there. Search would benefit from probability cuing and endogenous cuing. (b) *Valid arrow, sparse.* The arrow pointed at a sparse quadrant and the target appeared there. Search would benefit from endogenous cuing but not probability learning. (c) *Invalid arrow, rich*. The target appeared in the rich quadrant but the arrow pointed elsewhere. Search would benefit from probability learning but not endogenous cuing. (d) *Invalid arrow, sparse.* The target appeared in a sparse quadrant that was uncued by the arrow. Search could not benefit from either endogenous cuing or probability learning. These four conditions allowed us to assess whether there was a main effect of endogenous cuing, a main effect of probability cuing, and whether the two effects interacted.

Method.

Participants. Twelve college students completed Experiment 3. There were eight women and four men, with a mean age of 19 years old.

Procedure and design. Each participant completed two phases of the experiment administered continuously without interruptions. In both phases, a central arrow was presented on each trial and it predicted the target quadrant on 50% of the trials (similar to Experiment 2).

In addition, during the training phase (the first 432 trials), the target was more often located in a rich quadrant (it appeared there on 50% of the trials, similar to Experiment 1's training phase). To achieve the simultaneous presence of an uneven target distribution and valid endogenous cuing, it was necessary for the arrow to be directed toward the rich quadrant on 50% of the trials. Incidental learning could be derived from either the target's location probability or the arrow's uneven distribution. As we will see in the results, this ambiguity turned out not to be an issue. The four conditions mentioned above: *valid arrow, rich; valid arrow, sparse; invalid arrow, rich*; and *invalid arrow, sparse*; each had 108 trials. These trials were further divided equally into three set sizes (eight, 12, and 16). All trials were randomly intermixed. Participants were given a faithful description of the arrow's validity, but were not informed of the target's uneven spatial distribution.

Similar to Experiment 1, we added a testing phase (the last 216 trials) where the target's spatial distribution was even. However, the arrow remained valid with a 3:1:1:1 validity.

The recognition procedure was the same as the two-step question used in Experiment 1.

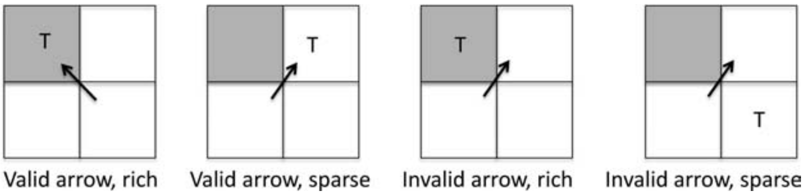
Results.

Training. Figure 6A plots mean RT for the four conditions in the training phase.

Visual search was faster when the target fell in the quadrant cued by the central arrow, producing a significant main effect of endogenous cuing, $F(1, 11) = 26.32$, $p < .001$. Search was also faster when set size was smaller, $F(2, 22) = 389.19$, $p < .001$. Replicating Experiment 2, a valid arrow cue significantly reduced search slope relative to an invalid arrow cue. Search slope was 120 ms/item when the arrow cue was valid, or 70% of the slope when the arrow cue was invalid (171 ms/item). The reduction in slope resulted in a significant interaction between endogenous cuing and set size, $F(2, 22) = 8.14$, $p < .002$.

In contrast to endogenous cuing, there was no effect of probability cuing. The main effect of probability cuing (rich vs. sparse) was not significant, $F(1, 11) = 2.61$, $p > .13$. None of the interaction effects involving probability cuing were significant: Probability Cuing × Endogenous Cuing, $F < 1$; Probability Cuing × Set Size, $F < 1$; three-way interaction $F(2, 22) = 2.74$, $p = .086$. Visual inspection suggested that when the target was validly cued by the arrow, RT may have been faster in the rich quadrant than the sparse quadrant. However, this observation was not statistically supported, $F(1, 11) = 1.40$, $p > .25$.

Testing. Given that probability cuing did not emerge during training, it is not surprising that it showed no persistence in the testing phase. Figure 6B shows data from the testing phase. Similar to the training phase, RT was predominantly affected by endogenous cuing but not by (residual) probability cuing. RT was faster when the central arrow cue was valid, $F(1, 11) = 32.22$, $p < .001$. In addition, search slope was shallower in the validly cued quadrant than the invalidly cued quadrant, $F(2, 22) = 111.56$, $p < .001$. There was no main effect of (residual) incidental learning, $F < 1$, neither did it interact with endogenous cuing, $F < 1$. The three-way interaction was also not significant, $F < 1$. However, the interaction between the (residual) probability cuing and set size



Valid arrow, rich Valid arrow, sparse Invalid arrow, rich Invalid arrow, sparse

Figure 5. A schematic illustration of the four conditions tested in Experiments 3 and 4's training phase. T represents where the target is. The shaded quadrant is the rich quadrant.

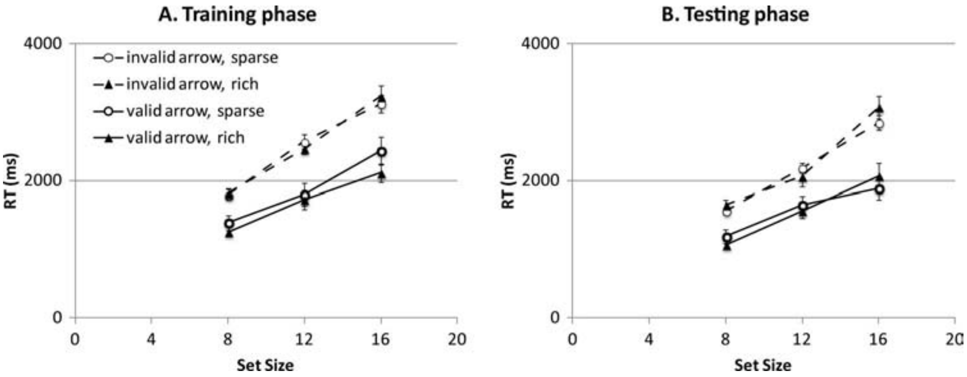


Figure 6. Results from Experiment 3. The target appeared three times more often in the rich quadrant than in any of the sparse quadrants during the training phase (Figure 6A). Its spatial distribution was even during the testing phase. The arrow cue was present during both phases. Error bars show ±1 *SE* of the mean.

reached significance, $F(2, 22) = 3.65$, $p < .043$. This is likely a statistical anomaly.

Recognition. Two of the 12 participants said that the target was unevenly distributed in space; among them, one person correctly identified the rich quadrant. Of the 10 people who said that the target was evenly distributed, 5 subsequently identified the rich quadrant. The total number of people correctly identifying the rich quadrant was six out of 12, higher than what would be expected by chance (25%). The uneven distribution of the arrow may have contributed to increased awareness of the target's uneven spatial distribution. Despite the presence of an explicit awareness, search performance was largely unaffected by the target's spatial distribution.

Discussion. Experiment 3 showed a nearly complete absence of probability cuing when a valid endogenous cue was also available during training and testing. This finding is surprising because the probability cuing manipulation used in Experiment 3 was the same as that used in Experiment 1. Indeed, to produce an uneven spatial distribution of the target and valid endogenous cuing during training, it was necessary for the endogenous cue to be spatially biased as well. The central arrow pointed toward the rich quadrant more often than it pointed toward any of the other quadrants. Had there been an effect of probability cuing, it could have been driven by learning the target's location probability or the cue's spatial distribution. Even though there were potentially two sources of learning, probability cuing did not occur.

These data suggest that endogenous cuing takes precedence over probability cuing in guiding spatial attention. However, they raise two questions. First, because the endogenous cue was present during both training and testing, the cue may have interfered with the expression of probability cuing rather than learning itself. To assess effects of endogenous cuing on learning, it was necessary to test the persistence of learning in the absence of an endogenous cue. Experiment 4 was designed to achieve this goal. Second, because there was no attentional bias due to incidental learning in the training phase of Experiment 3, it was necessary to ensure that it was in place before testing whether it would interact with endogenous cuing. Experiment 5 was designed to address this issue.

Experiment 4

This experiment was identical to Experiment 3 except that the arrow cue was removed in the testing phase[3]. We expected to replicate Experiment 3's finding in the training phase: RT would be faster on validly cued trials than on invalidly cued trials, but unaffected by the target's spatial distribution. If endogenous cuing interfered with just the expression of learning but not with learning itself, then the removal of the endogenous cue during the testing phase should unmask probability cuing. In contrast, if endogenous cuing interfered with incidental learning, then probability cuing should not be present even after the endogenous cue was removed.

Method.

Participants. Twelve college students (eight women and four men) completed Experiment 4. Their mean age was 20 years old.

Design. This experiment was the same as Experiment 3, except that the arrow cues were removed during the testing phase. Thus, the training phase had four conditions: *valid arrow, rich; valid arrow, sparse; invalid arrow, rich;* and *invalid arrow, sparse.* The testing phase had two conditions: The target was either in a previously rich quadrant or a previously sparse quadrant. The recognition task was the same as Experiment 3's.

Results. Figure 7A plots visual-search RT for the four conditions of the training phase.

Results from the training phase replicated those of Experiment 3. RT was faster when the target was in the quadrant directed by the arrow than in the other quadrants, leading to a significant main effect of endogenous cuing, $F(1, 11) = 22.33$, $p < .001$. Endogenous cuing also reduced visual-search slope from 170 ms/item on invalidly cued trials to 106 ms/item on validly cued trials (62%), resulting in a significant interaction between endogenous cue and set size, $F(2, 22) = 13.20$, $p < .001$. It is important to note that the presence of an endogenous cue completely blocked probability cuing. The main effect of probability cuing (e.g., whether the target fell in a rich or sparse quadrant) was not significant, $F < 1$, neither did probability cuing interact with the other factors (inter-

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[3] We thank Dr. Jiménez and an anonymous reviewer for suggesting this experiment.

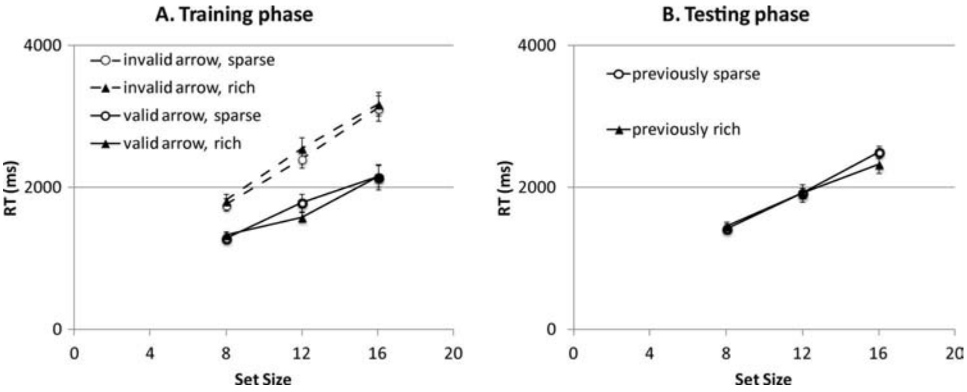

Figure 7. Results from Experiment 4. The target appeared three times more often in the rich quadrant than in any of the sparse quadrants during the training phase (Figure 7A). The arrow cue was absent during the testing phase (Figure 7B). Error bars show ±1 *SE* of the mean.

action with endogenous cuing: $F(1, 11)$ 2.06, $p > .15$; interaction with set size, $F < 1$; 3-way interaction, $F(2, 22) = 3.02$, $p = .10$).

Did endogenous cuing block incidental learning, or did it block its expression? Because the endogenous cue was absent in the testing phase, any latent learning of the target's spatial distribution from the training phase should be revealed. Figure 7B shows data in the testing phase. There was no evidence of probability cuing. RT was influenced by set size, $F(2, 22) = 77.37$, $p < .001$, but was unaffected by whether the target quadrant was a previously rich or sparse quadrant, $F < 1$. The interaction between probability cuing and set size was not significant, $F < 1$.

In the recognition phase, 10 of the 12 participants said that the target was evenly distributed. When asked to make a forced choice of the rich quadrant, six of the 12 participants selected the correct quadrant. The forced choice of the quadrant was higher than what would be expected by chance. Although participants had some conscious access to the probability manipulation, their performance was unaffected by this manipulation. We will discuss the role of conscious awareness in probability cuing after Experiment 5.

Discussion. Experiment 4 demonstrated that endogenous cuing not only blocked the expression of probability cuing, but also any latent learning of the target's spatial distribution. Even though probability cuing was highly effective at guiding spatial attention when it was the sole source of attentional guidance (Experiment 1), its effect was abolished when endogenous cuing was available. These data are consistent with *associative blocking* (Kamin, 1969): The association of a salient cue with a target blocks learning of the association between a less salient cue and the target. In Experiments 3 and 4, the endogenous cue corresponded to a physical stimulus that was on the screen during each trial, and that was to be intentionally used to guide attention. In contrast the probability cue needed to be learned over the course of many trials and was unlikely to have reached conscious awareness if it was learned. Thus, in Experiments 3 and 4 the only salient cue for attentional deployment was the centrally presented arrow. As a result, successful target detection may have been associated with the endogenous cue rather than the target's likely spatial location.

Experiments 3 and 4 clearly demonstrate that endogenous cuing takes precedence over probability cuing when they co-occur during training. Endogenous cuing blocks incidental learning of the target's spatial distribution. What is not clear, however, is how these two spatial biases interact once both are in place.

Experiment 5

Experiment 5 investigated the interaction between endogenous cuing and probability cuing when both were present and equally effective at guiding attention. To achieve this goal, the central arrow cue was not presented during the training phase of Experiment 5. However, the target was unevenly distributed during training. Because no endogenous cue was present to block learning, a spatial bias toward the rich quadrant should have developed during training. In the testing phase the target became evenly distributed. In addition, an endogenous cue appeared on every trial. Thus, Experiment 5 was identical to Experiment 1, except that the endogenous cue was added during the testing phase. Based on Experiment 1 and a previous study (Jiang et al., in press), the attentional bias toward the previously rich quadrant should persist during the testing phase. If probability cuing and endogenous cuing do not interact, both should effectively guide attention during testing. We examine how the persistent attentional bias from probability cuing interacts with an endogenous cue.

Method.

Participants. Twelve college students completed Experiment 5. There were nine women and three men with a mean age of 19 years.

Procedure and design. Participants completed two phases. In the *training* phase, the target's spatial distribution was uneven, with the ratio of rich to sparse quadrants of 3:1:1:1. There were no arrows. This phase was therefore identical to Experiment 1's training phase. There were 360 trials in this phase. The trials were evenly distributed among three set sizes (8, 12, or 16). Participants were not informed of the target's location probability or the transition from the training to the testing phase.

The *testing* phase differed from the training phase in two respects. First, the target's spatial distribution was even. Second, each trial involved a central arrow cue. The arrow was equally likely to point at any quadrant. However, for any given trial, the quadrant cued by the arrow had a higher probability (.50) of containing the target than any of the other quadrants (.167). This phase was therefore identical to Experiment 2. There were 360 trials in this phase. Probability cuing refers to whether the target occurred in the previously rich or previously sparse quadrants. Endogenous cuing refers to whether the arrow cue validly predicted the target's location. These two factors produced four conditions in the testing phase: *valid arrow, previously rich; valid arrow, previously sparse; invalid arrow, previously rich;* and *invalid arrow, previously sparse* (see Figure 5). The number of trials in these four conditions was 45, 135, 45, and 135, respectively. These trials were further divided evenly into three set sizes (8, 12, or 16). All trials were randomly intermixed. Participants were given a faithful description of the arrow's utility but were not informed of the probability-cuing manipulation.

The recognition test was the same as the two-step question used in Experiment 1.

Results.

Training phase (Figure 8A). Replicating Experiment 1, incidental learning of the target's likely location sped up RT, $F(1, 11) = 28.81$, $p < .001$. It also reduced search slope from 164 ms/item in the sparse quadrants to 118 ms/item in the rich quadrant (72% difference), resulting in a significant interaction between set size and target quadrant, $F(2, 22) = 7.47$, $p < .003$. The main effect of set size was also significant, $F(2, 22) = 134.51$, $p < .001$. The RT advantage afforded by probability cuing was very large and should persist in the testing phase (see Experiment 1; Jiang, et al., in press).

Testing phase. Data from the testing phase were markedly different from the training phase (Figure 8B). We conducted an ANOVA using endogenous cue (valid or invalid), probability cuing (previously rich or sparse quadrants), and set size (eight, 12, or 16) as within-subject factors. RT was primarily influenced by the endogenous cue. It was faster when the target appeared in the validly cued quadrant than in the invalidly cued quadrants, $F(1, 11) = 85.60$, $p < .001$. In addition, there was a significant interaction between endogenous cuing and set size, $F(2, 22) = 10.05$, $p < .001$. The main effect of set size was also significant, $F(2, 22) = 145.60$, $p < .001$.

Unlike Experiments 3 and 4, probability cuing did influence performance. RT was faster when the target appeared in the previously rich rather than in the previously sparse quadrants, resulting in a significant main effect of probability cuing, $F(1, 11) = 6.05$, $p < .032$. However, the effect of probability cuing was small and was confined to trials with a valid endogenous cue. The interaction between probability cuing and endogenous cuing was significant, $F(1, 11) = 11.56$, $p < .006$. When the target appeared in a quadrant that the arrow did not point to, RT was unaffected by whether the target quadrant was previously rich or sparse, $F < 1$. When the target appeared in the quadrant cued by the arrow, RT was faster if that quadrant was also biased by probability cuing, $F(1, 11) = 12.20$, $p < .005$. The other interactions were not significant, all $ps > .20$.

Recognition. When asked about the target's distribution, five of the 12 participants said that it was not evenly distributed. Four of these five correctly identified the rich quadrant. Seven people said that the target was evenly distributed, but when given the forced choice, one of them correctly identified the rich quadrant. Altogether five of the 12 participants identified the rich quadrant.

Discussion. Experiment 5 addressed a concern raised earlier in Experiment 3. In Experiment 5, we successfully established a learned bias prior to the introduction of an endogenous cue. Under this condition we found a significant effect of probability cuing. However, similar to Experiments 3 and 4, endogenous cuing dominated probability cuing. The effect of prior learning was small and only observed when the endogenous cue was valid. These data suggest that although probability cuing and endogenous cuing are individually effective in guiding attention, when combined together, endogenous cuing takes precedence over probability cuing.

In Experiment 5 the effect of a learned attentional bias was only observed when the rich quadrant was validly cued by the central arrow. This overadditive pattern is not commonly observed in studies on attention. When two sources of attention induce an attentional orienting response, their effects are typically underadditive. For example, Yantis and Jonides (1990) found that the effect of an abrupt onset was *smaller* in locations validly cued by a central arrow. That is, when spatial attention had already been summoned by an endogenous cue, adding an exogenous cue did not further influence search. In contrast, in Experiment 5 a learned attentional bias influenced search only in locations validly cued by a central arrow. These results suggest that experience-driven attention differs from exogenous cuing in its interaction with an observer's goal. Experience-driven attention is potentiated by a valid endogenous cue, whereas exogenous cuing is reduced by a valid endogenous cue.

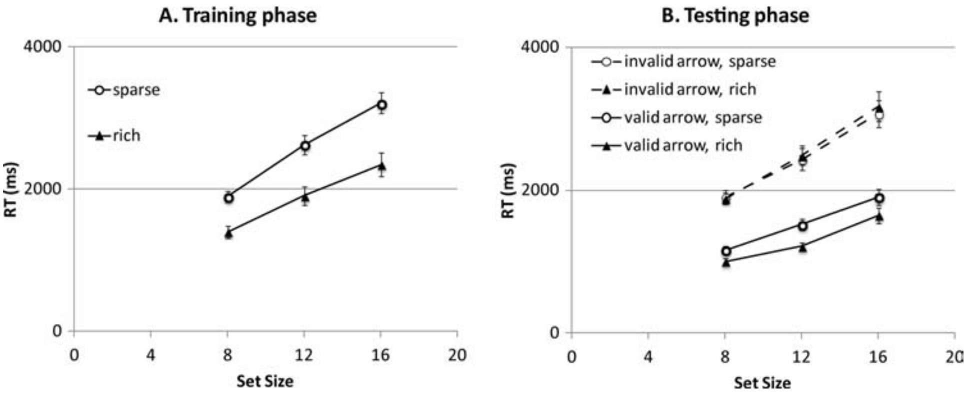

Figure 8. Results from Experiment 5: A. Training phase, B. Testing phase. Error bars show ±1 *SE* of the mean.

To what degree did explicit awareness contribute to probability cuing? In Experiments 3 through 5, the percentage of participants who were able to identify the rich quadrant was higher than chance. This suggests that the probability manipulation yielded explicit knowledge. However, there are several reasons to think that explicit awareness is not a critical part of probability cuing. First, the highest level of explicit awareness was shown in Experiments 3 and 4, yet in those experiments, performance was unaffected by probability cuing. In contrast, participants in Experiment 1 performed at chance levels in the recognition test, yet probability cuing was very strong. Therefore, there is a lack of correspondence between the level of awareness and the amount of learning. Second, we conducted an analysis in Experiment 5 separating participants into two groups: an “aware” group with those who correctly identified the rich quadrant, and an “unaware” group with those who failed to identify the rich quadrant. The pattern of data was similar for the two groups (see Figure 9). The interactions between group and the experimental manipulations were not significant, all $ps > .11$.

Because the outcome of learning may, at least in part, be accessible at an explicit level, location probability learning is not a form of implicit learning (Stadler & Frensch, 1998). Instead, it is similar to other visual statistical learning tasks that often yield explicit knowledge (e.g., Fiser & Aslin, 2001). The most appropriate classification of location-probability learning is “incidental learning.” Learning is driven largely by visual statistics as opposed to top-down goals, although its outcome may be partially explicit.

General Discussion

This study addresses the role of incidental learning of a target’s spatial distribution in spatial attention. In Experiment 1, an attentional bias developed toward a region that was likely to contain a target. This bias persisted long after the target was no longer unevenly distributed. Probability cuing reduced visual-search slope when the target appeared at the high-probability locations. Moreover, the effects of probability cuing were comparable to those of endogenous cuing (Experiment 2). However, when they were combined, the effects of endogenous cuing dominated those of probability cuing. In Experiments 3 and 4, the presence of an endogenous cue during training interfered with probability learning. In Experiment 5, a strong attentional bias produced by incidental learning was disrupted by the introduction of an endogenous arrow cue during testing. When the endogenous cue was present, the impact of an acquired attentional bias was only observed when the endogenous cue was valid. These data have important theoretical implications for understanding spatial attention.

The current study is the first step toward establishing incidental learning as a separate source of attentional guidance. Probability cuing bears a striking similarity to goal-driven (endogenous) attention in its impact on visual-search RT and search slope. However, there are important distinctions between them.

First, whereas endogenous cuing can be established immediately and adjusted on a trial-by-trial basis (Experiment 2), incidental learning takes time to emerge. Once acquired, its impact remains for several hundred trials after the bias no longer captures the current visual statistics (Experiment 1; see also Jiang et al., in press).

Second, incidental learning can guide attention without any intention to learn or awareness of the bias itself. This characteristic stands in contrast to the essence of goal-driven attention, which reflects the observer’s explicit knowledge and goals.

Although indirect, the dominance of endogenous cuing over probability cuing also suggests that the two sources of attention are different. Imagine that probability cuing and endogenous attentional biases are intrinsically similar—for instance, both may trigger spatial orienting toward specific locations. Then the most natural prediction would be first, orienting should occur when either probability cuing or endogenous cuing is valid; second, when spatial attention is already directed by an endogenous cue, a consistent probability cue should not add much and consequently the two cues should be underadditive. The actual finding differed from both of these predictions. The dominance of one cue over the other, and the overadditivity (as opposed to underadditivity) of the two sources argue against the idea that the two sources of attention are substitutes for each other.

The distinctions noted above lead us to propose that incidental learning of a target’s spatial distribution is a separate drive of spatial attention from goal-driven attention. Because we did not test exogenous attention, we cannot rule out the possibility that probability cuing biases attention in a bottom-up fashion (Desimone & Duncan, 1995). However, unlike canonical cases of

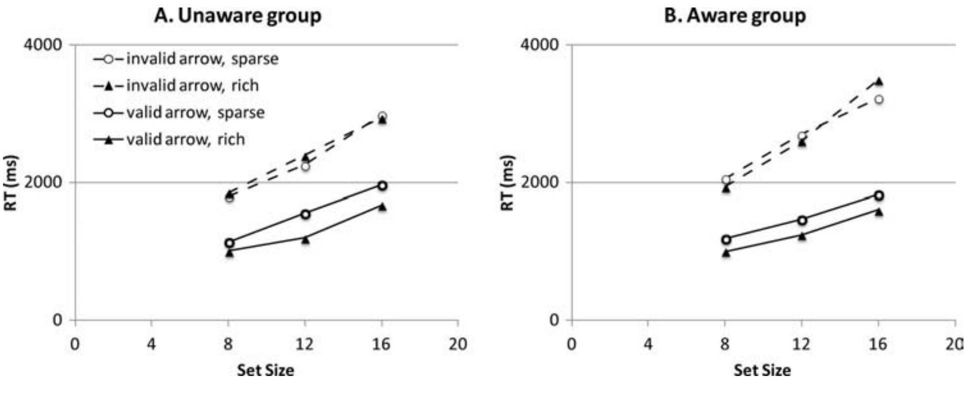

Figure 9. Results from Experiment 5’s testing phase, separately for participants who were unable to identify the rich quadrant (the unaware group) and participants who correctly identified the rich quadrant (the aware group).

bottom-up attention, probability cuing does not significantly modify the apparent perceptual saliency of stimuli. Moreover, the interactive effects of experience-driven attention with endogenous attention are qualitatively different from those between exogenous and endogenous attention (Yantis & Jonides, 1990). A tripartite model, where attention is driven by goals, perceptual saliency, and incidentally learned statistical information, may be warranted.

Although important, the tripartite model does not immediately explain the results from Experiments 3 to 5. How does probability cuing differ from endogenous cuing, and how can this difference give rise to the dominance of one cue over the other? Here we provide two suggestions. The first suggestion rationalizes the order of priority between the two sources of attention. Goal-driven attention reflects the observer's current goals and task demands, whereas experience-driven attention reflects only one's history. Reliance on goal-driven attention ensures that the current task's goal is prioritized even when it conflicts with prior learning. The relative priority is reminiscent of the interaction between goal-driven and stimulus-driven attention. Stimulus-driven attention is contingent on an observer's task goal and is often observed when the salient features are also what the observers are looking for (Egeth & Yantis, 1997; Folk, Remington, & Johnston, 1992). This prioritization results in associative blocking when probability cuing has not yet been established (Experiments 3 and 4).

Our second suggestion is that there may be a fundamental difference in how probability cuing and endogenous cuing are used. This suggestion is speculative, but it formulates a testable hypothesis for future research. Specifically, we propose that endogenous cuing affects the declarative aspect of attentional allocation. The cue is a form of declarative knowledge. In contrast, probability cuing affects the procedural aspect of attentional allocation. Visual search is a process that involves the shifting of attention from one item to another. Similar to other procedures such as riding a bike or tying one's shoes, visual search is influenced both by declarative knowledge and by procedural learning. This speculation makes a clear prediction: Probability cuing acquired in one task, like visual search, may not transfer to another task, such as change detection.

The above suggestion may also help explain the results from Experiment 5. In three of the four conditions (see Figure 5) the endogenous cue directs attention away from the rich quadrant. In these conditions, declarative knowledge about how attention should be deployed in space is incongruent with procedural knowledge. The incongruence may have interfered with the expression of an incidentally learned bias. Only in the first case, where the endogenous cue directed attention to the learned quadrant, was declarative knowledge consistent with procedural learning. This may explain why the effect of probability cuing was observed only when the endogenous cue was valid.

In sum, we have shown that one's previous experience, acquired in an incidental manner, can serve as a powerful cue for guiding spatial attention. Incidental learning of a target's likely locations facilitates search RT and search slope as effectively as endogenous cuing. Unlike endogenous cuing, which can be adjusted on a trial-by-trial basis, probability cuing requires learning and persists for several hundred trials after training has terminated. In addition, the presence of an endogenous cue largely outweighs the impact of a learned attention bias, revealing the precedence of one's current goal over previous experience. These data suggest that incidental learning of visual statistical information may constitute a third major source of spatial attention apart from goal-driven and stimulus-driven attention.

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Appendix

Mean RT in Epoch 4 of Experiment 2

	Invalid cue			Valid cue		
Set size	8	12	16	8	12	16
Mean	1613	2324	2809	1240	1680	2148
SE	91	177	156	75	107	151

Note. *SE* = standard error of the mean. Cue validity, set size, and their interaction were all significant, *p*s $< .021$.

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