Journal of Experimental Psychology:
Learning, Memory, and Cognition
2018, Vol. 44, No. 3, 387–398

0278-7393/18/$12.00 http://dx.doi.org/10.1037/xlm0000428

Attending Globally or Locally: Incidental Learning of Optimal Visual Attention Allocation

Melissa R. Beck and Rebecca R. Goldstein
Louisiana State University

Amanda E. van Lamsweerde
North Dakota State University

Justin M. Ericson
The George Washington University

Attention allocation determines the information that is encoded into memory. Can participants learn to optimally allocate attention based on what types of information are most likely to change? The current study examined whether participants could incidentally learn that changes to either high spatial frequency (HSF) or low spatial frequency (LSF) Gabor patches were more probable and to use this incidentally learned probability information to bias attention during encoding. Participants detected changes in orientation in arrays of 6 Gabor patches: 3 HSF and 3 LSF. For half of the participants, an HSF patch changed orientation on 75% of the trials, and for the other half, an LSF patch changed orientation on 75% of the trials. Experiment 1 demonstrated a change probability effect and an attention allocation effect. Specifically, change detection performance was highest for the probable-change type, and participants learned to use a global spread of attention (fixating between Gabor patches) when LSF patches were most likely to change and to use a local allocation of attention (fixating directly on Gabor patches) when HSF patches were most likely to change. Experiments 2 and 3 replicated these effects and demonstrated that an internal monitoring system is sufficient for these effects. That is, the effects do not require explicit feedback or point rewards. This study demonstrates that incidental learning of probability information can affect the allocation of attention during encoding and can therefore affect what information is stored in visual working memory.

Keywords: visual attention, incidental learning, visual working memory, spread of attention, eye movements

The level of visual detail that must be perceived varies depending on a given task. For example, when driving, on a highway, the primary goal may be to monitor the road for other cars changing lanes, in which case a global allocation of attention that encompasses the whole roadway would be sufficient. On the other hand, when waiting for a stoplight to change from red to green, attention must be allocated locally to the light to detect the color change. There is, however, a natural bias to focus on and remember global information over local details (Ericson, Beck, & van Lamsweerde, 2016; Navon, 1977). Therefore, adjusting the focus of attention to a scope that is most appropriate to the task at hand requires flexibility. Furthermore, this flexible adaptation may not be explicitly taught, and the optimal attention allocation is therefore most likely learned through experience (i.e., incidental learning). The current study tested whether it is possible to incidentally learn to utilize either a global or local attention allocation, depending on the optimal allocation that would produce successful change detection.

Global Versus Local Attention Allocation

Attention allocation is commonly thought of as a shift in attention to various locations in space; however, the allocation of attention can also refer to the spread of attention. The spread of attention can be wide (i.e., a global allocation of attention) or narrow (i.e., a local allocation of attention; Eriksen & Yeh, 1985); the optimal spread of attention depends on the type of information that needs to be processed. The visual world contains information across an amplitude spectrum, and the visual system is set up to process low spatial frequency (LSF) and high spatial frequency (HSF) information through different visual pathways (Van Essen & Deyoe, 1995). The processing of HSF information is linked to processing at the fovea, whereas processing of LSF information is associated with peripheral areas of the retina (Henriksson, Nurminen, Hyvärinen, & Vanni, 2008; Sasaki et al., 2001). Furthermore, the perception of both HSF and LSF information can be enhanced if attention is primed toward the relevant frequency (Flevaris, Bentin, & Robertson, 2010). Therefore, the allocation of attention, either to the fine detail at the fovea (i.e., local attention allocation) or to coarser information in the periphery (i.e., global attention

This article was published Online First June 29, 2017.

Melissa R. Beck and Rebecca R. Goldstein, Department of Psychology, Louisiana State University; Amanda E. van Lamsweerde, Department of Psychology, North Dakota State University; Justin M. Ericson, Department of Psychology, The George Washington University.

Justin M. Ericson is now at Microsoft in Seattle, Washington.

Correspondence concerning this article should be addressed to Melissa R. Beck, Department of Psychology, Louisiana State University, 236 Audubon Hall, Baton Rouge, LA 70803. E-mail: mbeck@lsu.edu

allocation), can determine the type of information (high or low spatial frequency, respectively) that is optimally processed.

When attention is allocated globally, attention is spread over a larger region and potentially multiple objects, but only the coarse details of the objects (LSF information) are processed in peripheral vision (Henriksson et al., 2008; Sasaki et al., 2001). In contrast, with a local attention allocation, attention is focused on a smaller region at the fovea and potentially on only one (or part of one) object, but now the fine details of the object (HSF information), are available for processing (Henriksson et al., 2008; Sasaki et al., 2001). Therefore, a global allocation of attention is used to process the LSF information of multiple objects, whereas a local attention allocation is used to process the HSF information of a single object. Furthermore, whereas a local attention strategy would be most effective for processing objects at fixation, a global attention strategy would be most effect for processing objects in the periphery when there are no objects at fixation, because when there is perceptual load at fixation, processing of peripheral information is limited (Williams, 1989). Participants may be able to preferentially process high or low spatial frequency information by allocating attention either globally or locally based on which attention strategy is optimal for detecting the probable-change information.

Incidental Learning

In the absence of explicit instruction, individuals are sensitive to statistical information in the environment and use it to incidentally learn language (for a review see Gómez & Gerken, 2000), music (Saffran, 2002), and associations between visual objects (Fiser & Aslin, 2005; Saffran, 2002). Additionally, it is possible to incidentally learn to detect changes that are more likely to occur over changes that are unlikely. The *change probability effect* refers to this tendency to detect probable changes more accurately than improbable changes (Beck, Angelone, & Levin, 2004; van Lamsweerde & Beck, 2011). This change probability effect occurs for familiar everyday objects (e.g., lamps turning on and off), as well as after training with novel objects that have undisclosed experimenter-assigned change probabilities. For example, Beck et al. (2004) asked participants to detect color changes to arrays of six shapes arranged in two rows of three objects each. Across many training trials, the change was more likely to occur in either the top row or the bottom row. Participants were never explicitly informed about this probability information. Then, in a subsequent set of test trials, the change was equally likely to occur in the top and bottom rows. During these test trials, change detection performance was better for the row that contained a change during the training trials. Critically, this change probability effect was the result of incidental learning, because participants were never explicitly told about the change probability information (Beck et al., 2004).

Can incidentally learned probability information be used to bias attention allocation? It is possible that the change probability effect in Beck et al. (2004) occurred because participants learned to allocate attention during encoding to the row of objects that was most likely to change. Change detection requires attention to the prechange information so that it can be encoded into visual working memory (VWM; Hollingworth & Henderson, 2002; Levin & Simons, 1997; Rensink, O'Regan, & Clark, 1997; Simons, 2000). Therefore, biased attention to the objects in the row that are likely to change would improve the ability to detect changes to these objects. However, attention and VWM encoding are not sufficient for accurate change detection. There are several stages of processing necessary for accurate change detection: attention during encoding, maintenance of encoded information in VWM, retrieval and comparison, and decision. Although the bias toward the probable-change information could occur at any one or more of these stages, research thus far has attributed the change probability effect to biases during the retrieval and comparison (Beck, Peterson, & Angelone, 2007) and decision (Yang, Chang, & Wu, 2013) stages but not the attention during encoding stage (Beck et al., 2007). Therefore, it remains unknown whether incidentally learned regularities can affect attention allocation while encoding information into VWM.

Probability information can impact the allocation of attention to specific locations in visual attention tasks. For example, there is considerable research demonstrating that the *location* of attention can be preferentially biased in visual search due to learned regularities about probable target locations (Brockmole & Henderson, 2006; Chun & Jiang, 1998; Chun & Nakayama, 2000; Druker & Anderson, 2010; Geng & Behrmann, 2002; Jiang, Won, & Swallow, 2014; Miller, 1988; Peterson & Kramer, 2001; Zhao et al., 2012). These findings support the idea that the allocation of visual attention to specific locations can be altered due to incidentally learned regularities in visual search tasks. However, despite these advances, it is currently unknown whether the spread of attention during encoding into VWM is similarly impacted by incidentally learned regularities. The current study aimed to create a situation in which either a global or a local allocation of attention was optimal for detecting the probable-change type to see whether the optimal attention allocation could be learned and implemented to improve performance.

Reward

Probability information alone may not be sufficient for employment of the optimal attention allocation for the probable change. Previous research has indicated that reward can increase incidental learning (Freedberg, Schacherer, & Hazeltine, 2016) and impact the allocation of attention (Anderson, Laurent, & Yantis, 2011; Della Libera, & Chelazzi, 2006; Hickey, Chelazzi, & Theeuwes, 2010; Lee & Shomstein, 2013; Shomstein & Johnson, 2013). Droll, Abbey, and Eckstein (2009) found that reward can enhance learning of probability information and the impact of this learning on saccadic behavior. They used a visual search task in which a cue (colored circle) predicted the target location. Participants could learn this information through experience with the task (i.e., incidental learning) and use it to improve performance. Participants who were provided with feedback (*Correct* or *Incorrect* was presented after each trial) showed effects of learning on saccadic behavior, whereas participants without this feedback did not. The authors concluded that feedback can be a reward signal for saccadic behavior, leading the participant to use saccadic behavior that optimizes the reward. In the current study, we examine the effects of probability information on the ability to learn to use the optimal attention allocation with and without reward.

The Current Study

The purpose of this study was to determine whether probability information in a change detection task can be incidentally learned and used to optimize the allocation of attention (global or local) during encoding. Specifically, the change detection task was designed such that the probable-change information could be more readily detected with a particular type of attention allocation. Therefore, improving change detection for the probable-change information (i.e., a change probability effect) required the use of the allocation of attention during encoding that was optimal for the probable type of change.

Participants were tasked with detecting a change in the orientation of one of six Gabor patches: three HSF patches and three LSF patches. These Gabor patches were presented at a distance from the center where the orientation of multiple LSF patches could be perceived with a global spread of attention (fixating in the center of the array of patches rather than directly on each patch); in contrast, the orientation of the HSF patches could be perceived only by using a local attention allocation (fixating directly on the patches one at a time). For each participant, one type of patch was more likely to change than the other. For example, if HSF patches were the probable-change type, then one of the HSF patches changed orientation on 75% of the trials, whereas one of the LSF patches changed orientation on 25% of the trials. It is important to note that participants were explicitly instructed to detect a change to any one of the six patches and thus were give no direct instruction concerning the change probability manipulation. Therefore, any evidence of a change probability effect would be due to incidental learning.

In these experiments, we aimed to create a task for which only one type of attention allocation was effective for detecting the probable change. Therefore, on each trial, selection of the change patch was fixation-contingent, such that detecting LSF changes required a global spread of attention and detecting HSF change required a local spread of attention. On HSF change trials, the change was made to an HSF patch that *was* fixated during encoding of the study array. On LSF change trials, the change was made to an LSF patch that *was not* fixated during encoding of the study array. As discussed previously, encoding of HSF information can occur for only fixated items, whereas only LSF information can be encoded for nonfixated items. The fixation-contingent selection of the changing patch created a contingency between the allocation of attention during encoding and the patch that changed.

To increase the link between the probable change and the correct attention allocation, we included no-change trials so that successful change detection for the probable change was possible only when the correct attention allocation was used. Specifically, when the correct attention allocation was not used, no patches changed. Participants were unaware that no-change trials were possible and were still required to choose a changed patch location on the response screen, thereby being forced to guess. A no-change trial would occur if one of the following conditions were met during encoding: (a) the trial was designated to be an HSF change trial in the HSF-probable condition, but none of HSF patches were fixated, and (b) the trial was designated to be an LSF change trials in the LSF-probable conditions but all of the LSF patches were fixated. Therefore, the response would always be incorrect on probable-change trials when the correct attention allocation was not used, and successful change detection would be possible only when the correct attention allocation was employed during encoding. If participants were unable to learn the correct attention allocation for the probable-change type, then no-change trials should be frequent. However, if they could learn the correct attention allocation, the number of no-change trials should be low.

If participants could learn which type of Gabor patch was most likely to change and to apply the most effective attention allocation for that type of information, then change detection performance should be higher for the probable change (i.e., a change probability effect). Furthermore, if a change in the allocation of attention during encoding were associated with the change probability effect, then participants should (a) spend more time fixating on the Gabor patches in the HSF-probable condition (local spread of attention) and spend less time fixating directly on the Gabor patches in the LSF-probable condition (global spread of attention) and (b) fixate HSF patches more than LSF patches in the HSF-probable condition and rarely fixate either type of patch in the LSF-probable condition.

Experiment 1

Method

Participants. Data were collected from 23 participants. Data from two participants were excluded due to a failure to complete the experiment, and data from one participant were excluded due to below-chance performance (.16). Therefore, data from 20 participants were included in the experiment. Ten participants were randomly assigned to the HSF-probable condition, and 10 were assigned to the LSF-probable condition. The average age for these participants was 20 (one participant did not report age), and there were 16 female participants.

Apparatus and stimuli. Experiment Builder (SR Research, Canada) presented stimuli and recorded key presses while an EyeLink II eye tracker (SR Research) recorded eye movements (sampling rate of 500 Hz). Samples were analyzed to determine when velocity was above 30 deg/s, and this triggered the end of a fixation and the beginning of a saccade. When velocity was below this threshold, the saccade ended and a fixation began. Participants viewed a monitor with a 1,024 × 768 resolution binocularly, with eye movements recorded from the eye chosen by the eye tracker based on a 9-point calibration. Head movements were stabilized with a chin rest positioned 57 cm from the monitor.

Arrays of six Gabor patches were created by selecting from high (7.5 cycles per degree of visual angle) and low (1.25 cycles per degree of visual angle) spatial frequency Gabor patches (2.5° visual angle each) oriented 45° to the left or to the right (left or right diagonal). All arrays contained three HSF patches and three LSF patches alternating in the six equally spaced locations around the center of the display (the center of each Gabor patch was 10.5 cm from the center of the screen and measured 2 cm on the screen). The Gabor patches were presented on a gray background (Red, Green, Blue [RGB] = 127, 127, 127). The orientation of each Gabor patch (45° left or right) was randomly determined. The test arrays were the same as the study arrays except on the change trials, in which one patch changed orientation. The response screen consisted of six circles placed in the same spatial locations as the Gabor patches that appeared in the study and test arrays (see Figure 1).

Procedure. Informed consent was provided by the participants prior to starting the experiment. Written instructions and a pictorial representation of a sample trial were displayed onscreen

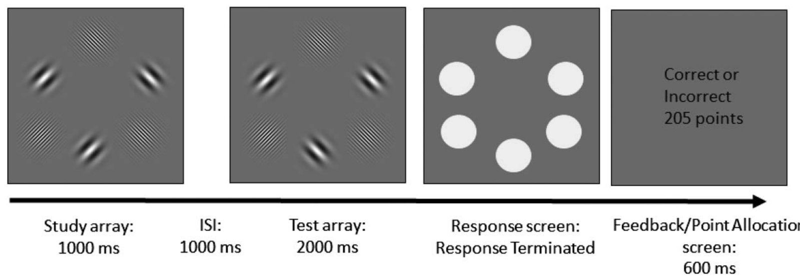

Figure 1. Stimuli and sequence of events in the change detection task. There are six Gabor patches in the arrays: three high spatial frequency and three low spatial frequency. The size and spatial frequency of the Gabor patches have been modified to make the patches visible in the figure. In Experiment 3, the *feedback/point allocation* screen was not present. In Experiment 2, the number of points earned was not presented on the feedback screen. The text is not drawn to scale, and on the *feedback* screen, *Correct* was presented in green font and *Incorrect* was presented in red font. ISI = interstimulus interval.

while the instructions were read aloud. Instructions were followed by eye tracker calibration. Following eye tracker setup, participants completed six practice trials: two trials with three HSF Gabor patches, two trials with three LSF Gabor patches, and two trials with all six Gabor patches (three HSF and three LSF). Feedback (*Correct* or *Incorrect*) followed all practice trials. Participants then completed three blocks of 40 change detection trials.

Each trial started with a central fixation drift correct screen, followed by the study array for 1,000 ms. After a 1,000-ms interstimulus interval, the test array was presented for 2,000 ms. Immediately following the test array, the response screen was presented until a response was given. To respond, participants clicked on the circle that marked the location of the changed patch. Participants were required to click on a location even if they were not sure which patch changed.

Participants were randomly assigned to either the HSF-probable or LSF-probable condition. In the HSF-probable condition, an HSF patch changed orientation on 75% of the trials (i.e., 30 of the 40 trials in each block). On the remaining 25% of trials, an LSF patch changed orientation. In the LSF-probable condition, an LSF patch changed orientation on 75% of the trials, whereas an HSF patch changed on the remaining 25% of trials. Participants were not informed of the change probability information.

The Gabor patch chosen to change on each trial was contingent on the participants' fixations on the study array. On the HFS change trials, in the HSF-probable condition, the change patch was randomly chosen from the HSF patches that were fixated during encoding. If no HSF patches were fixated on an HSF change trial, the trial was forced to a no-change trial. On the LSF change trials in the HFS-probable condition, the patch was randomly chosen from the patches that had not been fixated during encoding. If all the LSF patches were fixated, a patch was randomly chosen from all three LSF patches.

On the LSF trials in the LSF-probable condition, when an LSF patch changed, the patch was randomly chosen from the LSF patches that had not been fixated during encoding. If all LSF patches were fixated on LSF change trials in the LSF-probable condition, the trial was forced to a no-change trial. On the HSF change trials in the LSF-probable condition, the patch was randomly chosen from the patches that had been fixated. If no HSF patches were fixated, a patch was randomly chosen from all three HSF patches.

No-change trials were forced on probable-change trials when the correct attention allocation was not used. For these forced no-change trials, participants were still presented with the response screen and had to choose one location as the change location. Therefore, these trials always resulted in *Incorrect* being presented on the feedback screen, and the trial was repeated at the end of the block. Each block continued until there were 30 probable-change trials with the correct attention allocation. Participants were not informed of the possibility of no-change trials.

Feedback and point allocations were presented on the screen for 600 ms following the response screen. For the feedback, *Correct* (in green font) or *Incorrect* (in red font) was presented. For the point allocation, the number of points earned for the trial and the total number of points earned were presented. A correct response for the probable change earned a participant 5 points, and a correct response for the improbable change earned 1 point. Incorrect responses (including all no-change trials) earned 0 points. The maximum number of possible points earned was 480.

At the end of the experiment, participants were asked to answer several questions regarding their awareness of the probability manipulation and the strategies they used to complete the change detection task. Questions started open-ended and became more specific as the questionnaire progressed. The first question asked participants to describe any strategies they may have used to detect the change. After describing their strategies, participants were asked two questions in which they chose the description that best described their strategy. The first of these two questions asked participants to choose which of two options best described their strategy: (a) looked at the items or (b) looked between the items. The second asked them to choose which of three options best described their strategy: (a) trying to remember only the items with thick lines, (b) trying to remember only the items with skinny lines, or (c) trying to remember both. Participants then chose whether they thought HSF or LSF patches changed more than the other. They were then presented with a number line representing the possible ratios of LSF to HSF changes. Using the mouse, they clicked on the ratio that they thought best represented the proportion of LSF changes to HSF changes (e.g., 80/20 would mean that LSF patches changed on 80% of the trials and HSF patches changed on 20% of the trials).

Results

Overall, the data indicate the presence of a change probability effect in both change detection performance and attention allocation. Specifically, participants performed better on the probable trials than the improbable trials and were more likely to fixate on objects during encoding in the HSF-probable condition than in the LSF-probable condition. Across all analyses in all experiments, Greenhouse-Geisser corrections were used when there was a violation of sphericity.

The change probability effect. The change probability effect was evident, because participants performed better on the probable-change trials than the improbable-change trials in both probability conditions (see Figure 2). The proportion of correct trials in the HSF-probable and LSF-probable conditions (probability condition) for high and low spatial frequency changes (change type) during blocks (1, 2, and 3) was submitted to a 2 × 2 × 3 mixed-design analysis of variance (ANOVA). Probability condition was treated as a between-subjects variable, and change type and block were treated as within-subject variables. There was a significant interaction between change type and probability condition, $F(1, 18) = 51.5$, $p < .001$, $\eta^2 = .74$, and a significant three-way interaction, $F(2, 36) = 15.93$, $p < .001$, $\eta^2 = .47$. None of the main effects were significant: change type, $F(1, 18) = .528$, $p = .48$, $\eta^2 = .03$; probability condition, $F(1, 18) = 2.6$, $p = .62$, $\eta^2 = .01$; block, $F(2, 36) = 3.4$, $p = .08$, $\eta^2 = .16$. The interaction between change type and block was not significant ($p = .70$).

One-way ANOVAs for each type of change in each condition revealed that in the LSF-probable condition, accuracy increased across blocks for the LSF changes, $F(2, 18) = 18.55$, $p < .001$, $\eta^2 = .67$, but not for the HSF changes, $F(2, 18) = .17$, $p = .85$, $\eta^2 = .02$. In the HSF-probable condition, accuracy decreased across blocks for the LSF changes, $F(2, 18) = 3.8$, $p = .04$, $\eta^2 = .30$, and increased across blocks for the HSF changes, $F(2, 18) = 7.04$, $p = .006$, $\eta^2 = .44$.

Attention allocation during encoding. Changes in attention strategy were revealed in both the number of no-change trials,

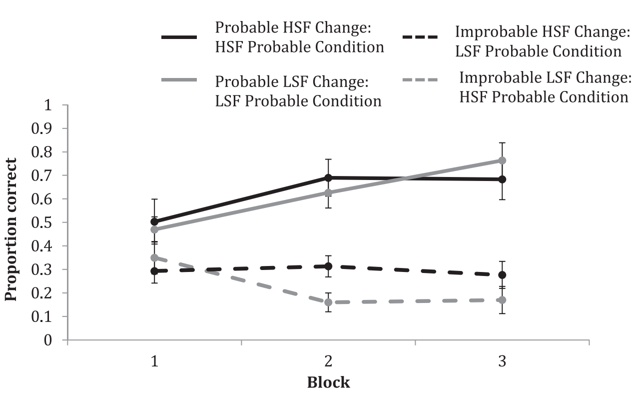

Figure 2. Accuracy (proportion correct) on the change detection task in Experiment 1 for both high spatial frequency (HSF) and low spatial frequency (LSF) change types in each condition. Solid lines represent the probable changes, and dotted lines represent the improbable changes. Improbable LSF change and probable HSF change data points are for participants in the HSF-probable condition, and the probable LSF and improbable HSF data points are for participants in the LSF-probable condition. Error bars represent standard error of the mean.

which decreased over time, and eye movement data, which revealed more time spent fixating on objects in the HSF-probable condition than the LSF-probable condition.

No-change trials. First, the number of no-change trials in each block was examined as a measure of participants' ability to learn to use the appropriate attention allocation. The logic behind this measure is that the appropriate attention allocation was not used if a no-change trial occurred. Therefore, decreases in the number of no-change trials across blocks would reflect learning of the appropriate attention strategy.

The number of no-change trials did decline across blocks, demonstrating that participants learned to use the correct attention allocation in each probability condition (see Figure 3A). The number of no-change trials per block was submitted to a 3 × 2 mixed-design ANOVA with block (1, 2, 3) as a within-subject variable and probability condition (HSF-probable, LSF-probable) as a between-subjects variable. There were significant main effects of block, $F(1.15, 20.73) = 4.54$, $p = .017$, $\eta^2 = .20$, and probability condition, $F(1, 18) = 8.12$, $p = .01$, $\eta^2 = .31$. The interaction between block and condition was not significant, $F(1.15, 20.73) = .35$, $p = .59$, $\eta^2 = .02$. The probability effect was caused by more no-change trials in the LSF condition than in the HSF condition.

Eye movements. To examine the degree to which attention was allocated locally (on individual Gabor patches) versus globally (not on patches), we first measured the total amount of time spent fixating patches during presentation of the study array and then the number of each type of patch fixated (see Figure 3). Fixations were classified as being on a patch if they occurred within an 8-cm circle centered on each Gabor patch. Eye movement data revealed adoption of the appropriate attention allocation: Participants spent more time looking at patches in the HSF condition than in the LSF condition and also were more likely to look at the probable-change objects (see Figure 3B).

First, participants spent more time looking at patches overall in the HSF condition than the LSF condition. A 3 (block) × 2 (probability condition) mixed-design ANOVA revealed an interaction between block and probability condition, $F(1.14, 20.52) = 8.25$, $p = .007$, $\eta^2 = .31$, and significant main effects of block, $F(1.14, 20.52) = 5.85$, $p = .022$, $\eta^2 = .25$, and probability condition, $F(1, 18) = 13.83$, $p = .002$, $\eta^2 = .43$. The amount of time spent looking at patches decreased across blocks in the LSF condition, $F(1.11, 10.02) = 7.25$, $p = .021$, $\eta^2 = .45$, and remained unchanged in the HSF condition, $F(2, 18) = 2.33$, $p = .13$, $\eta^2 = .21$. More time was spent on patches in the HSF-probable condition than in the LSF-probable condition for all three blocks (all ps $< .009$). Therefore, participants were more likely to adopt a global-attention strategy in the LSF condition and a local-attention strategy in the HSF condition.

In addition to the amount of time spent fixating on patches, analysis of the number and type of patches fixated (change trials only) revealed probability-contingent changes in attention allocation. Participants looked at more of the probable-change patch type and looked at more patches overall in the HSF-probable condition than in the LSF-probable condition (see Figure 3C). A 3 (block) × 2 (patch type) × 2 (probability condition) mixed-design ANOVA revealed an interaction between probability condition and patch type, $F(1, 18) = 20.1$, $p < .001$, $\eta^2 = .53$. Specifically, HSF patches were fixated more in the HSF-probable condition, whereas

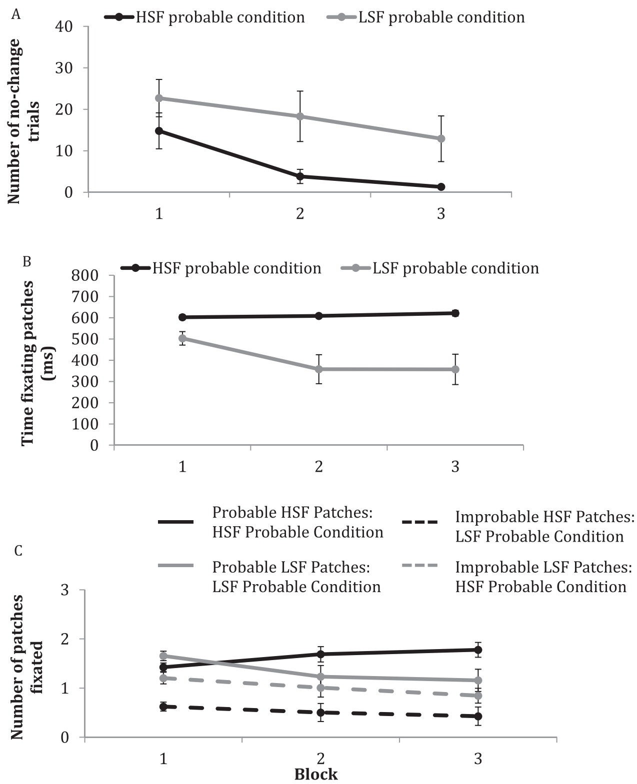

Figure 3. Attention allocation measures for high spatial frequency (HSF) and low spatial frequency (LSF) conditions in Experiment 1. Panel A: Number of no-change trials. Panel B: Average time spent fixating patches on each trial. Panel C: Number of patches fixated. Error bars represent standard error of the mean.

LSF patches were fixated more in the LSF condition. Furthermore, there was a main effect of probability condition, $F(1, 18) = 12.47$, $p = .002$, $\eta^2 = .41$, due to more patches being fixated in the HSF-probable condition than in the LSF-probable condition (mirroring the analysis of time spent fixating on objects). There was a main effect of block, $F(1.29, 23.22) = 4.62$, $p = .02$, $\eta^2 = .20$, and an interaction between block and probability condition, $F(2, 36) = 5.16$, $p = .01$, $\eta^2 = .23$. There was also an interaction between block and patch type, $F(1.17, 21.13) = 4.66$, $p = .04$, $\eta^2 = .21$, due to the number of fixated LSF patches, but not HSF patches, declining across blocks. There was no three-way interaction, $F(2, 36) = .72$, $p = .49$, $\eta^2 = .04$, and no main effect of patch type, $F(1, 18) = .46$, $p = .51$, $\eta^2 = .03$.

To further examine the interaction between block and probability condition, we conducted one-way repeated-measures ANOVAs, which revealed that in the LSF-probable condition, the number of LSF patches fixated did not change across blocks for the LSF patches, $F(1.2, 10.74) = 3.5$, $p = .08$, $\eta^2 = .28$, or for the HSF patches, $F(1.12, 10.1) = 1.27$, $p = .31$, $\eta^2 = .12$. In the HSF-probable condition, the number of LSF patches fixated declined across blocks, $F(2, 18) = 3.57$, $p = .05$, $\eta^2 = .28$, and the number of HSF patches fixated increased across blocks, $F(1.15, 10.33) = 5.25$, $p = .04$, $\eta^2 = .37$.

Awareness. Although the purpose of this study was to determine incidental, rather than implicit, learning, we were interested in the degree to which explicit awareness of the probability information arose over the course of the experiment. To this end, we measured both participant awareness of the probability information itself and their awareness of their own attention allocation strategies. Overall, participants were more likely to be aware of the probability information in the HSF than the LSF condition, and a number of participants expressed awareness of their own attention strategies.

Overall, 65% of participants had awareness of the change probability information. In the HSF-probable condition, 80% of participants responded that one type of patch changed more frequently than did the other and then correctly chose the HSF patch as the object type that changed more frequently. In the LSF-probable condition, 50% of participants responded that one type of patch changed more frequently than did the other and then correctly chose the LSF patch as the object type that changed more frequently. The number of participants aware was not significantly different between the conditions ($p = .2$, Fisher's exact test). The aware participants, on average, were fairly accurate in estimating the number of trials for which the probable changes occurred (HSF-probable condition: $M = 80\%$, $SD = 7.56$, and LSF-probable condition: $M = 70\%$, $SD = 0$).

Participants also reported awareness of using the optimal attention strategy. One of the questions asked participants to indicate whether they looked *at* patches or *between* patches. In the HSF-probable condition, 60% of participants indicated that they looked at patches, and in the LSF-probable condition, 80% indicated that they looked between patches. Another question asked participants to indicate whether they tried to remember the LSF patches, HSF patches, or both. In the HSF-probable condition, 70% of participants indicated that they tried to remember the HSF patches, and in the LSF-probable condition, 70% indicated that they tried to remember the LSF patches.

Discussion

In Experiment 1 there was evidence of a change probability effect accompanied by a shift in attention allocation during encoding that was most beneficial for detecting the probable-change type. Specifically, accuracy increased for the more-probable-change type, and participants adopted global attention strategies in the LSF-probable condition and local attention strategies in the HSF-probable condition. Therefore, probability information was used to determine the most effective allocation of attention for encoding the stimuli. In Experiments 2 and 3, we aimed to replicate these effects and to determine whether reward was necessary for the effects.

In some of the research demonstrating a role for reward in learning optimal attention allocation, the reward was delivered through feedback on trial performance (e.g., Droll et al., 2009), and in others it was delivered through a point system similar to the that used in Experiment 1 (Shomstein & Johnson, 2013). In the absence of explicit feedback or point allocations based on performance, the participant must rely on self-monitoring of performance to optimize the behaviors that lead to success. However, change detection can occur implicitly (Fernandez-Duque & Thornton, 2003; Laloyaux, Destrebecqz, & Cleeremans, 2006), and so explicit feedback may be necessary for learning probability information for optimizing the allocation of attention.

Experiments 2 and 3

To examine whether the change probability and the attention allocation effects require reward or whether they can occur with only a self-monitoring system that receives no external feedback, in Experiment 2 we removed the point allocation from the design, and in Experiment 3 we provided neither feedback nor points. Experiments 2 and 3 were identical to Experiment 1 in all other respects.

Method

Participants. In Experiment 2, data were collected from 21 participants, but data from one participant were excluded due to chance-level performance. Therefore, data from 20 participants were included in the experiment. Ten participants were randomly assigned to the HSF-probable condition, and 10 were assigned to the LSF-probable condition. The average age for these participants was 20, and 18 were female.

In Experiment 3, data were collected from 21 participants, but data from one participant were excluded due to a failure to complete the experiment. Therefore, data from 20 participants were included in the experiment. Ten participants were randomly assigned to the HSF-probable condition, and 10 were assigned to the LSF-probable condition. The average age for these participants was 20, and 13 were female.

Procedure. The stimuli and procedure for Experiment 2 were the same as in Experiment 1 except that a reward was not presented on the feedback screen. The stimuli and procedure for Experiment 3 were the same as in Experiment 2 except that feedback was not presented.

Results: Experiment 2 (Feedback but No Point Allocation)

The change probability effect. As in Experiment 1, there was a change probability effect (see Figure 4), because participants performed better on probable trials than improbable trials. Specifically, a 2 (change type) × 2 (probability condition) × 3 (block) mixed-design ANOVA revealed a significant interaction between change type and probability condition, $F(1, 18) = 36.1$, $p < .001$, $\eta^2 = .67$, and a significant three-way interaction, $F(2, 36) = 19.19$, $p < .001$, $\eta^2 = .52$. The main effects of change type, $F(1, 18) = 1.95$, $p = .18$, $\eta^2 = .098$, and probability condition, $F(1, 18) = 2.19$, $p = .16$, $\eta^2 = .11$, were not significant. There was a significant main effect of block, $F(2, 36) = 5.67$, $p = .007$, $\eta^2 = .24$. The two-way interaction between change type and block was not significant ($p = .48$).

One-way repeated-measures ANOVAs revealed that in the LSF-probable condition, accuracy increased across blocks for the LSF changes, $F(2, 18) = 14.34$, $p < .001$, $\eta^2 = .62$, but not for the HSF changes, $F(2, 18) = .42$, $p = .67$, $\eta^2 = .04$. In the HSF-probable condition, accuracy did not change across blocks for the LSF changes, $F(2, 18) = 3.28$, $p = .06$, $\eta^2 = .27$, and increased across blocks for the HSF changes, $F(2, 18) = 5.75$, $p = .012$, $\eta^2 = .39$.

Attention allocation during encoding. The eye movement data revealed changes in attention allocation as a function of probability condition, because participants adopted a more global strategy in the LSF and local strategy in the HSF trials.

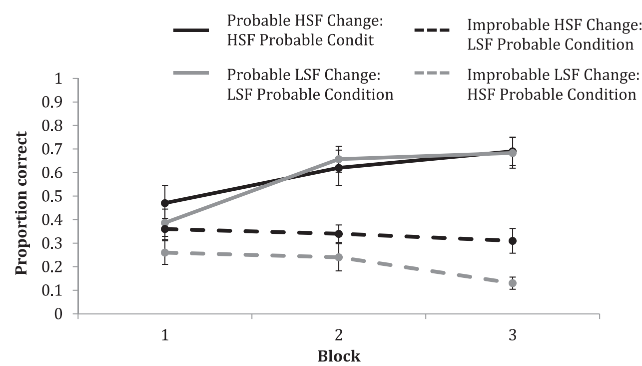

Figure 4. Accuracy (proportion correct) on the change detection task in Experiment 2 for both high spatial frequency (HSF) and low spatial frequency (LSF) change types in each condition. Solid lines represent the probable changes, and dotted lines represent the improbable changes. Improbable LSF change and probable HSF change data points are for participants in the HSF-probable condition, and the probable LSF and improbable HSF data points are for participants in the LSF-probable condition. Error bars represent standard error of the mean.

No-change trials. There was no difference in the number of no-change trials as a result of probability condition or block in Experiment 2 (see Figure 5A)[1]. Specifically, a 3 (block) × 2 (probability condition) mixed-design ANOVA of the number of no-change trials revealed no main effects of block, $F(1.91, 21.45) = .96$, $p = .39$, $\eta^2 = .05$, or probability condition, $F(1, 18) = .04$, $p = .85$, $\eta^2 = .002$. The interaction between block and condition was not significant, $F(1.91, 21.45) = 2.44$, $p = .13$, $\eta^2 = .12$.

Eye movements. Both time spent looking at patches and number and type of patches fixated revealed changes in attention allocation as a function of change probability. First, in Blocks 2 and 3, participants spent more time looking at patches in the HSF-probable condition than in the LSF-probable condition. A 3 (block) × 2 (probability condition) mixed-design ANOVA of total time spent fixating patches during change trials revealed an interaction between block and probability condition, $F(1.19, 21.33) = 4.12$, $p = .049$, $\eta^2 = .19$. The main effect of block was not significant, $F(1.19, 21.33) = .86$, $p = .38$, $\eta^2 = .05$, and the main effect of probability condition was marginal, $F(1, 18) = 4.39$, $p = .05$, $\eta^2 = .43$. This was because the change in attention allocation occurred during the later blocks only: More time was spent on patches in the HSF-probable condition than in the LSF-probable condition for Blocks 2 and 3 (all $ps < .046$) but not in Block 1 ($p = .86$).

Furthermore, the amount of time spent looking at patches remained unchanged across blocks in the LSF-probable condition, $F(1.18, 10.58) = 2.28$, $p = .16$, $\eta^2 = .20$, and increased in the HSF-probable condition, $F(1.22, 10.84) = 6.64$, $p = .02$, $\eta^2 = .43$.

[1] One participant had 150 no-change trials in Block 1, but had zero in Block 2 and only one in Block 3. When this participant was excluded, the number of no-change trials in Block 1 of the HSF-probable condition ranges from five to 34, with a mean of 12.33. This outlier resulted in a high level of variability for the HSF-probable condition in Block 1, as can be seen in Figure 5A. However, both main effects and the interaction remain nonsignificant when the participant's data were removed from the no-change analysis.

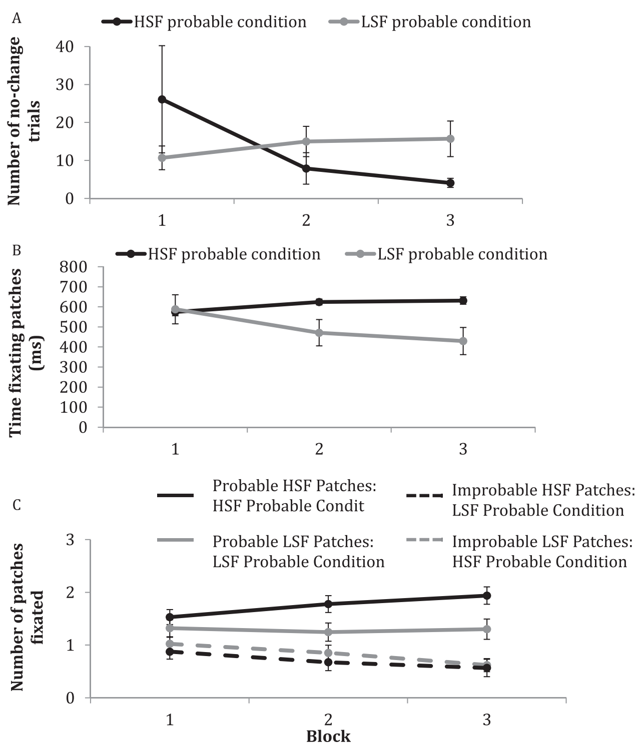

Figure 5. Attention allocation measures for the high spatial frequency (HSF) and low spatial frequency (LSF) conditions in Experiment 2. Panel A: Number of no-change trials. Panel B: Average time spent fixating patches on each trial. Panel C: Number of patches fixated. Error bars represent standard error of the mean.

Analysis of the number and type of patches fixated also revealed probability-dependent changes in attention allocation. More HSF patches were fixated in the HSF-probable condition, indicating a change in the allocation of attention allocation due to probability information (see Figure 5C). A 3 (block) × 2 (patch type) × 2 (probability condition) mixed-design ANOVA of the number of patches fixated during the study array on change trials revealed an interaction between probability condition and patch type, $F(1, 18) = 40.67$, $p < .001$, $\eta^2 = .69$; a three-way interaction, $F(2, 36) = 5.98$, $p = .006$, $\eta^2 = .25$; and a main effect of probability condition, $F(1, 18) = 5.52$, $p = .03$, $\eta^2 = .24$. There was no main effect of block, $F(2, 36) = 1$, $p = .37$, $\eta^2 = .05$; no interaction between block and probability condition, $F(2, 36) = 1.5$, $p = .24$, $\eta^2 = .08$; and no interaction between block and patch type, $F(2, 36) = 1.36$, $p = .27$, $\eta^2 = .07$. There was also no main effect of patch type, $F(1, 18) = 2.02$, $p = .17$, $\eta^2 = .10$.

One-way repeated-measures ANOVAs revealed that in the LSF-probable condition, the number of LSF patches fixated did not change across blocks, $F(2, 18) = .07$, $p = .93$, $\eta^2 = .01$, and declined across blocks for the HSF patches, $F(2, 18) = 4.11$, $p < .03$, $\eta^2 = .31$. In the HSF-probable condition, the number of LSF patches fixated declined across blocks, $F(2, 18) = 6.75$, $p = .006$, $\eta^2 = .43$, and increased across blocks for the HSF patches, $F(2, 18) = 7.95$, $p = .003$, $\eta^2 = .47$.

Awareness. As in Experiment 1, a number of participants expressed awareness of both the probability information and their own attention strategies.

Overall, 60% of participants had awareness of the change probability information. In the HSF-probable condition, 80% of participants responded that one type of patch changed more frequently than did the other and then correctly chose the HSF patch as the object type that changed more frequently. In the LSF-probable condition, 40% of participants responded that one type of patch changed more frequently than did the other and then correctly chose the LSF patch as the object type that changed more frequently. The number of participants aware was not significantly different between the conditions ($p = .09$, Fisher's exact test). The aware participants, on average, were fairly accurate in estimating the number of trials for which the probable changes occurred (HSF-probable condition: $M = 72.5\%$, $SD = 7.07$, and LSF-probable condition: $M = 67.5\%$, $SD = 5$).

Participants also reported awareness of using the optimal attention strategy. In the HSF-probable condition, 44.4% of participants (data on this question were missing for one participant) indicated that they looked *at* patches, and in the LSF-probable condition, 70% indicated that they looked *between* patches. Another question asked participants to indicate whether they tried to remember the LSF patches, HSF patches, or both. In the HSF-probable condition, 77.8% of participants (data on this question were missing for one participant) indicated that they tried to remember the HSF patches, and in the LSF-probable condition, 90% indicated that they tried to remember the LSF patches.

Results: Experiment 3 (No Feedback and No Point Allocation)

The change probability effect. Once again, the change probability effect was present, because accuracy increased across blocks for the probable-change type (see Figure 6). A 2 (change type) × 2 (probability condition) × 3 (block) mixed-design ANOVA revealed a significant interaction between change type and probability condition, $F(1, 18) = 26.34$, $p < .001$, $\eta^2 = .59$, and a significant three-way interaction, $F(2, 36) = 8.34$, $p = .001$, $\eta^2 = .32$. None of the main effects were significant: change type,

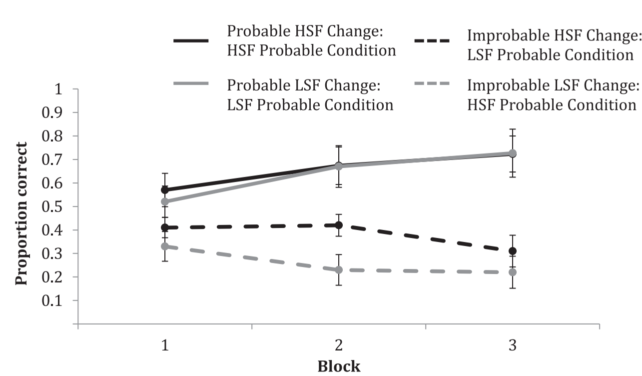

Figure 6. Accuracy (proportion correct) on the change detection task in Experiment 3 for both high spatial frequency (HSF) and low spatial frequency (LSF) change types in each condition. Solid lines represent the probable changes, and dotted lines represent the improbable changes. Improbable LSF change and probable HSF change data points are for participants in the HSF-probable condition, and the probable LSF and improbable HSF data points are for participants in the LSF-probable condition. Error bars represent standard error of the mean.

$F(1, 18) = .38$, $p = .454$ $\eta^2 = .02$; probability condition, $F(1, 18) = 1.19$, $p = .29$, $\eta^2 = .06$; block, $F(2, 36) = 1.45$, $p = .25$, $\eta^2 = .08$. The two-way interaction between change type and block was not significant ($p = .67$).

To follow up on the interaction between change type and probability condition, we conducted one-way repeated-measures ANOVAs, which revealed that in the LSF-probable condition, accuracy increased across blocks for the LSF changes, $F(2, 18) = 10.57$, $p = .007$, $\eta^2 = .54$, but not for the HSF changes, $F(2, 18) = 1.93$, $p = .18$, $\eta^2 = .18$. In the HSF-probable condition, accuracy did not change across blocks for the LSF changes, $F(2, 18) = .745$, $p = .49$, $\eta^2 = .08$, and increased across blocks for the HSF changes, $F(2, 18) = 6.35$, $p = .008$, $\eta^2 = .41$.

Attention allocation during encoding. Probability-dependent changes in attention allocation were found again in Experiment 3, because eye movement data revealed that participants used a more global allocation of attention in the LSF-probable condition and a more local spread of attention in the HSF-probable condition.

No-change trials. The number of no-change trials did not decline across blocks (see Figure 7A). A 3 (block) × 2 (probability condition) mixed-design ANOVA on the number of no-change trials revealed no significant main effects of block, $F(2, 36) = 2.16$, $p = .13$, $\eta^2 = .11$, or probability condition, $F(1, 18) = 1.61$, $p = .22$, $\eta^2 = .08$. The interaction between block and condition was not significant, $F(2, 36) = 1.22$, $p = .31$, $\eta^2 = .06$.

Eye movements. The amount of time spent fixating patches was sensitive to probability: Participants spent more time looking at patches in the LSF condition and more time off patches in the HSF condition. This was revealed by a 3 (block) × 2 (probability condition) mixed-design ANOVA of total time spent fixating on patches. There was an interaction between block and probability condition, $F(2, 36) = 10.6$, $p < .001$, $\eta^2 = .37$, and significant main effects of block, $F(2, 36) = 3.57$, $p = .04$ $\eta^2 = .17$, and probability condition, $F(1, 18) = 20.54$, $p < .001$, $\eta^2 = .53$. The amount of time spent fixating on patches decreased across blocks in the LSF-probable condition, $F(2, 18) = 7.51$, $p = .1004$ $\eta^2 = .46$, and increased in the HSF-probable condition, $F(2, 18) = 4.07$, $p = .035$, $\eta^2 = .31$. More time was spent fixating on patches in the HSF-probable condition than in the LSF-probable condition for all blocks (all $ps < .04$).

The number of patches fixated was also sensitive to probability: More patches were fixated in the HSF than LSF condition; furthermore, in the HSF-probable condition, more HSF patches were fixated than were LSF patches. The number of patches fixated during the study array was submitted to a 3 (block) × 2 (patch type) × 2 (probability condition) mixed-design ANOVA. The interaction between probability condition and patch type was significant, $F(1, 18) = 31.65$, $p < .001$, $\eta^2 = .64$, and there was a significant three-way interaction, $F(2, 36) = 7.43$, $p = .002$, $\eta^2 = .29$. There was also a main effect of block, $F(1.53, 27.56) = 6.72$, $p = .003$, $\eta^2 = .2$, and a significant interaction between block and probability condition, $F(2, 36) = 4.57$, $p = .02$, $\eta^2 = .20$. The interaction between block and patch type was not significant, $F(1.34, 24.2) = 1.36$, $p = .054$, $\eta^2 = .17$. Furthermore, there was a main effect of probability condition, $F(1, 18) = 10.77$, $p = .004$, $\eta^2 = .37$, due to more patches being fixated in the HSF-probable condition than in the LSF-probable condition. There was no main effect of patch type, $F(1, 18) = .06$, $p = .81$, $\eta^2 = .003$.

One-way repeated-measures ANOVAs revealed that in the LSF-probable condition, the number of LSF patches fixated did not change across blocks for LSF patches, $F(2, 18) = 1.34$, $p = .29$, $\eta^2 = .13$, and declined across blocks for the HSF patches, $F(1.13, 10.13) = 14.77$, $p < .001$, $\eta^2 = .62$. In the HSF-probable condition, the number of LSF patches fixated declined across blocks, $F(2, 18) = 11.54$, $p = .001$, $\eta^2 = .56$, and increased across blocks for the HSF patches, $F(1.2, 11) = 5.86$, $p = .03$, $\eta^2 = .40$.

Awareness. As in Experiments 1 and 2, participants were generally aware of both the probability information and their own attention strategies.

Overall, 80% of participants had awareness of the change probability information. In the HSF-probable condition, 100% of participants responded that one type of patch changed more frequently than did the other and then correctly chose the HSF patch as the patch type that changed more frequently. In the LSF-probable condition, 60% of participants responded that one type of patch changed more frequently than did the other and then correctly chose the LSF patch as the patch type that changed more frequently. The number of participants aware was not significantly different between the conditions ($p = .04$, Fisher's exact test). The aware participants, on average, were fairly accurate in estimating the number of trials for which the probable changes occurred (HSF-probable condition: $M = 74\%$, $SD = 9.66$, and LSF-probable condition: $M = 70\%$, $SD = 10.95$).

Participants also reported awareness of using the optimal attention strategy. In the HSF-probable condition, 77.8% of participants (data on this question were missing for one participant) indicated

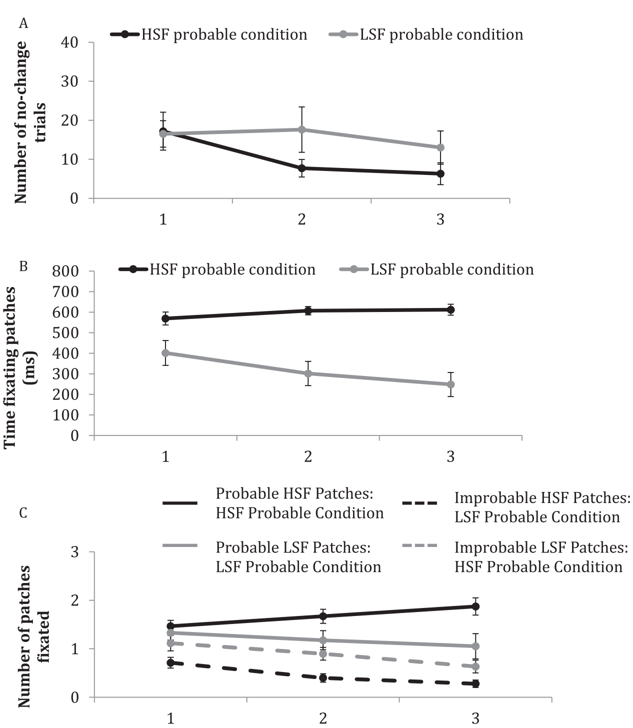

Figure 7. Attention allocation measures for the high spatial frequency (HSF) and low spatial frequency (LSF) conditions in Experiment 3. Panel A: Number of no-change trials. Panel B: Average time spent fixating patches on each trial. Panel C: Number of patches fixated. Error bars represent standard error of the mean.

that they looked *at* patches, and in the LSF-probable condition, 60% indicated that they looked *between* patches. In the HSF-probable condition, 77.8% of participants (data on this question were missing for one participant) indicated that they tried to remember the HSF patches, and in the LSF-probable condition, 100% indicated that they tried to remember the LSF patches.

Discussion

Experiments 2 and 3 replicated Experiment 1 by providing evidence of a change probability effect accompanied by use of the most beneficial attention allocation during encoding. Participants spent more time looking at patches in the HSF-probable condition than in the LSF-probable condition. Furthermore, the number of HSF patches fixated in the HSF-probable condition increased across blocks, whereas the number of LSF patches fixated in the LSF-probable condition did not change across blocks. Therefore, probability information was used to determine the most effective allocation of attention for encoding the stimuli. In addition, the robust change probability effect and attentional allocation effect were sustained even when there was no reward and no feedback. This indicates that a self-monitoring system without any explicit feedback is sufficient for the effects. This self-monitoring system relied on the probability information and the saccade contingent change manipulations for determining the optimal attention allocation.

General Discussion

Across three experiments, participants improved their change detection performance for high or low spatial frequency Gabor patches dependent upon which patch type was more likely to change orientation. These results provide evidence supporting the change probability effect for object categories defined by spatial frequency. Critically, the change probability effect was accompanied by a change in the allocation of attention during encoding. Therefore, incidentally learned probability information can be used to facilitate the use of either a local or global spread of attention, depending on which level is more effective for detecting a probable-change type. This study is the first to demonstrate the use of an optimal spread of attention, based on statistical learning within a change detection task.

Probability Information and Attention

This study expands upon the previous understanding of the use of probability information in directing attention in two ways. First, it demonstrates that the *spread* of attention can be changed via learning, whereas previous research has focused primarily on how learning affects the *location* of attention. For example, participants can learn the likely location of a target based on a repeated context in a visual search task to improve their ability to locate the target (contextual cueing; Chun & Jiang, 1998; Chun & Nakayama, 2000). In addition, targets in probable locations are found more quickly than are targets in improbable locations (probability cueing; Druker & Anderson, 2010; Geng & Behrmann, 2002; Miller, 1988). As in the current study, eye movement data have supported the conclusion that learning affects the direction of attention: There is a tendency to move the eyes toward the predictable target location over other locations (Brockmole & Henderson, 2006; Peterson & Kramer, 2001; Zhao et al., 2012), and first fixations, as a measure of attentional guidance, are more likely to go to the probable target location (Jiang et al., 2014). Taken together, these studies suggest that learned probability information does influence the allocation of attention to a given location. The current study adds to this by demonstrating that participants can also incidentally learn to allocate attention either globally (a broad spread of attention) or locally (a narrow spread of attention).

Second, the current study also expands the understanding of *when* (i.e., during which stage of processing) incidental learning can affect the allocation attention during a change detection task. Although previous studies have demonstrated improved performance with probability information in change detection tasks, it has been unclear whether these effects were due to the allocation of attention during encoding or during the retrieval or comparison phases of the change detection process. For example, Droll, Gigone, and Hayhoe (2007) demonstrated that participants spent more time fixating objects that had a higher probability of changing, suggesting that learned probability information affected the allocation of attention. However, a flicker change detection task was used, in which the study and test arrays alternated back and forth until the change was detected. Therefore, a greater number of fixations to the high change probable objects could have been due to either more time encoding the objects or more time comparing the objects to encoded representations (retrieval and comparison stage). The current study clearly demonstrated that probability information can impact the allocation of attention during encoding and can therefore influence what type of information is stored in VWM.

Role of Reward

In the current study, the change probability effect and the attention allocation effect were evident even after feedback and point rewards were removed. Therefore, the change probability and attention contingent changes were sufficient to produce the effects. This demonstrates that the effects occurred on the basis of internal signals from processing the stimuli and did not rely on external feedback. Some previous studies have suggested that the internal signals from responses alone are not sufficient for learning where to attend based on probabilistic information in the visual environment (e.g., Droll et al., 2009). In the study by Droll et al. (2009), informative feedback was necessary for learning to occur. Although there are many differences between this study and the current study, one of them that may be particularly important is that the authors were measuring saccadic decisions (report the target by looking at it) rather than attention allocation during encoding, and this may explain the difference between their results and ours. It is clear that there are some instances where reward may play a larger role in eye movement behavior than what was found in the current study.

Although reward was not necessary for the change probability effect or for the attention allocation effect, it may have strengthened the use of the optimal attention allocation. The only experiment to demonstrate a decrease in the number of no-change trials across blocks was the experiment that included point allocations as a reward (Experiment 1). Therefore, the point allocation reward appears to have strengthened the allocation of attention effect. When Jiang, Sha, and Remington (2015) examined the relative impact of task goals, probability cueing, and reward on spatial attention, they found that task goals played the largest role, followed by probability cueing, and reward had the smallest, most negligible, effect. This supports the conclusion that the probability information is a more important factor than is reward for training optimal allocation of attention. The current study demonstrates that there may be some instances where reward can strengthen an attention allocation effect beyond what statistical information can achieve.

Role of Explicit Awareness

Many studies have examined the role of explicit awareness in statistical learning. For example, there is evidence that statistical learning occurs without awareness (Kim, Seitz, Feenstra, & Shams, 2009). Across all experiments, levels of awareness were generally high, and almost all participants in the HSF probability conditions indicated awareness of the change probability information (Experiment 1 = 80%, Experiment 2 = 80%, Experiment 3 = 100%). To examine the relationship between explicit awareness and the change probability effect, we quantified the size of the change probability effect by subtracting the proportion correct on the probable-change trials from the proportion correct on the improbable-change trials during Block 3 across Experiments 1, 2, and 3. This change probability effect value for each participant was correlated with the participant's estimate of the percentage of trials that contained probable changes. For the HSF-probable conditions, there was a significant positive correlation ($r = .655$, $n = 30$, $p < .001$), indicating that participants who had larger change probability effects were also more explicitly aware of the higher number of trials that contained changes to the probable-change type. However, in the LSF-probable conditions, the correlation was not significant ($r = -.17$, $n = 30$, $p = .36$). Participants' level of awareness of how often LSF patches changed was not related to the strength of their change probability effect.

The lack of a relationship between the size of the change probability effect and awareness of the probability information in the LSF-probable conditions may be due to a preexisting bias toward LSF information. This bias is evident in previous research on change detection performance for changes to LSF and HSF features of objects that demonstrate a global precedence effect (higher change detection performance for LSF changes than for HSF changes; Ericson et al., 2016). Potentially, when the probability information is consistent with the preexisting bias, explicit awareness is less likely to occur and less likely to be related to the size of the change probability effect.

The level of awareness of the change probability information may have also been related to the degree to which participants adopted the appropriate attention allocation. To examine this question, we correlated the estimate of the percentage of trials that contained probable changes with the number of no-change trails in Block 3 across the three experiments. Negative correlations were found in both the HSF-probable conditions ($r = -.39$, $n = 30$, $p = .03$) and the LSF-probable conditions ($r = -.57$, $n = 30$, $p = .001$). That is, as the estimated number of probable-change type trials increased, the number of no-change trials decreased. Therefore, awareness of the probability information is associated with a tendency to adopt the optimal attention allocation.

The relationships between awareness and the size of the change probability and attention allocation effects demonstrate that explicit awareness can strengthen the effects of learning. This is interesting because the learning was incidental. That is, participants were never explicitly told about the change probability information or that there was an optimal attention strategy for detecting each type of change: They learned this information through interacting with the task. Although incidental learning often leads to implicit knowledge, it can also lead to explicit knowledge (Frensch et al., 2002). This current study does not speak to whether implicit or explicit knowledge is required for learning, but it does indicate that stronger effects are likely when learning reaches an explicit level.

Conclusion

The current study demonstrates several important findings. First, incidental learning of statistical information can occur for objects defined by spatial frequency and can impact the spread of attention during encoding. Second, a probable-change type paired with an optimal attention strategy is sufficient to find the change probability and the attention allocation effects. Finally, reward and explicit knowledge of the statistical information may enhance the change probability and/or attention allocation effects. These findings advance the understanding of the relationship between incidental learning of statistical information and its impact on visual attention.

References

Anderson, B. A., Laurent, P. A., & Yantis, S. (2011). Value-driven attentional capture. *Proceedings of the National Academy of Sciences of the United States of America, 108,* 10367–10371. http://dx.doi.org/10.1073/pnas.1104047108

Beck, M. R., Angelone, B. L., & Levin, D. T. (2004). Knowledge about the probability of change affects change detection performance. *Journal of Experimental Psychology: Human Perception and Performance, 30,* 778–791. http://dx.doi.org/10.1037/0096-1523.30.4.778

Beck, M. R., Peterson, M. S., & Angelone, B. L. (2007). The roles of encoding, retrieval, and awareness in change detection. *Memory & Cognition, 35,* 610–620. http://dx.doi.org/10.3758/BF03193299

Brockmole, J. R., & Henderson, J. M. (2006). Recognition and attention guidance during contextual cueing in real-world scenes: Evidence from eye movements. *Quarterly Journal of Experimental Psychology, 59,* 1177–1187. http://dx.doi.org/10.1080/17470210600665996

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

Chun, M. M., & Nakayama, K. (2000). On the functional role of implicit visual memory for the adaptive deployment of attention across scenes. *Visual Cognition, 7,* 65–81. http://dx.doi.org/10.1080/135062800394685

Della Libera, C., & Chelazzi, L. (2006). Visual selective attention and the effects of monetary rewards. *Psychological Science, 17,* 222–227. http://dx.doi.org/10.1111/j.1467-9280.2006.01689.x

Droll, J. A., Abbey, C. K., & Eckstein, M. P. (2009). Learning cue validity through performance feedback. *Journal of Vision, 9:* 18. http://dx.doi.org/10.1167/9.2.18

Droll, J. A., Gigone, K., & Hayhoe, M. M. (2007). Learning where to direct gaze during change detection. *Journal of Vision, 7:* 6. http://dx.doi.org/10.1167/7.14.6

Druker, M., & Anderson, B. (2010). Spatial probability AIDS visual stimulus discrimination. *Frontiers in Human Neuroscience, 4:* 63.

Ericson, J. M., Beck, M. R., & van Lamsweerde, A. E. (2016). Binding global and local object features in visual working memory. *Attention, Perception, & Psychophysics, 78,* 94–106. http://dx.doi.org/10.3758/s13414-015-1008-0

Eriksen, C. W., & Yeh, Y.-Y. (1985). Allocation of attention in the visual field. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 583–597. http://dx.doi.org/10.1037/0096-1523.11.5.583

Fernandez-Duque, D., & Thornton, I. M. (2003). Explicit mechanisms do not account for implicit localization and identification of change: An empirical reply to Mitroff et al. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 846–858. http://dx.doi.org/10.1037/0096-1523.29.5.846

Fiser, J., & Aslin, R. N. (2005). Encoding multielement scenes: Statistical learning of visual feature hierarchies. *Journal of Experimental Psychology: General, 134,* 521–537. http://dx.doi.org/10.1037/0096-3445.134.4.521

Flevaris, A. V., Bentin, S., & Robertson, L. C. (2010). Local or global? Attentional selection of spatial frequencies binds shapes to hierarchical levels. *Psychological Science, 21,* 424–431. http://dx.doi.org/10.1177/0956797609359909

Freedberg, M., Schacherer, J., & Hazeltine, E. (2016). Incidental learning of rewarded associations bolsters learning on an associative task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42,* 786–803. http://dx.doi.org/10.1037/xlm0000201

Frensch, P. A., Haider, H., Runger, D., Neugebauer, U., Voigt, S., & Werg, J. (2002). The route from implicit learning to verbal expression of what has been learned. In L. Jimenez (Ed.), *Attention and implicit learning* (pp. 335–366). Amsterdam, the Netherlands: Benjamin.

Geng, J. J., & Behrmann, M. (2002). Probability cuing of target location facilitates visual search implicitly in normal participants and patients with hemispatial neglect. *Psychological Science, 13,* 520–525. http://dx.doi.org/10.1111/1467-9280.00491

Gómez, R. L., & Gerken, L. (2000). Infant artificial language learning and language acquisition. *Trends in Cognitive Sciences, 4,* 178–186. http://dx.doi.org/10.1016/S1364-6613(00)01467-4

Henriksson, L., Nurminen, L., Hyvärinen, A., & Vanni, S. (2008). Spatial frequency tuning in human retinotopic visual areas. *Journal of Vision, 8:* 5. http://dx.doi.org/10.1167/8.10.5

Hickey, C., Chelazzi, L., & Theeuwes, J. (2010). Reward changes salience in human vision via the anterior cingulate. *Journal of Neuroscience, 30,* 11096–11103. http://dx.doi.org/10.1523/JNEUROSCI.1026-10.2010

Hollingworth, A., & Henderson, J. M. (2002). Accurate visual memory for previously attended objects in natural scenes. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 113–136. http://dx.doi.org/10.1037/0096-1523.28.1.113

Jiang, Y. V., Sha, L. Z., & Remington, R. W. (2015). Modulation of spatial attention by goals, statistical learning, and monetary reward. *Attention, Perception, & Psychophysics, 77,* 2189–2206. http://dx.doi.org/10.3758/s13414-015-0952-z

Jiang, Y. V., Won, B.-Y., & Swallow, K. M. (2014). First saccadic eye movement reveals persistent attentional guidance by implicit learning. *Journal of Experimental Psychology: Human Perception and Performance, 40,* 1161–1173. http://dx.doi.org/10.1037/a0035961

Kim, R., Seitz, A., Feenstra, H., & Shams, L. (2009). Testing assumptions of statistical learning: Is it long-term and implicit? *Neuroscience Letters, 461,* 145–149. http://dx.doi.org/10.1016/j.neulet.2009.06.030

Laloyaux, C., Destrebecqz, A., & Cleeremans, A. (2006). Implicit change identification: A replication of Fernandez-Duque and Thornton (2003). *Journal of Experimental Psychology: Human Perception and Performance, 32,* 1366–1379. http://dx.doi.org/10.1037/0096-1523.32.6.1366

Lee, J., & Shomstein, S. (2013). The differential effects of reward on space- and object-based attentional allocation. *Journal of Neuroscience, 33,* 10625–10633. http://dx.doi.org/10.1523/JNEUROSCI.5575-12.2013

Levin, D. T., & Simons, D. J. (1997). Failure to detect changes to attended objects in motion pictures. *Psychonomic Bulletin & Review, 4,* 501–506. http://dx.doi.org/10.3758/BF03214339

Miller, J. (1988). Components of the location probability effect in visual search tasks. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 453–471. http://dx.doi.org/10.1037/0096-1523.14.3.453

Navon, D. (1977). Forest before the tress: The precedence of global features in visual perception. *Cognitive Psychology, 9,* 353–383. http://dx.doi.org/10.1016/0010-0285(77)90012-3

Peterson, M. S., & Kramer, A. F. (2001). Attentional guidance of the eyes by contextual information and abrupt onsets. *Perception & Psychophysics, 63,* 1239–1249. http://dx.doi.org/10.3758/BF03194537

Rensink, R. A., O'Regan, J. K., & Clark, J. J. (1997). To see or not to see: The need for attention to perceive changes in scenes. *Psychological Science, 8,* 368–373. http://dx.doi.org/10.1111/j.1467-9280.1997.tb00427.x

Saffran, J. R. (2002). Constraints on statistical language learning. *Journal of Memory and Language, 47,* 172–196. http://dx.doi.org/10.1006/jmla.2001.2839

Sasaki, Y., Hadjikhani, N., Fischl, B., Liu, A. K., Marret, S., Dale, A. M., & Tootell, R. B. H. (2001). Local and global attention are mapped retinotopically in human occipital cortex. *Proceedings of the National Academy of Sciences of the United States of America, 98,* 2077–2082. http://dx.doi.org/10.1073/pnas.98.4.2077

Shomstein, S., & Johnson, J. (2013). Shaping attention with reward: Effects of reward on space- and object-based selection. *Psychological Science, 24,* 2369–2378. http://dx.doi.org/10.1177/0956797613490743

Simons, D. J. (2000). Current approaches to change blindness. *Visual Cognition, 7,* 1–15. http://dx.doi.org/10.1080/135062800394658

Van Essen, D. C., & Deyoe, E. A. (1995). Concurrent processing in the primate visual cortex. In M. S. Gazzaniga & M. S. Gazzaniga (Eds.), *The cognitive neurosciences* (pp. 383–400). Cambridge, MA: MIT Press.

van Lamsweerde, A. E., & Beck, M. R. (2011). The change probability effect: Incidental learning, adaptability, and shared visual working memory resources. *Consciousness and Cognition, 20,* 1676–1689. http://dx.doi.org/10.1016/j.concog.2011.09.003

Williams, L. J. (1989). Foveal load affects functional field of view. *Human Performance, 2,* 1–28. http://dx.doi.org/10.1207/s15327043hup0201_1

Yang, C.-T., Chang, T.-Y., & Wu, C.-J. (2013). Relative change probability affects the decision process of detecting multiple feature changes. *Journal of Experimental Psychology: Human Perception and Performance, 39,* 1365–1385. http://dx.doi.org/10.1037/a0030693

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

Received August 31, 2016
Revision received March 16, 2017
Accepted April 10, 2017 ■