Selective attention modulates implicit learning

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The effect of selective attention on implicit learning was tested in four experiments using the "contextual cueing" paradigm (Chun & Jiang, 1998, 1999). Observers performed visual search through items presented in an attended colour (e.g., red) and an ignored colour (e.g., green). When the spatial configuration of items in the attended colour was invariant and was consistently paired with a target location, visual search was facilitated, showing contextual cueing (Experiments 1, 3, and 4). In contrast, repeating and pairing the configuration of the ignored items with the target location resulted in no contextual cueing (Experiments 2 and 4). We conclude that implicit learning is robust only when relevant, predictive information is selectively attended.

Both attention and learning are fundamental processes in human visual processing. Selective attention allows us to pick up behaviourally relevant information and ignore vast amounts of irrelevant information. Failure to attend to critical information reduces the efficiency of visual processing. In extreme cases, inattention can make observers functionally blind. This point is well illustrated by recent research on inattentional blindness (Mack & Rock, 1998), the attentional blink (Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992), change blindness (Rensink, O'Regan, & Clark, 1997; Simons & Levin, 1997), as well as classic studies of selective attention (Neisser & Becklen, 1975). In these cases, clearly visible information goes unnoticed before the eyes of the observers when the information is not under focused attention. Equally indispensable in visual processing are learning mechanisms. People process visual information more efficiently when visual experience provides schemata to organize complex scenes (Biederman, 1972). In the current article, we focus on one type of learning: learning without intention and conscious awareness—that is implicit learning (Reber, 1989; Seger,

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1994; Stadler & Frensch, 1998). Implicit learning may allow perceivers to acquire useful information about the structure of the visual world (Chun & Jiang, 1998, 1999).

Although these two topics, attention and implicit learning, have largely been investigated separately, they interact in meaningful ways to facilitate visual processing. On the one hand, implicit learning shapes selective attention. An important factor that determines what gets attended in a given situation is past experience. Gibson (1966) talks about the "education of attention" or, in other words, how attention is affected by perceptual learning. Recently, Chun and colleagues (Chun, 2000; Chun & Jiang, 1998, 1999; Chun & Nakayama, 2000; Chun & Phelps, 1999) have demonstrated that implicit learning of visual context guides attention toward targets in a visual search task. On the other hand, attention also influences the extent of implicit learning. What is learned is partly determined by how much attention is allocated to it (Nissen & Bullemer, 1987). Thus, there is a bi-directional interaction between attention and implicit learning.

In this paper we first review empirical evidence on how implicit learning guides visual attention. We then focus on the converse effect—how attention modulates implicit learning. Previous research on how attention affects implicit learning has produced inconsistent results, and such research has largely emphasized attention as a *resource* instead of attention as a *selection* mechanism (Johnston & Dark, 1986; Kahneman, 1973). The present study focuses on the selective nature of attention. In four experiments, we investigate how selective attention modulates implicit learning in visual search.

Implicit learning guides visual attention

In a series of studies, Biederman and his colleagues (Biederman, 1972; Biederman, Mezzanotte, & Rabinowitz, 1982) demonstrated that visual context, or schema, significantly affects visual processing. For example, objects in a jumbled scene take longer to be spotted than those in a congruent scene. Reaction time (RT) and accuracy to detect the targets are affected by whether the targets fit into the scene or are out of the context (but see Hollingworth & Henderson, 1998). These studies, however, did not reveal how schemata are formed and how visual contexts could be defined. To address these questions, Chun and colleagues have recently examined how contextual knowledge may be acquired through implicit learning (Chun & Jiang, 1998, 1999; Chun & Nakayama, 2000; Chun & Phelps, 1999). These studies show that implicit learning of context can efficiently guide visual attention toward target information.

Using a visual search task, Chun and Jiang (1998) asked observers to search a rotated "T" target among rotated "L" distractors. The configuration of a trial was defined by the spatial layout formed by all the items on that trial. The experiment was decomposed into 24 blocks. Each trial in a block had a unique target location and a unique spatial configuration. Across blocks, a particular target location was either consistently paired with the same configuration (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977), or paired with a configuration newly generated on that trial. Observers were not informed of the consistent mapping and were merely instructed to perform the visual search task. The question of central interest was whether search performance would be facilitated by consistent spatial configurations. Results showed that search RT for targets in consistent configurations was faster than in random configurations. This suggests that subjects learned the configurations as well as their consistent associations with embedded target locations. Such contextual knowledge then guided visual attention toward the target locations, facilitating search. The guidance of attention in this paradigm is called *contextual cueing*.

Interestingly, learning in this paradigm was implicit (Chun & Jiang, 1998). None of the observers reported having tried to memorize the spatial configurations intentionally. Indeed, the repetition of the spatial configuration was seldom noticed. In addition, the memory formed through the learning was also implicit. Observers were not able to recognize the new and the old configurations at above-chance levels. Contextual cueing reveals a powerful learning mechanism, as complex invariant information can be more efficiently acquired by implicit mechanisms than by explicit mechanisms (Reber, 1989, 1993; see Stadler & Frensch, 1998, for reviews).

Contextual cueing is not restricted to learning of spatial configurations. Further studies revealed that information about the item shapes could be implicitly learned to facilitate visual search of novel objects. In addition, complex motion trajectories could be implicitly learned to help localize a moving target (Chun & Jiang, 1999). Thus, various visual attributes can be implicitly learned to guide visual attention toward the relevant aspects of the displays.

Attention modulates implicit learning

Conversely, one can ask how attention modulates implicit learning. This issue was first examined in a now classic study by Nissen and Bullemer (1987) and has since been investigated by other researchers (Cohen, Ivry, & Keele, 1990; Frensch, Lin, & Buchner, 1998; Jimenez & Mendez, 1999; Stadler, 1995). However, taken together, the results from these studies are not very clear.

Most studies used the same implicit learning paradigm: the Serial Reaction Time (SRT) task. In addition, most studies manipulated attention in much the same way: using a secondary tone-counting task to reduce the amount of attentional resources available to the SRT task. In Nissen and Bullemer's (1987) SRT task, a stimulus was presented in one of four horizontal locations on the screen. There were four keys, and observers were instructed to press the key corresponding to the location of the stimulus. The next trial started soon after a response was given. Unknown to the observers, the stimulus locations of a sequence of 10 trials were recycled and repeatedly used in the experiment. When the SRT task was performed alone, observers gave faster RTs to repeated sequences than to newly generated sequences. The benefit was found even when observers were not aware of the repetition. In other words, serial sequence learning was implicit. How is sequence learning affected by attention? To find out, Nissen and Bullemer (1987) added a secondary tone-counting task to the SRT task. While they were doing the SRT task, observers counted the number of high-pitched tones among randomly presented high- and low-pitched tones. This additional task reduced the amount of attentional resources available to the SRT task (Kahneman, 1973). Results showed no sequential learning under the dual-task condition. Nissen and Bullemer proposed that attention is necessary for implicit learning of the SRT task. As the amount of attention is reduced, implicit sequence learning is impaired.

This conclusion was amended later by Cohen et al. (1990). Cohen et al. found that the role of attention in SRT task depended on the structure of the sequences. A sequence can be unique, ambiguous, or hybrid. In a unique sequence, the stimulus location on one trial reliably predicts the stimulus location on the next trial. For example, suppose A, B, C, and D represent the four locations used in a task. Sequence “DBACDBAC” constitutes a unique sequence. An ambiguous sequence, on the other hand, is a sequence in which the location on one trial does not determine the location of the next trial. For instance, sequence “DCABCDBA” is an ambiguous sequence, where D is followed by either C or B. Hybrid sequences contain both unique and ambiguous structures. Cohen et al. found that the secondary tone-counting task had no effect on learning of unique sequences, yet it reduced learning of ambiguous sequences. Thus, the effect of attention is affected by the nature of the sequence. Unique sequences can be learned through simple pair-wise associations, and such learning may proceed automatically without attention. Ambiguous sequences have to be encoded hierarchically, and hence learning may be more vulnerable to the reduction of attentional resources.

However, in a later study, Frensch et al. (1998) failed to replicate Cohen et al.’s (1990) finding. Specifically, Frensch et al. found that implicit learning of neither type of sequence was affected by tone counting. The secondary task only affected the expression of what was learned, not learning per se. The issue of how attention affects sequence learning is further complicated by Stadler’s (1995) finding that the disruption effect of the tone-counting task was not due to the reduction of attentional resources. Rather, the random structure of the tone task interfered with sequence formation in the SRT task. Specifically, Stadler found that sequence learning was not affected by a letter memory task that took away attentional resources but that did not impose a new temporal structure. Interestingly, sequence learning was disrupted by irregular blank intervals that did not impose attentional requirement but that added a new temporal structure.

In summary, these past studies give conflicting answers to how attention affects implicit learning. Although Nissen and Bullemer’s original study found that attention was necessary for implicit learning, this conclusion appears to be valid only for learning of ambiguous sequences (Cohen et al., 1990). Other researchers proposed that attention does not influence sequence learning at all, it only affects what is expressed (Frensch et al., 1998). Still other researchers suggested that the role of attention is not clear, because the results can be better explained by structural interference (Stadler, 1995).

The controversy may be partly due to the limitations of the SRT paradigm and the dual-task design. First, these studies used the same implicit learning paradigm, the SRT task. In the SRT task, learning has a large motor component but a restricted visual component. Only one stimulus is presented on each trial, and the sequence is relatively simple compared to the complexity of visual events that we encounter in daily life. Thus, it may not generalize to implicit learning situations that use more complex visual stimuli.

Second, past studies emphasized the resource nature, rather than the selection nature, of attention (Johnston & Dark, 1986). The role of the tone task was to reduce the amount of attentional resources available to the SRT task. Although it is important to understand the effect of diminished attention, such manipulations have disadvantages. One critical concern is that auditory tasks may not completely interfere with visual tasks because there may be separate attentional resources for visual and auditory processing (Duncan, Martens, & Ward, 1997; Potter, Chun, Banks, & Muckenhoupt, 1998; Treisman and Davies, 1973). When there is no effect of a secondary task on sequence learning, one cannot rule out the possibility that the learning would have been impaired had the secondary task truly tapped into the same pool of resources consumed by the SRT task. Another concern is that these studies ignored the selective aspect of attention. The importance of attention can be more clearly shown in situations where the target information has to be selected among to-be-ignored distractor information. The selective aspect of attention is difficult to study in the SRT task because only one stimulus is presented at any given time.

Recently, Jimenez and Mendez (1999) examined the selective aspect of attention as well as the resource aspect. These authors used the SRT task in which observers always had to respond and attend to locations. In addition, they introduced a second regularity in that the shape of an item predicted the next location. The predictability of shape contributed to SRT performance only when its shape was attended, suggesting an important role for selective attention. In contrast, learning was not affected by reduction of attentional resources induced by a secondary counting task. This dissociation indicates that it is meaningful to distinguish selection from resources and effort (Kahneman, 1973). Jimenez and Mendez proposed that implicit learning is an automatic associative process that does not rely on attentional resources, supporting the conclusions drawn by Frensch et al. (1998) and Stadler (1995). However, this does not imply that attention does not affect implicit learning at all. Rather, shape has to be selectively attended for associations between shape and location to be learned. In sum, attention is not a simple construct. When studying the relationship between attention and implicit learning, researchers must clarify which aspect of attention is under investigation.

In this study, we seek converging evidence towards how selective attention affects implicit learning. It is not clear whether the results from Jimenez and Mendez's (1999) study can generalize to implicit learning of more complex visual information. It is also unclear whether the results based on dimension selection can generalize to object selection. The visual search task used by Chun and colleagues provides an ideal platform to answer these questions. Recall that in the contextual cueing paradigm (Chun & Jiang, 1998), observers must learn the spatial configuration of items. Thus, the displays used in contextual cueing are more complex than the single stimulus displays used in SRT tasks. The present study extends findings from the SRT paradigm, which is based on sequential, visuo-motor skills, to a task that requires learning of more complex, spatio-configural information. Moreover, using displays with multiple items, attention can be deployed to some items over others in an object-based manner (Duncan, 1984; Kanwisher & Driver, 1992). Thus, this task allows us to extend Jimenez and Mendez's results on attention to a dimension (shape) to a task based on object selection.

In this study each visual search trial contained eight red items and eight green items. Observers were instructed to attend to only one of the colours (e.g., red) and ignore the other colour (e.g., green). Past studies have shown that observers can use colour information to selectively attend to the appropriate subset of visual stimuli, hence improving search performance significantly (Egeth, Virzi, & Garbart, 1984; Kaptein, Theeuwes, & van der Heijden, 1995; Treisman & Sato, 1990; Wolfe, Cave, & Franzel, 1989). In Experiment 1, the spatial configurations of the attended items were consistently paired with target locations across different blocks. In Experiment 2, the spatial configurations of the ignored items were consistently paired with target locations. The baseline was a condition in which all distractors, those in both the attended colour and the ignored colour, were presented at random locations across blocks. If implicit learning of invariant configurations and their associations with embedded target locations only occurs when invariant configurations are selectively attended to, we should find a benefit of repeating attended configurations, but not of repeating ignored configurations. On the contrary, if selective attention plays no role in implicit learning, repetition of attended configurations should have the same effect as repetition of ignored configurations. Using pairs of words, Logan and Etherton (1994) demonstrated that attention is important for learning co-occurrences. Based on that finding, we predict that attention should modulate implicit learning in our task. An important extension of the present work is that the information to be learned is more complex and that the attended information and ignored information were intermixed with each other across the display.

EXPERIMENT 1

In Experiment 1, we tested the influence of attended set on contextual cueing. The effect of ignored set is presented in Experiment 2. Eight red and eight green items were presented on each visual search display. Observers were instructed to search for a rotated "T" among rotated "L"s appearing in the attended colour while ignoring "L"s in the other to-be-ignored colour. The spatial layout formed by items in the attended colour was the attended configuration, whereas the spatial layout formed by items in the ignored colour was the ignored configuration. The target was always in the attended colour. The experiment consisted of 24 blocks, and each block contained 24 trials. Trials in each block were divided into two conditions. Within a block, each trial had a unique target location, a unique attended configuration, and a unique ignored configuration. The target locations were repeated across blocks. Across different blocks, the target location of a trial was paired with a new, ignored configuration randomly generated on that trial. In the *control condition*, the configuration of the attended items was also randomly generated on each trial. In the *attended-old* condition, the target location was consistently paired with a configuration in the attended colour, repeated from previous blocks.

The main difference between this experiment and the original contextual cueing experiments (Chun & Jiang, 1998) was that the configurations of only half of the distractors were repeated here, namely, those that were attended to. The locations of the unattended half of the distractors were randomized. An immediate question is whether any implicit learning would be obtained at all. That is, is repetition of half of the items sufficient to produce learning? If yes, does it matter whether the repeated configuration was attended or ignored? Experiment 1 answers the first question; Experiment 2 answers the latter.

Method

Participants

A total of 16 undergraduate volunteers participated in this experiment for course credit. All were naïve observers. They had normal colour vision and normal or corrected-to-normal visual acuity. Informed consent was obtained at the beginning of the experiment.

Stimuli and apparatus

The stimuli were composed of line segments. The target was a "T" rotated 90° to the left or to the right. The distractors were rotated (0°, 90°, 180° or 270°) "L"s with a small offset (2 pixels) at the line junctions. Each item subtended about 1 cm × 1 cm. At a viewing distance of 57 cm, 1 cm corresponds to 1° visual angle.

On each trial, eight red and eight green items were presented. Half of the observers were instructed to search through the red items, the other half were to search through the green items. The target was presented on every trial and was always presented in the attended colour. The target plus the seven distractors in the attended colour were the attended set. The other eight distractors in the ignored colour were the ignored set. All items were randomly positioned in an invisible 12×8 matrix that subtended 26.25 cm × 17.50 cm. The colour of the background was grey.

The experiment was conducted on a Macintosh computer with a 17″ colour monitor. The program was run by MacProbe software (Hunt, 1994). Observers were tested in normal interior lighting. Unrestricted viewing distance was about 57 cm. The computer recorded reaction time and accuracy.

Design

This was a 24×2 within-subject design. The first factor was block. Observers were tested in 24 experimental blocks; each block contained 24 trials. The block factor allowed us to observe the progress of learning. The second factor was condition. Half of the trials in each block were in the control condition and the other half in the attended-old condition. This factor gave us a measure of whether repetition of the attended spatial layout would support implicit learning. The conditions were contrived as follows.

At the beginning of the entire experiment, 24 locations were randomly chosen and assigned as the target locations for the 24 trials. So each trial within a block had a unique target location, but across blocks the same 24 target locations were used. The repetition of the target location was a constant factor for the control and the attended-old conditions. Thus, any learning observed for the attended-old condition could not be attributed to learning of target locations per se.

In the control condition, both the ignored and the attended configurations were generated at the beginning of each block. Each trial was associated with a novel ignored and a novel attended configuration. The target location was thus paired with a new configuration in each trial. No specific learning of spatial configurations was possible.

In the attended-old condition, distractors in the ignored colour were newly generated for a particular trial. However, distractor locations in the attended colour were generated only once at the beginning of the experiment. These attended distractor configurations were repeatedly presented in every block, and each configuration was consistently paired with a particular target location. Finally, the identity of the target (left or right "T") and the corresponding response keys were not paired with the repeated spatial configurations of the attended colour. The orientation of the target was randomly chosen on every trial with the constraint that there were equal numbers of left and right rotated "T"s within a block. Learning of the association between the motor response and the configuration was thus impossible, contrasting this paradigm with standard SRT procedures, in which responses typically co-vary with stimulus repetition.

Procedure

On each trial, a white fixation point (0.4 cm in diameter) was presented for 500 ms. The search display was then presented until response. Sound feedback of response accuracy was provided immediately after the response. The next trial was presented 1 s later. Observers were allowed to take a break (around 20 s) at the end of each block. They completed 1 practice block and 24 experimental blocks. Spatial configurations used in the practice were different from those used in the experimental blocks. The whole session lasted about 40 min.

Results

In this and Experiments 2 and 3, trials with RT longer than 3,000 ms were trimmed (less than 1% of trials were deleted this way). In addition, incorrect responses were not included in the RT analysis. Whether the attended colour was red or green did not affect the results, so this

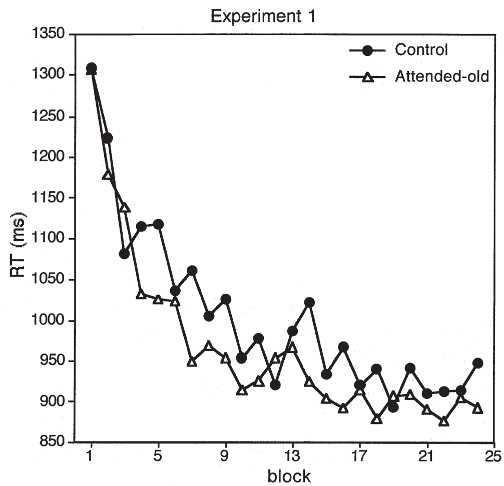

Figure 1. Mean RT data from Experiment 1.

factor was excluded from the analysis. The mean accuracy for each condition at each block ranged from 97% to 99%. Analysis of variance (ANOVA) of accuracy showed that it was not affected by condition, block, or their interaction (all *F*s < 2.0, *p*s > .10).

RT data are presented in Figure 1. We entered condition (attended-old vs. control) and block (1–24) into a multivariate analysis of variance (MANOVA) test. The main effect of condition was significant, $F(1, 15) = 4.92$, $p < .042$. RT was faster when the attended set was repeated than when it was new. The main effect of block was significant, $F(23, 345) = 22.87$, $p < .001$, showing that observers responded faster as they progressed in the task. Importantly, there was a significant interaction between condition and block, $F(23, 345) = 1.76$, $p < .018$. This confirms spatial configuration learning in the attended-old condition, which emerged after a few repetitions.

As revealed in Figure 1, the two conditions had comparable RTs at the beginning of the experiment. Mean RTs were virtually identical when patterns in the two conditions were presented for the first time ($M = 1307.8$ ms for the control condition, and $M = 1306.8$ ms for the attended-old condition), $F(1, 15) < 1$. By the fourth block, RT was faster in the attended-old condition ($M = 1031.9$ ms, compared with 1114.2 ms in the control condition), $F(1, 15) = 5.48$, $p < .033$. An advantage was shown in 19 out of the last 21 blocks.

Discussion

When the spatial layout of the attended set of distractors was consistently paired with the target location, target search was facilitated, but only after a few (e.g., three) repetitions. This indicates that observers were able to extract the invariant spatial layout embedded among noise produced by the random positioning of the ignored set. Thus, contextual cueing is quite robust to perturbation of the global spatial configuration (Chun & Jiang, 1998; see also Olson & Chun, in press). These results suggest that contextual learning can be restricted to a subset of attended events within a visual array.

Is contextual cueing affected by whether the invariant spatial configuration is attended or ignored? To answer this question, we carried out a second experiment in which the ignored set was invariant across blocks whereas the attended set was variable. If attention modulates implicit learning in this paradigm, we should find smaller or no contextual cueing in the next experiment. Conversely, if implicit learning of configurations is not affected by selective attention, we should find comparable contextual cueing between Experiments 1 and 2.

EXPERIMENT 2

Method

All aspects of Experiment 2 were the same as those in Experiment 1, except that the distractors in the ignored colour were made invariant across blocks, and the distractors in the attended colour were variable. This condition is called the *ignored-old* condition. It was contrasted with the control condition, as in Experiment 1. Targets were always presented in the attended colour. A total of 17 new observers were tested.

Results

Data from one observer were not included in this analysis because of low accuracy (79%). For the other 16 observers, the mean accuracy was 98%. As in Experiment 1, accuracy was not affected by block, condition, or their interaction, all *p*s > .10. Mean RT data are shown in Figure 2.

We carried out a MANOVA test on condition (ignored-old vs. control) and block (1–24). The main effect of condition was not significant, $F(1, 15) < 1$, *ns*. The main effect of block was significant, $F(23, 345) = 17.58$, $p < .001$, showing that observers had faster RT as the experiment progressed. The interaction between condition and block was not significant, $F(23, 345) = 1.30$, $p > .15$. Even when the analysis was focused on the second half of the experiment, which provides better sensitivity to observe contextual cueing (Chun & Jiang, 1998, 1999), the

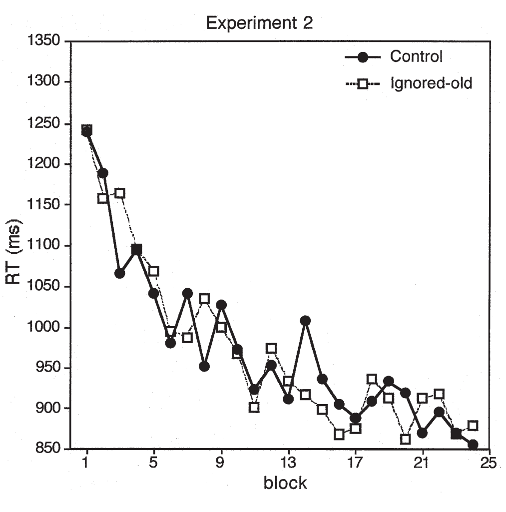

Figure 2. Mean RT data from Experiment 2.

condition main effect was still not significant, $F(1, 15) < 1$, *ns*. Thus, there was no hint of significant learning of ignored configurations.

Discussion

Experiments 1 and 2 show that contextual cueing is modulated by selective attention. In Experiment 1, we found that when the invariant set was attended to, performance in a visual search task was facilitated by contextual learning. In Experiment 2, performance was not significantly improved when the invariant set was ignored during search. Thus, implicit learning of invariant configurations and their associations with embedded target locations was modulated by selective attention. Learning was significant only when the invariant information was attended to, consistent with Logan and Etherton's (1994) proposal that attention determines what is learned.

Can the different pattern of results in these two experiments be explained by factors other than selective attention? Before we make a conclusive answer, we first consider whether other subtle differences can account for the different results between these experiments.

First, the number of repeated distractors was seven in the attended set and eight in the ignored set. The subtle difference in distractor set size may have affected the magnitude of learning. In fact, in a previous study we found that contextual cueing was affected by differences in display set size (Chun & Jiang, 1998, Experiment 4). However, contextual cueing was numerically larger with larger set sizes. We would have obtained larger contextual cueing in Experiment 2 than in Experiment 1 if the number of invariant items had been the critical factor. The opposite results were observed, however, suggesting that the set size differences in the invariant set could not explain the difference between the two experiments.

Second, in Experiment 1, the invariant distractors had the same colour as the target. Yet in Experiment 2, the invariant distractors had a different colour from the target. Perhaps the association between the invariant distractors and the target was more difficult to establish if they had different colours. Previous results make this suggestion unlikely (Chun & Jiang, 1998; Chun & Phelps, 1999). In fact, contextual cueing was quite robust even when items in the search display had heterogeneous colours, suggesting that contextual cueing was not impaired by differences in colour between the target and the distractors. Moreover, a study from our laboratory that directly tested the role of colour grouping suggests that colour differences do not affect contextual cueing at all (Olson & Chun, in press).

Thus, we conclude that implicit learning in the contextual cueing paradigm was affected by selective attention. Contextual cueing was statistically significant only when the invariant spatial layouts were attended to.

EXPERIMENT 3

The purpose of Experiment 3 was two-fold. First, we would like to provide more empirical evidence for the role of selective attention in implicit learning. This is necessary given the relatively small (though significant) magnitude of contextual cueing effect obtained in Experiment 1. Pooling trials across the second half of Experiment 1, the contextual cueing was only 37 ms. Although it was significantly above zero, this value is close to the nonsignificant 10-ms difference found in Experiment 2. A replication would strengthen our conclusions. Second, although no significant contextual cueing was found in Experiment 2, it is still possible that contextual cueing based on ignored invariant information may be detected with a more powerful design.

To examine these issues, we carried out a within-subject design with four conditions: control, attended-old, ignored-old, and both-old. By including the attended-old and ignored-old conditions in the same experiment, we can obtain a more sensitive within-subject comparison between these conditions. We also increased the duration of training from 24 to 30 blocks. This should increase the power to detect a contextual cueing effect. In addition, we tried to reduce random errors induced by target eccentricity. In Experiments 1 and 2, target locations were randomly chosen, and no attempt was made to equate target eccentricity between the attended-old (or ignored-old) and the control conditions (Carrasco & Yeshurun, 1998). In this experiment, we equated target eccentricity for the four conditions. These modifications provided us with a more powerful design.

Method

The methods were similar to those of Experiments 1 and 2 except for the following modifications:

1. A total of 17 new observers were tested.
2. There were 24 trials in each block. They were divided into four conditions, which were produced by crossing two factors: whether the attended set was invariant or random, and whether the ignored set was invariant or random.
   Control condition: Both the attended sets and the ignored sets were located at newly generated locations in each block;
   Attended-old condition: The attended sets were invariant spatial configurations repeated across blocks, but the ignored sets were variable.
   Ignored-old condition: The ignored sets were invariant configurations repeated across blocks and the attended sets were variable;
   Both-old condition: Both the attended and the ignored sets had repeated spatial configurations. This was the same as the old condition used in the original contextual cueing study (Chun & Jiang, 1998).
3. There were 30 blocks of experimental trials.
4. Target eccentricity was equated for the four conditions. The method to equate eccentricity was as follows. Suppose the centre of the display had a coordinate of (0, 0). If a target in one condition was positioned at (x, y), then $(x, -y)$, $(-x, y)$ and $(-x, -y)$ would be the target locations for the other three conditions. The target location distribution across the four quadrants was roughly balanced for the four conditions. The exact assignment of quadrants was randomized for different observers.

Results

One observer performed with low accuracy (82%), and the associated data were not included in the analysis. For the other 16 observers, accuracy averaged 98%. Because each condition had only six trials per block, a block-by-block analysis would provide an unstable pattern of results. To clarify the results we grouped every five blocks into a single epoch. The experiment was thus composed of six epochs. Accuracy was not affected by condition, epoch, or their interaction, all ps > .15.

Mean RT data are shown in Figure 3. We performed two MANOVA tests on these data. In the first MANOVA test, we entered three factors in the analysis: epoch (1 through 6), attended set (repeated or random), and ignored set (repeated or random). The main effect of epoch was significant, showing a general practice effect, $F(5, 11) = 32.98$, $p < .001$. In addition, both the main effect of attended set and that of ignored set were significant. For the attended set factor, RT was significantly faster when the attended set was invariant than when it was variable, $F(1, 15) = 12.68$, $p < .01$. This replicated the finding in Experiment 1. For the ignored set factor, RT was also significantly faster when the ignored set was invariant, $F(1, 15) = 9.73$, $p < .01$. This effect was not detected in Experiment 2. We discuss this finding in more detail a little later.

None of the two-way interactions was significant. The interaction between attended set and epoch was not significant, $F(5, 11) = 1.27$, $p > .20$. However, when we restricted analysis to Epoch 1 and Epoch 6 only, the interaction was significant, $F(1, 15) = 5.50$, $p < .05$, indicating that there was a significantly larger effect of attended set in the last epoch compared with that in the first epoch. The interaction between ignored set and epoch was not significant either when all epochs were examined, $F < 1$, or when the first and the last epochs were contrasted, $F < 1$. This indicates that learning for the ignored set was not powerful enough to be detected statistically. The interaction between attended set and ignored set was not significant, $F < 1$, indicating that the effects of attended set and ignored set were additive. Figure 4A shows the main effect of attended set and Figure 4B shows the main effect of ignored set. The two figures differ in two aspects. First, the effect of attended set was larger. Second, only learning of the attended set showed an increase in magnitude as the experiment progressed. Learning of the ignored set appeared to be almost constant across blocks. The null interaction between ignored set and epoch indicates that learning of the ignored set was equivocal.

Finally, there was a significant three-way interaction, $F(5, 11) = 5.26$, $p < .05$. This is best explained by the fact that in the first epoch, there was a hint of early learning for the both-old condition, but not for the attended-old or the ignored-old conditions. In fact, the both-old condition was faster than the control condition by 33 ms. But the combined effect of attended-

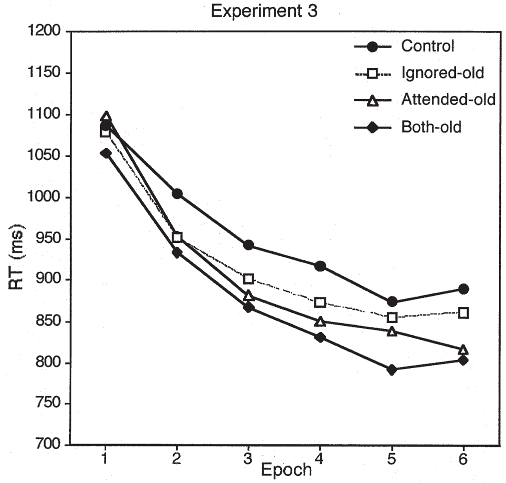

Figure 3. Mean RT data from Experiment 3.

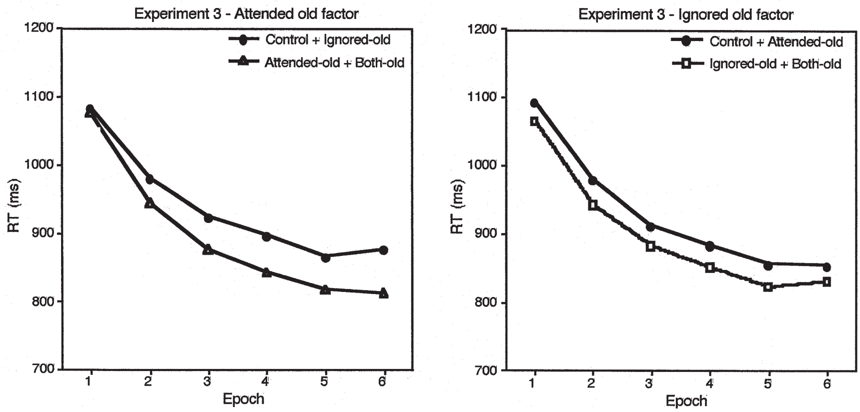

Figure 4. The effect of the attended set factor (A) and the effect of the ignored set factor (B) obtained in Experiment 3.

old and ignored-old over the control condition was −1 ms. Thus, at the beginning of the experiment, the attended set and ignored set factors were not additive. Yet in later blocks, the benefit of the both-old condition over the control condition was very close to the sum of the benefit in the other two conditions. This pattern can be explained by the fact that when the whole spatial configuration was repeated, learning not only was stronger in magnitude, but also had an earlier time course. Of course, this explanation is speculative, because the 33-ms difference between the control and the both-old condition in Epoch 1 was not statistically significant, $t(15) = 1, p > .20$.

In the second analysis, we contrasted the control condition with the other three conditions. This analysis was restricted to the second half of the experiment only, where contextual cueing was more obvious. Such a restricted analysis follows prior convention (Chun & Jiang, 1998, 1999; Chun & Phelps, 1999). First, the both-old condition was faster than the control condition, $F(1, 15) = 17.45, p < .01$. The average RT difference was 84 ms for the second half of the experiment. This finding replicated the original contextual cueing result (Chun & Jiang, 1998). Second, the attended-old condition had faster RT than the control condition, $F(1, 15) = 11.56, p < .01$. The RT difference here was 57 ms. Again, the significant difference was a replication of Experiment 1. Thirdly, the ignored-old condition was also significantly faster than the control condition, $F(1, 15) = 4.53, p < .05$, although the RT benefit was only 31 ms.

By providing more training and reducing random noise in this experiment, we were able to detect facilitation produced by repetition of the ignored set. Does this mean that attention played no role in modulating implicit learning? To answer this question, we compared mean RT in the attended set condition and that in the ignored set condition in the second half of the experiment. Here, we found a significant difference of 26.7 ms, $F(1, 15) = 7.03, p < .02$. Thus, contextual cueing was stronger when the invariant spatial layout was attended.

Discussion

By using a more powerful design, we found several interesting results. First, we replicated the finding from Experiment 1 that contextual cueing was robust to the perturbation of the spatial configurations. Contextual cueing was significant even when only half of the items were repeated. Second, we strengthened the claim that selective attention modulates implicit learning in this paradigm. When the invariant layout was attended to, learning was stronger than when the invariant layout was ignored. This suggests that selective attention is an important factor in implicit learning of complex visual attributes, providing converging evidence to Jimenez and Mendez's (1999) demonstration that selective attention is important in implicit sequence learning.

One unclear aspect of our results is how to explain the small but significant benefit of repeating an ignored set. As pointed out, learning of the ignored set was equivocal. Specifically, the interaction between epoch and ignored set was not significant (see Figure 4B). The lack of interaction cannot be explained by early learning. When the first epoch was broken down into five blocks, the data failed to reveal any consistent learning (all *p*s > .20). If the apparent benefit for the ignored set in the first epoch was produced by chance, the benefit shown in the later epochs may also be problematic. However, chance alone does not adequately explain away the significant main effect of ignored set.

A second more reasonable possibility is that selective attention was not perfect in Experiment 3. That is, although observers were instructed to selectively attend to one colour, unused attentional resources may have spilled over to the unattended items. One reason for this may have been the presence of both-old trials, which presented predictive information in the ignored set. Involuntary spreading of attention to the ignored set was potentially rewarding because the distractors had predictive power on some trials. A more important reason may be due to the overall difficulty of the task. This possibility is predicted by perceptual load theory (Lavie, 1995; Lavie & Tsal, 1994). According to perceptual load theory, the perceptual load of the task determines whether the ignored distractors can be truly ignored. When the task is easy under conditions of low perceptual load, observers cannot prevent leftover attentional resources from spilling to the distractors. As the perceptual load of a task increases, however, no attentional resources are left to process distractors. Thus, the higher the perceptual load, the more efficient the selective attention system can filter out irrelevant items. Lavie (1995) showed that as the search task was changed from an easy, simple feature search task to a difficult, conjunction search task, the irrelevant distractors were less processed. Applying the perceptual load theory to our task, it is possible that Experiment 3 was not difficult enough to prevent attentional resources from spilling over from the attended set to the ignored set. A more difficult search task should enhance the efficiency of attentional selectivity. This will ensure that the items in the ignored colour are effectively ignored.

Note that perceptual load theory does not distinguish selectivity and resources as two completely independent aspects of attention. Increasing perceptual load reduces the amount of attentional resources that is left from target selection. This in turn enhances the efficiency of attentional selection. To examine whether leftover attentional resources may have supported implicit learning of the ignored configuration, Experiment 4 adopted a more difficult search task.

EXPERIMENT 4

To increase search difficulty, we increased the offset in the line junction of the "L" distractors (7 pixels as opposed to 2 pixels). This made the "L" distractors more similar to the target "T"

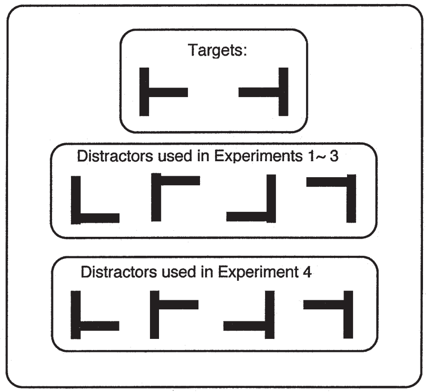

Figure 5. The targets and distractors used in the experiments.

and accordingly increased the difficulty of visual search (Chun & Phelps, 1999; Duncan & Humphreys, 1989). Figure 5 shows the targets and the distractors used in Experiments 3 and 4. According to perceptual load theory (Lavie & Tsal, 1994), this should reduce the amount of attentional resources that go unused. Therefore, the items in the ignored set would receive fewer attentional resources.

How would visual search difficulty affect contextual cueing? Past studies suggest that the numerical magnitude of contextual cueing increases as the search task becomes more difficult (Chun & Jiang, 1998). If contextual cueing is insensitive to selective attention, search difficulty should enhance contextual cueing of the ignored as well as the attended set. Conversely, if contextual cueing relies on selective attention, and if the efficiency of attentional selectivity is enhanced by increasing task difficulty, we should find a robust contextual cueing effect for only the attended set. In other words, increasing the difficulty of the task will reduce allocation of attention to the ignored set, minimizing implicit learning of the ignored set.

Method

The method used in this experiment was identical to that in Experiment 3, except that the distractor shapes were more similar to the target shapes. A total of sixteen new observers participated in this experiment.

Results

Mean accuracy ranged from 96% to 98% in different epochs. Accuracy was not significantly affected by any of the factors or their interactions, all *p*s > .10. Correct RTs that were shorter than 4,000 ms were included in the mean RT analysis. These data are plotted in Figure 6. Just like Experiment 3, we grouped five blocks into an epoch to clarify the data presentation and analyses. Mean RT in this experiment was about 650 ms longer than mean RT in Experiment 3, confirming that our manipulation of task difficulty was successful.

MANOVA analysis on attended set (repeated vs. random), ignored set (repeated vs. random), and epoch (1 to 6) showed a significant main effect of attended set, $F(1, 15) = 11.31, p < .004$. RT was faster when the attended configurations were repeated. The main effect of

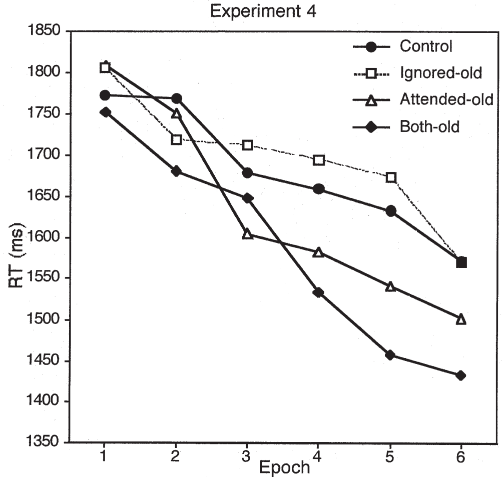

Figure 6. Mean RT data from Experiment 4.

ignored set was not significant, $F(1, 15) < 1$, *ns*, showing no benefit of repeating ignored configurations. The main effect of epoch was significant, $F(5, 75) = 19.89$, $p < .001$, indicating that observers responded faster as the experiment progressed.

Two way interactions showed a significant interaction between attended set and epoch, $F(5, 75) = 3.41$, $p < .008$. The benefit of repeating the attended configuration was larger as learning progressed. This trend can be clearly seen from Figure 7A. The interaction between ignored set and epoch was not significant, $F(5, 75) = 1.27$, $p > .25$. This also confirms that there was no learning whatsoever of the ignored configurations. The difference between the *Both-old* and *Attended-old* conditions was not significant when restricted to the second half of the experiment, $p > .15$. The null result is clearly visible in Figure 7B. Finally, the interaction between attended set and ignored set was not significant, $F(1, 15) = 1.48$, $p > .20$, showing that

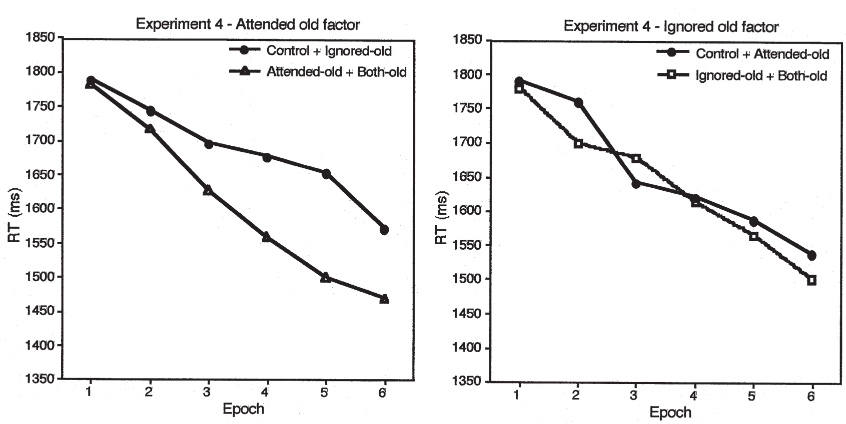

Figure 7. The effect of the attended set factor (A) and the effect of the ignored set factor (B) obtained in Experiment 4.

the two factors—attended set and ignored set—were largely additive. The three-way interaction was not significant, $F(5, 75) < 1$, *ns*.

Discussion

Using a more difficult search task, we found that implicit learning of spatial configurations only occurred for attended items. This confirms the hypothesis that the small learning effect of the ignored configuration found in Experiment 3 may have been the result of imperfect attentional selection (Lavie & Tsal, 1994). Increasing task difficulty reduced the amount of attentional resources inadvertently allocated to the ignored items. This enhanced the selectivity of attention, and it eliminated implicit learning of the ignored configurations. Taken together, Experiments 3 and 4 showed that implicit learning of ignored configurations is not robust, and a weak effect may only be observed when conditions allow some attentional resources to "spill" over to the ignored items. In contrast, learning of attended configurations was robust and repeatedly observed in all of our different experiments. Thus, the invariant configuration has to be selectively attended for robust contextual cueing to occur.

GENERAL DISCUSSION

In four experiments using the contextual cueing paradigm, we found that implicit learning of complex visual configurations is modulated by selective attention. Contextual cueing was only observed when the invariant information was selectively attended. These results provide converging evidence for the idea that implicit learning relies on selective attention (Jimenez & Mendez, 1999; Logan & Etherton, 1994). This study extends prior work from implicit learning in SRT tasks (Jimenez & Mendez, 1999) or word pair learning (Logan & Etherton, 1994) to learning of complex visual configurations. In addition, whereas Jimenez and Mendez asked observers to selectively attend to the shapes of the placeholders in the SRT task, we asked observers to select a subset of objects intermingled with another subset of objects to ignore. Thus, implicit learning is sensitive not just to attention to dissociable dimensions, but also to selection by objects.

Furthermore, we found that the extent that items in an ignored colour are truly ignored depends on the difficulty of visual search. The more difficult the search task is, the more likely the ignored items would be filtered out early on and thus would produce no benefit of repetition. This is consistent with perceptual load theory that predicts enhanced attentional selectivity with increased attentional load (Lavie, 1995; Lavie & Tsal, 1994). The perceptual load theory embraces both the selection and the resource aspects of attention and postulates a close link between the two.

However, it is not clear whether resources and selection are tightly related in all tasks. Recall that Jimenez and Mendez (1999) found a dissociation between selection and resources. Imposing attentional resources by a secondary counting task did not affect sequence learning, whereas selective attention to shapes was crucial for obtaining sequence learning of the association between shape and location. Unlike our study that implies a close link between attentional resources and selectivity, Jimenez and Mendez's study indicates that resources and selection do not affect implicit learning in the same way. However, because the dissociation found in that study was in a single direction, it is not clear whether resources and selection are qualitatively different processes, or whether implicit learning is just more sensitive to selective attention than to attentional load. The latter hypothesis is reasonable when one considers the fact that the secondary load task may not have used the same pool of attentional resources required for the primary implicit learning task. To argue that the two aspects of attention have a qualitatively different impact on implicit learning, one needs to find an implicit learning task that is affected by load but not by selection instructions. So far, there has not been any empirical evidence for this. Thus, it is an open question as to how selection and resources differ in their effects on implicit learning.

In any case, it is clear that implicit learning is modulated by selective attention. Robust implicit learning is found only when the invariant information is attended. This finding re-emphasizes Nissen and Bullemer's (1987) notion that consciousness and attention are not one and the same. Critical information that is learned implicitly, or without conscious awareness, nevertheless has to be selectively attended for a learning effect to occur.

In conclusion, selective attention and implicit learning are interactive processes. Studies using the contextual cueing paradigm have revealed that implicit learning of configurations guides selective attention toward important information. Using this paradigm, we have shown that implicit learning of the configurations is robust only when the repeated configuration is selectively attended. Future studies should be directed towards understanding whether implicit learning is affected by attentional selection and attentional resources in a qualitatively different way, or whether implicit learning is more sensitive to selection than to load.

REFERENCE

Biederman, I. (1972). Perceiving real-world scenes. *Science*, *177*, 77–80.

Biederman, I., Mezzanotte, R.J., & Rabinowitz, J.C. (1982). Scene perception: Detecting and judging objects undergoing relational violations. *Cognitive Psychology*, *14*, 143–177.

Carrasco, M., & Yeshurun, Y. (1998). The contribution of covert attention to the set-size and eccentricity effects in visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 673–692.

Chun, M.M. (2000). Contextual cueing of visual attention. *Trends in Cognitive Sciences*, *4*, 170–178.

Chun, M.M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology*, *36*, 28–71.

Chun, M.M., & Jiang, Y. (1999). Top-down attentional guidance based on implicit learning of visual covariation. *Psychological Science*, *10*, 360–365.

Chun, M.M., & Nakayama, K. (2000). On the functional role of implicit visual memory for the adaptive deployment of attention across views. *Visual Cognition*, *7*, 65–81.

Chun, M.M., & Phelps, E.A. (1999). Memory deficits for implicit contextual information in amnesic patients with hippocampal damage. *Nature Neuroscience*, *2*, 844–847.

Chun, M.M., & Potter, M.C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 109–127.

Cohen, A., Ivry, R.I., & Keele, S.W. (1990). Attention and structure in sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *16*, 17–30.

Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General*, *113*, 501–517.

Duncan, J., & Humphreys, G.W. (1989). Visual search and stimulus similarity. *Psychological Review*, *96*, 433–458.

Duncan, J., Martens, S., & Ward, R. (1997). Restricted attentional capacity within but not between sensory modalities. *Nature*, *387*, 808–810.

Egeth, H.E., Virzi, R.A., & Garbart, H. (1984). Searching for conjunctively defined targets. *Journal of Experimental Psychology: Human Perception and Performance*, *10*(1), 32–39.

Frensch, P.A., Lin, J., & Buchner, A. (1998). Learning versus behavioral expression of the learned: The effects of a secondary tone-counting task on implicit learning in the serial reaction time task. *Psychological Research*, *61*, 83–98.

Gibson, J.J. (1966). *The senses considered as perceptual systems*. Boston, MA: Houghton Mifflin.

Hollingworth, A., & Henderson, J.M. (1998). Does consistent scene context facilitate object perception? *Journal of Experimental Psychology: General*, *127*, 398–415.

Hunt, S.M.J. (1994). Macprobe: A Macintosh-based experimenter's workstation for the cognitive sciences. *Behavior Research Methods, Instruments, and Computers*, *26*, 345–351.

Jimenez, L., & Mendez, C. (1999). Which attention is needed for implicit sequence learning? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*, 236–259.

Johnston, W.A., & Dark, V.J. (1986). Selective attention. *Annual Review of Psychology*, *37*, 43–75.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

Kanwisher, N., & Driver, J. (1992). Objects, attributes, and visual attention: Which, what, and where. *Current Directions in Psychological Science*, *1*(1), 26–31.

Kaptein, N.A., Theeuwes, J., & van der Heijden, A.H.C. (1995). Search for a conjunctively defined target can be selectively limited to a colour-defined subset of elements. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 1053–1069.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 451–468.

Lavie, N., & Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Perception & Psychophysics*, *56*, 183–197.

Logan, G.D., & Etherton, J.L. (1994). What is learned during automatization? The role of attention in constructing an instance. *Journal of Experimental Psychology : Human Perception and Performance*, *20*, 1022–1050.

Mack, A., & Rock, I. (1998). *Inattentional blindness*. Cambridge, MA: MIT Press.

Neisser, U., & Becklen, R. (1975). Selective looking: Attending to visually specified events. *Cognitive Psychology*, *7*, 480–494.

Nissen, M.J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*, *19*, 1–32.

Olson, I.R., & Chun, M.M. (in press). Perceptual constraints on implicit learning of spatial context. *Visual Cognition*.

Potter, M.C., Chun, M.M., Banks, B., & Muckenhoupt, M. (1998). Two attentional deficits in serial target search: The visual attentional blink and an amodal task-switch deficit. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*, 979–992.

Raymond, J.E., Shapiro, K.L., & Arnell, K.M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance*, *18*(3), 849–860.

Reber, A.S. (1989). Implicit learning and tacit knowledge. *Journal of Experimental Psychology: General*, *118*, 219–235.

Reber, A.S. (1993). *Implicit learning and tacit knowledge: An essay on the cognitive unconscious*. New York: Oxford University Press.

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*(5), 368–373.

Schneider, W., & Shiffrin, R.M. (1977). Controlled and automatic human information processing: I. Detection, search and attention. *Psychological Review*, *84*, 1–66.

Seger, C.A. (1994). Implicit learning. *Psychological Bulletin*, *115*, 163–196.

Shiffrin, R.M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. *Psychological Review*, *84*, 127–190.

Simons, D., & Levin, D. (1997). Change blindness. *Trends in Cognitive Science*, *1*, 261–267.

Stadler, M.A. (1995). Role of attention in implicit learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *21*, 819–827.

Stadler, M.A., & Frensch, P.A. (Eds.). (1998). *Handbook of implicit learning*. Thousand Oaks, CA: Sage Publications.

Treisman, A.M., & Davies, A. (1973). Divided attention to ear and eye. In S. Kornblum (Ed.), *Attention and performance IV* (pp. 101–117). New York: Academic Press.

Treisman, A., & Sato, S. (1990). Conjunction search revisited. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(3), 459–478.
Wolfe, J.M., Cave, K.R., & Franzel, S.L. (1989). Guided search: An alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *15*(3), 419–433.

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