COGNITIVE PSYCHOLOGY **36,** 28–71 (1998)
ARTICLE NO. CG980681

Contextual Cueing: Implicit Learning and Memory of Visual Context Guides Spatial Attention

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Global context plays an important, but poorly understood, role in visual tasks. This study demonstrates that a robust memory for visual context exists to guide spatial attention. Global context was operationalized as the spatial layout of objects in visual search displays. Half of the configurations were repeated across blocks throughout the entire session, and targets appeared within consistent locations in these arrays. Targets appearing in learned configurations were detected more quickly. This newly discovered form of search facilitation is termed contextual cueing. Contextual cueing is driven by incidentally learned associations between spatial configurations (context) and target locations. This benefit was obtained despite chance performance for recognizing the configurations, suggesting that the memory for context was implicit. The results show how implicit learning and memory of visual context can guide spatial attention towards task-relevant aspects of a scene.

Visual images and scenes are typically comprised of a rich, detailed mosaic of features, surfaces, objects, and events. But only a small subset of this information is available to conscious awareness or working memory at any given moment (Luck & Vogel, 1997; Pashler, 1988; Rensink, O'Regan, & Clark, 1997; Simons & Levin, 1997; Sperling, 1960). Powerful and sophisticated selection mechanisms exist to focus attention towards a restricted set of objects and events (Eriksen & Yeh, 1985; Treisman & Gelade, 1980),

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We thank Adam Anderson, Patrick Cavanagh, Ken Nakayama, Molly Potter, Ron Rensink, Dan Simons, Jeremy Wolfe, and numerous other colleagues for helpful discussions. Wookyoung Ahn and Ingrid Olson provided helpful comments on an earlier draft of this article. This paper has also benefited greatly from constructive feedback from Gordon Logan, Mike Stadler, and our other reviewers. We thank Joanie Sanchez for her assistance in running Experiment 1. This research was supported by a Social Science Faculty Research Award from Yale University. Portions of this research were presented at the Annual Meeting of the Association for Research in Ophthalmology and Vision, Fort Lauderdale, FL, in May, 1997, and at the Annual Meeting of the Psychonomic Society, Philadelphia, PA, in November, 1997.

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0010-0285/98 $25.00

and an important goal of attentional systems is to rapidly prioritize aspects of a complex scene that are of significant behavioral relevance. Such efficient, ''smart'' deployment of attention is crucial for adaptive functioning. But how does the visual system determine where to attend and look? A random selection process would clearly be inefficient.

A number of factors have been found to increase the efficacy of attentional deployment. These have typically been studied using visual search tasks in which observers detect targets presented among multiple, competing distractor stimuli. They can be broadly categorized into bottom-up, image-driven factors or top-down volitional factors (see Wolfe, 1994a, or Yantis, 1996, for comprehensive reviews). For instance, in visual search tasks, image-based factors that attract attention include salient or unique features (Bravo & Nakayama, 1992; Egeth, Jonides, & Wall, 1972; Theeuwes, 1992; Treisman & Gelade, 1980), abrupt onsets (Yantis & Jonides, 1984), and the presence (as opposed to absence) of features (Treisman & Gormican, 1988). Top-down, knowledge-based, factors include search templates which focus attention toward items that share features with the target (Egeth, Virzi, & Garbart, 1984; Wolfe, Cave, & Franzel, 1989), automaticity effects (Schneider & Shiffrin, 1977), novelty effects (Johnston, Hawley, Plew, Elliott, & DeWitt, 1990), familiarity effects (Wang, Cavanagh, & Green, 1994), and expectancy effects for locations which have a high likelihood of containing the target (Miller, 1988; Shaw, 1978; Shaw & Shaw, 1977). These all undoubtedly play an important role in guiding selection for targets in complex arrays. However, an ecologically critical factor appears to be missing from this list.

Target items in visual search tasks and especially objects in the real world are almost always accompanied by other objects forming a global context or scene (Biederman, 1972). Visual contexts and scenes contain a rich, complex structure of covariation between visual objects and events. Meaningful regularities exist, and the visual world is by and large stable over time forming invariants.[1] Although presented in a different theoretical framework and level of analysis, J. J. Gibson (1966) spoke about the attunement of perceptual systems to invariant information in the physical world. The development of this attunement, or what he refers to as the ''education of attention,'' depends on past experience. In short, sensitivity to regularities in the environment would be informative. Reber (1989) makes a similar point in stating that, when the stimulus environment is structured, people learn to exploit the structure to coordinate their behavior in a coherent manner.

The visual environment is presented to an observer in the form of rich global images; hence, it seems plausible that meaningful, covariational structure in this rich context may serve to constrain visual processing. Past work

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[1] Moving objects are ubiquitous, but even these generally move in prototypical ways. People don't fly. Cars don't move sideways.

has demonstrated that a coherent, semantically related visual context can facilitate the detection and identification of component objects and events (Biederman, 1972; Biederman, 1981; Biederman, Mezzanotte, & Rabinowitz, 1982; Boyce, Pollatsek, & Rayner, 1989; Friedman, 1979; Loftus & Mackworth, 1978; Mandler & Johnson, 1976; Palmer, 1975). These empirical demonstrations employed natural scenes which tap into the rich background knowledge and extensive visual experience of observers. But these important variables are difficult to control in the lab, delaying progress for resolving how visual context can be defined, how it influences visual processing, and how contextual knowledge is acquired and represented. These are the issues examined in this study.

Specifically, our main proposal is that visual context guides the deployment of visual attention, critical for processing complex visual inputs. Global properties of an image can prioritize objects and regions in complex scenes for selection, recognition, and control of action. We refer to this process as *contextual cueing*. For example, in visual search tasks, global context may direct spatial attention towards the location of targets embedded among an array of distractors. This contextual guidance of visual attention reflects sensitivity to meaningful regularities and covariances between objects and events within a scene. Such higher-level invariants in the richly structured stimulus environment serve to cue how attention should be deployed to complex images.

Second, such contextual knowledge is acquired through *implicit learning* processes which allow complex information about the stimulus environment to be acquired without intention or awareness (Berry & Dienes, 1993; Reber, 1989; Stadler & Frensch, 1998). We further propose that incidentally acquired contextual knowledge forms a highly robust, instance-based, *implicit memory* for context. The advantage of implicit learning is that it allows more information to be acquired than is possible through consciously mediated channels (Lewicki, Hill, & Bizot, 1988). Characterizing the resulting memory as implicit allows for these representations to facilitate behavior even while conscious recognition or recollection is not supported (Jacoby & Witheerspoon, 1982; Schacter, 1987; Squire, 1992). Implicit learning and implicit memory are distinct processes (Buchner & Wippich, 1998; Stadler & Frensch, 1994). Implicit learning can produce explicit knowledge, and certain forms of explicitly learned information are only accessible through implicit measures. Our study, however, respects characteristics of both: Implicit learning of visual context produces representations of context which themselves are also implicit in nature. For our purposes, it will be important to establish that these implicit representations for context not accessible to conscious awareness are nevertheless potent enough to facilitate critical visual processes.

Note that we do not take an implicit/explicit memory distinction as support for multiple dissociable memory systems. The concepts of implicit and explicit memory per se ''neither refer to, nor imply the existence of, two independent or separate memory systems'' (Schacter, 1987, p. 501). A multiple systems view requires converging support from other types of evidence, and a large body of empirical work has been provided to support a multiple systems view for a variety of domains (for comprehensive surveys, see Schacter & Tulving, 1994; Squire, 1992; Tulving & Schacter, 1990). However, for the visual context information examined in this study, at present we hypothesize that a single memory system exists for both implicit/explicit visual context information which can be accessed in different ways through multiple cognitive (and perceptual) procedures which can be characterized as explicit or implicit (Roediger, 1990).

Finally, we propose that the memory for contextual information is *instance-based,* and that these episodic memory traces interact with attentional mechanisms to guide search. Hence, we consider contextual cueing as a form of memory-based automaticity. Memory-based theories (Logan, 1988) propose that automaticity (performance improvement) is based on retrieval of past solutions from instances of past interactions stored in memory. During performance of a task, memory retrieval processes race with algorithmic processes, and the winner determines ultimate performance. In the visual search tasks examined here, target detection is mediated by generic attentional mechanisms (algorithmic computation) in early stages of training. As the perceiver continues to perform the task, memory traces of these interactions are established. These accumulate to provide solutions to the search task more quickly than a memory-free attentional mechanism would. Most important, these memory traces are instance-based, allowing for a distinction between stimuli that were presented in the history of perceptual interactions from novel stimuli that were not. With respect to visual search, instance theory predicts that memory for context allows for the solution (target location) to emerge before an algorithmic process (uninformed search) does. Facilitation in performance would be specific to the contexts observers were trained on. Note that the memory/algorithm distinction is independent of the implicit/explicit learning and memory distinction established in the previous section.

Hence, the overarching goal of this study is to highlight the importance of understanding how memory and attention interact to optimize visual processes such as search. We propose that attention can be deployed toward objects and locations which were behaviorally significant to the observer in similar contexts in the past. According to this view, the role of context is to allow for a match between the incoming perceptual input with invariant, covariational context knowledge acquired through visual experience. This rich memory for context interfaces with general-purpose spatial attention mechanisms to guide deployment to complex visual arrays. Contemporary research has typically treated attentional operations as a memory-free process. Yet, memory and attention interact in important, meaningful ways

(Desimone, 1996; Desimone & Duncan, 1995), and our new paradigm will highlight the functional significance of such interactions.

The Contextual Cueing and Learning Paradigm

We investigated how visual context is learned and how it influences visual processing in standard visual search tasks which required observers to localize and identify targets presented among multiple distractors. This is an ideal task because the items can be arrayed randomly on the computer screen in a large number of distinct visual configurations. The spatial layout of the search array in turn defines the global visual context for a target embedded in this array (see Fig. 1a and 1b). In short, global context can be operationalized precisely as spatial layout. Note that although visual context was operationalized as the global configuration of the display, in the real world, the content or identity of component objects also clearly plays an important role. In this study we focus on configuration alone to first establish a role for global visual context in visual processing. We believe general principles of contextual cueing obtained in this study can subsequently be applied toward understanding the role of semantic content in a future study.

We test whether the global spatial configuration of the search array can be incidentally learned to facilitate visual search for a target within these arrays. Search configurations are repeated throughout the experimental session, and targets are usually presented in the same location within any given configuration. Hence, the invariant visual context is predictive of the target location, a critical variable in search tasks. If observers performing the visual search task are sensitive to the global configuration of the array the target appears in, then learning the consistent mapping between visual contexts and target locations will facilitate search on future encounters (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977).

The use of novel, arbitrary, otherwise meaningless configurations allowed us to examine the effects of global, visual context without relying on natural scenes. This enables us to rule out effects of background knowledge and associations between items semantically related to one another. It gives us control over all parameters including familiarity, similarity, and component object salience. In addition, the visual search task allowed us to present spatial configurations to the subjects without asking them to explicitly encode the stimuli in any way, while maintaining the requirement of having subjects attend to aspects of the entire display.

It is not obvious that a benefit for search in repeated configurations should be obtained. First, Wolfe, Klempen, and Dahlen (1997) demonstrated that search does not improve appreciably for targets appearing in arrays that were repeated. This is consistent with recent proposals that details of the visual world do not need to be retained in memory because the visual environment itself can serve as a memory, readily accessible when needed (Intraub, 1997; O'Regan, 1992; Rensink et al., 1997; Simons & Levin, 1997). Thus, there is no direct evidence that the visual system would pick up the contextual spatial layout information and make use of it. Second, the spatial configurations used to operationalize global context in our study were designed to be somewhat indiscriminable from each other in recognition memory. Each experiment typically presented a total of 300 to 372 different configurations from which the observer needed to discriminate 12 repeated arrays. Moreover, these were presented in cycles of blocks so that an average of 12 different configurations typically intervened between repetitions. A powerful and sophisticated memory is needed to encode and maintain distinctive representations of such rather homogeneous displays. Finally, the demands of our search task minimize the chances that any observer would spontaneously try to consciously learn or encode the search arrays. Without an intent to learn the displays, it is not clear whether the visual system focused on a primary task (search) should retain any information about the global input. We employed search tasks which could be classified as ''serial'' and inefficient (Treisman & Gelade, 1980; Wolfe, 1994a), hence reducing any attentional capacity to perform explicit cognitive operations other than search. These incidental learning conditions contrast our paradigm with other implicit memory studies which tested explicitly learned novel visual patterns (Musen & Treisman, 1990).

In our first experiment we introduce the contextual cueing paradigm showing how context facilitates search. Experiments 2 and 3 examine the nature of memory for context. These experiments test whether the memory is explicit or implicit, whether the learning is intentional or incidental, and whether the representations are specific or abstract. Experiment 4 further examines how context influences the efficiency of search using target slope measures as a function of set size. Contextual cueing should produce shallower search slopes. Experiment 5 employs flashed displays to examine whether contextual cueing is dependent on motor skill learning expressed through eye movements. Experiment 6 further establishes the robustness and generality of contextual cueing.

EXPERIMENT 1

The first experiment examines whether observers implicitly learn the global context of targets in visual search tasks and whether this context can serve to cue the target location to facilitate search performance in subsequent encounters. Observers performed visual search for targets appearing among distractor stimuli arrayed in invariant (Old) or variable (New) spatial configurations, randomly intermixed within blocks. Old configurations were repeated across blocks throughout the entire session. Importantly, targets appeared within consistent locations within Old configurations. Sensitivity to global configurations should lead to faster target search performance in repeated configurations compared to baseline configurations that were newly generated for each block (New). This facilitation should only appear after exposure to one or more repetitions. In addition, we ensured that the probability of a target appearing in any given location was equated in Old and New conditions by repeating the location of the target in New configurations also. Hence, any differences in search performance must be due to contextual guidance rather than sensitivity to absolute target location probabilities. In addition, observers were not informed of the repetition manipulation nor were they instructed to encode the display in any way. Thus, any learning effects obtained in this experiment may be characterized as incidental and implicit.

The task was visual search for rotated T's among heterogeneously rotated L distractors, a classic ''serial'' search task that typically exhibits significant, positive slopes as a function of set size (e.g., Duncan & Humphreys, 1989; Wolfe et al., 1989). These search images did not contain other image cues that could be used to optimize selection. Each trial contained one of two possible targets, and subjects were instructed to press a response key corresponding to the appropriate target. Target-absent trials were not tested since these are typically influenced by various factors not relevant to this study (Chun & Wolfe, 1996). Presenting targets on every trial also increases the statistical power while ensuring that subjects are attending to the target when making a response (Bravo & Nakayama, 1992). Furthermore, the identity of the target was randomly chosen for each trial and did *not* correlate with any of the configurations it appeared in. Thus, any benefit for Old configurations cannot be attributed to priming of an associated response.

Methods

Subjects. Sixteen observers from the Yale University community participated in this experiment in partial fulfillment of an Introduction to Psychology course requirement or as paid volunteers. This pool was used for all of the experiments used in this study. All observers reported normal or corrected-to-normal visual acuity and normal color vision. None of the subjects was aware of the purpose of this study nor had they participated in visual search tasks before.

Design and procedure. The two main variables were configuration (Old vs New) and epoch (1–6). The Old set of stimuli consisted of 12 randomly generated configurations which were repeated throughout the entire experiment, once per block. A randomly chosen target always appeared in the same location within any particular configuration. The New set consisted of 12 different configurations which were newly generated for each block to serve as a control baseline. To rule out location probability effects, the target appeared equally often in each of 24 possible locations throughout the experiment: 12 locations were used in Old configurations, and the other 12 were used in New configurations. Hence, any difference in performance must be attributed to learning of invariant spatial contexts and not absolute target location likelihoods. The eccentricity or spatial location of the targets was randomly chosen and assigned to the two configuration conditions. The distractor locations in each configuration were randomly sampled from all possible locations including target locations used in other configurations. Configurations were generated separately for different observers.

Each session consisted of 30 blocks of 24 trials each (12 Old, 12 New), for a total of 720 trials. To increase the power of our statistical analyses, blocks were grouped in sets of 5 into epochs. Hence, each session yielded 6 epochs which served as the units for statistical analyses.

The target was a T stimulus rotated 90 degrees to the right or to the left. Subjects pressed one of the two buttons corresponding to whether the bottom of the T was pointed to the right or to the left. The distractor stimuli were L shapes presented randomly in one of four orientations (0, 90, 180, 270). The identities of the distractors within their respective spatial locations in Old configurations were preserved across repetitions. A target was present on every trial. This target was randomly chosen so that the identity of the target (and its corresponding response) did not correlate with any of the configurations it appeared in.

Each display contained 12 items which could appear within an array of 8×6 locations. The search array was heterogeneously colored, comprised of an equal number of red, green, blue, and yellow colored items. These colors were randomly assigned to each of the items within a configuration. The only constraint was that an equal number of targets was presented in each color for each configuration condition (Old/New). The color assignments of both targets and distractors in Old configurations were preserved across repetitions, and the color of targets appearing within any given spatial location was preserved across blocks for New configurations.

The observer pressed the space bar to begin each block. Each trial started with a small dot appearing in the middle of a computer screen for fixation. After a brief pause of 500 ms, the array of stimuli (as shown in Fig. 1a and 1b) appeared on the screen. The observer searched for the target and pressed a button as soon as she/he could upon detection. They pressed the ‘‘z’’ key if the target was pointing left, and the ‘‘/’’ key if it was pointing right. The response cleared the display with a blank screen, and feedback was given in the form of a brief high-pitched chirp for correct responses or a prolonged low-pitched tone for errors. After a brief pause of a second, the following trial was initiated by the computer. A mandatory break of 10 s was given at the end of each block of 24 trials. At the end of the break, subjects were free to proceed to the next block, or rest further if needed.

The experiment began with instructions followed by a practice block of 24 trials to familiarize subjects with the task and procedure. The spatial configurations used in practice were not used in the actual experiment. Most important, subjects were not informed that the spatial configurations of the stimuli in some trials would be repeated, nor were they told to attend to or encode the global array. They were simply given instructions on the visual search task procedure and shown sample displays of what the targets and nontargets looked like. It was stressed that they were to respond as quickly and as accurately as possible. The entire experiment took around 40 minutes.

Apparatus and stimuli. The experiment was conducted on a Macintosh computer using MacProbe software (Hunt, 1994). The stimuli were presented on a 17-inch color monitor. Unrestrained viewing distance was approximately 50 cm, and the visual search array appeared within an invisible 8×6 grid that subtended approximately 37.2×28.3 degrees in visual angle. The background was set at gray, and the stimuli were colored as described above. The size of the stimuli in this and all subsequent experiments were about 2.3×2.3 degrees in visual angle. The position of each item was jittered within the rectangular array to prevent colinearities with other stimuli. Within each cell of the 8×6 matrix display, the center position of each item was randomly jittered in steps of 0.2 degrees within a range of ± 0.8 degrees in visual angle along the vertical and horizontal axes. This constraint prevented any stimulus from appearing within 1 degree of visual angle of a neighboring item (measured from edge to edge). The jittered position for each item was held constant throughout the experiment for Old arrays. The jittered position was allowed to vary across repetitions in Experiment 6.

Results

Overall error rates were quite low at 2% in both Old and New conditions, with no significant effects of configuration, epoch, or interaction between configuration and epoch (all F’s < 1.28, p’s $> .28$). This error rate pattern was consistent across all of the experiments reported in this study, and we

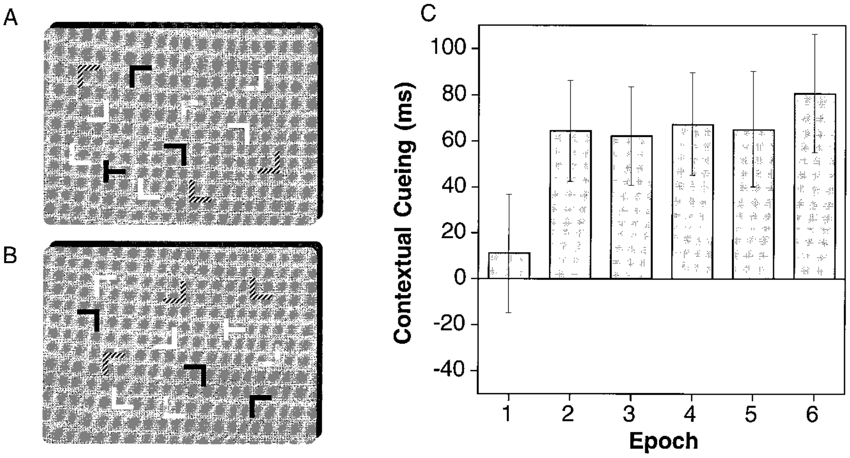

FIG. 1. (a and b) Schematic example of the search task used in Experiment 1. Two sample configurations are shown, each associated with a different target location. The differential shading represents the four different colors (red, green, yellow, and blue) used for the items. (b) The contextual cueing effect as a function of epoch in Experiment 1. Contextual cueing is defined as the difference in search performance between New and Old configuration conditions. Positive values indicate a benefit for Old configurations. Error bars represent the standard error of the mean.

will not discuss these in further detail since they never correlated with our variables of interest.

The mean RT for all correct trial responses within an epoch was computed separately for each condition, and these were submitted to repeated-measures ANOVA with configuration (Old vs New) and epoch (1–6) as factors. RT's that exceeded 4000 ms were discarded. Fewer than 1% of the data were omitted by this procedure in Experiment 1 and in all subsequent experiments.

The results are summarized in Table 1 which presents the mean RT for each condition as a function of epoch. Figure 1c illustrates the mean RT difference between Old and New conditions as a function of epoch. For each

TABLE 1
Response Time as a Function of Configuration and Epoch in Experiment 1
(Standard Error in Parentheses; *t* Tests Two-Tailed)

	Epoch 1	Epoch 2	Epoch 3	Epoch 4	Epoch 5	Epoch 6
New	1081.46	970.95	906.24	881.23	888.74	880.35
	(39)	(38)	(28)	(32)	(36)	(45)
Old	1070.39	906.67	844.16	813.83	823.80	799.72
	(38)	(35)	(29)	(34)	(42)	(41)
t(15)	0.43	2.91	2.91	3.04	2.62	3.16
p	.67	.011	.011	.008	.019	.006

epoch, mean search performance for Old configurations was subtracted from that for New configurations; positive values indicate a search benefit for targets appearing in Old configurations.

The main finding is that observers were able to localize and discriminate targets more efficiently in invariant (Old) configurations than in variable (New) configurations. The benefit in performance is termed the *contextual cueing effect*. This facilitation in search performance became significant after just 1 epoch, or 5 cycles through the repeated Old Set. An ANOVA revealed main effects of configuration, $F(1,15) = 9.09$, $p < .01$, and epoch, $F(5,75) = 31.99$, $p < .001$. The interaction between configuration and epoch was also significant, $F(5,75) = 2.61$, $p < .05$. A contrast examining only the first and last epoch (Epochs 1 and 6) also revealed a significant interaction between Configuration × Epoch, $F(1,15) = 6.18$, $p < .03$. Planned comparisons at each epoch are presented in Table 1. To avoid multiple comparison issues in this and subsequent experiments, we report, but do not discuss, the statistical significance of differences at each epoch. Instead, we measure contextual cueing as the difference between Old and New conditions, collapsed across the last three epochs of the session (second half of the experiment). According to this measure, the magnitude of contextual cueing was 71 ms in Experiment 1, $F(1,15) = 11.55$, $p < .005$. This procedure will be used to assess the magnitude of contextual cueing across experiments, as well as to provide a consistent measure of its statistical significance. These results show that contextual cueing is a benefit that emerges after training.

For this first experiment, we also report the data as a function of individual blocks to provide a detailed portrayal of the learning curve in our search task. The means of correct RT's were collected for each condition as a function of block instead of epoch for each individual. The means of these individual means are presented in Fig. 2. Confirming the trend in the epoch analysis, there is no difference between configuration conditions in early stages of training, while the curves diverge with increased training.

Discussion

A significant benefit was obtained for target search performance in repeated (Old) configurations, and we term this the contextual cueing effect. Contextual cueing reflects sensitivity to and learning of the global spatial layout of the display, as no other cues distinguish the Old and New configurations. Indeed, search performance was equivalent for the two configuration types at the beginning stages of training. The contextual cueing effect indicates that the invariant global layout of items, the visual context, can be used to guide attention toward probable target locations. This represents a new factor influencing the deployment of visual attention.

The present results can and should be distinguished from the location probability effect reported in previous attention research. Targets appearing in locations that commonly contain targets are detected more rapidly than when

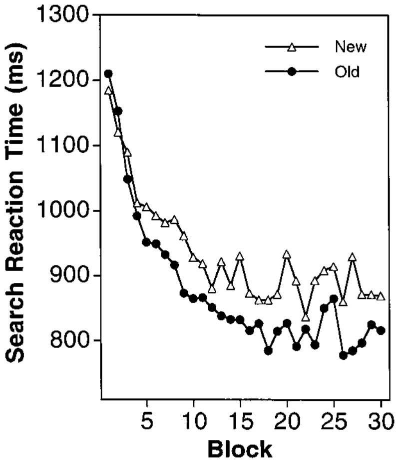

FIG. 2. Reaction time data is shown as a function of block for each configuration condition in Experiment 1 to provide a detailed characterization of the learning function.

they appear in locations that are unlikely to contain targets. Such location probability effects have been shown for absolute spatial position (Shaw, 1978; Shaw & Shaw, 1977) and also for relative positions within a row of stimuli (Miller, 1988). This type of perceptual learning has both retinotopic and object-based components (Suzuki & Cavanagh, 1993). Treisman, Vieira, and Hayes (1992) have additionally demonstrated that such facilitation can be specific for certain types of targets. Logan (in press) has also demonstrated that the spatial location of targets is encoded during target search. In these studies, location probabilities were manipulated by increasing the proportion of targets appearing within a location. Expectancies can also be manipulated with explicit instruction. Both manipulations lead to facilitation in highly likely locations. In contrast, the present study held absolute target location probabilities constant across the Old and New configuration sets, and any facilitation for a given target location was contingent on contextual cues provided by the surrounding configuration. What is common is that given a learned configuration, the location probability effects contingent on that configuration are driving the cueing effect. Both effects exemplify how attention can be allocated in an optimal way to visual displays, maximizing target detection accuracy and search efficiency.

Contextual cueing relies on a highly discriminative instance-based memory for spatial configurations. The visual system is sensitive to spatial layout as demonstrated in change detection paradigms (Simons, 1996) or priming tasks using naturalistic images or line drawings (Sanocki & Epstein, 1997). Most important here is that contextual cueing is based on a discrimination between Old and New spatial layouts, suggesting that the representations are instance-based. This result is highly consistent with a previous study by Lassaline and Logan (1993) who demonstrated automaticity in enumeration tasks using arbitrary visual configurations. Counting performance improved for arbitrary configurations which were repeated throughout the study. An important aspect of their findings was that performance improvements did not transfer to novel configurations, suggesting that instance-based memory representations specific to learned configurations were driving the facilitation instead of general improvement of the algorithm and processes used to count dots. Similarly, we propose that contextual cueing is driven by a beneficial interaction between an instance-based visual memory and spatial attention rather than facilitation of perceptual and attentional processing per se. We refer to these instance-based visual memory traces of context as context maps. The nature of context maps will be examined more specifically in Experiments 3 and 4.

How are context maps acquired? As proposed, contextual cueing represents a form of incidental or implicit learning (Berry & Dienes, 1993; Reber, 1989; Stadler & Frensch, 1998). Subjects were not informed that certain configurations would be repeated, and the speeded response demands of the visual search task would seem to discourage conscious efforts to encode the visual arrays into memory. Although a proportion of observers reported in post hoc questioning that they began to notice that ''something'' was being repeated, it seems unlikely that they would have been able to encode the configurations with much fidelity. None of the observers who noticed repetitions reported making an effort to encode any aspects of the display. Most critically, the results generalized across the entire sample of subjects, the majority of whom did not seem to pick up on this critical manipulation of the experiment.

The cueing benefit obtained from spatial context in this study is akin to the spatial orienting benefit obtained in sequence learning paradigms which illustrate learning without explicit awareness (Cohen, Ivry, & Keele, 1990; Lewicki et al., 1988; Mayr, 1996; Nissen & Bullemer, 1987). In these studies, observers became faster at responding to targets presented in invariant sequences of targets presented in different spatial locations. Each target location was associated with a different response, so that spatial orienting and motor learning were typically confounded. The contribution of spatial orienting versus sequential response production was unclear until Mayr (1996) recently demonstrated spatial orienting learning independent of response output regularities. However, these studies still focused on learning of *temporal* sequences of *single target* presentations toward which an explicit response was always performed. The present contextual cueing effect goes beyond this in demonstrating that a *spatial* array of *nontarget* events can guide spatial orienting.

Yet we have not fully established that learning and the resulting memory were indeed implicit. In the following experiment, we confirm that learning was incidental and, further, test whether the representations for context (context maps) are explicit or implicit by administering a recognition test.

EXPERIMENT 2

In this experiment, we examine the nature of the memory for visual context. The first issue is perceptual specificity. Are observers learning configurations or are they just developing perceptual expertise specific to the surface features (item identities) of the search array? To examine this, the background distractor set of items was changed to a different set of distractors while preserving Old configurations in the second half of the experiment. If observers were learning detailed element identities, little transfer of learning should occur. If they were learning abstract configurations or low spatial frequency aspects of the display, then contextual cueing should persist. Transfer of learning across distractor identity changes in the contextual cueing paradigm would support proposals that representations of visual context can be activated by coarse spatial (low spatial frequency) information in scene recognition (Biederman, 1981; Boyce et al., 1989; Schyns & Oliva, 1994).

The issue of perceptual specificity is important for understanding the nature of representations guiding visual performance. Using a counting task, Lassaline and Logan (1993) demonstrated that instance-based automaticity transferred to new displays in which configurations were preserved but element identity or color was changed. This suggests that instance-based representations do not preserve information that is not relevant to performing a task. In their counting task, the color and identity of the items were truly irrelevant. But in search tasks such as those employed in this study, the identity of items is critical for performance. This may produce highly specific learning which would not transfer across changes in the distractor set. Note, however, that although identity information is important for distinguishing targets and distractors, individual identity information does not need to be specifically encoded. It would be sufficient to tag an item as ''a target'' or ''a distractor'' in order to benefit from repetition. If this is the case, we may expect to replicate Lassaline and Logan's demonstration of transfer across changes in distractor identity even in our search task.

The second issue examined in this experiment was whether this learning occurred without the subjects' conscious effort to learn and recognize the configurations. A configuration recognition task was administered at the end of the present experiment to confirm that the subjects did not explicitly learn to recognize the configurations. The results of this will be important for characterizing contextual memory as explicit or implicit (Schacter, 1987).

Finally, we employed a different search task as well as less discriminative contexts in this experiment to further generalize the contextual cueing effect. Experiment 1 used heterogeneously colored displays, which increases the

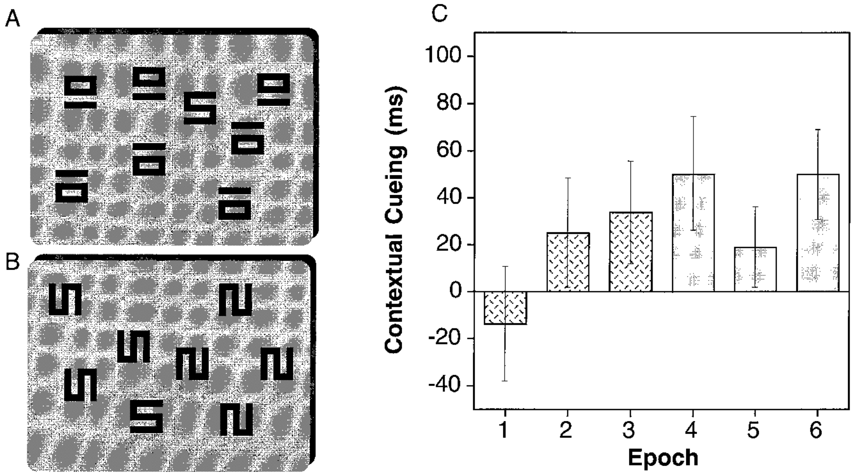

FIG. 3. A schematic example of the search task used in the first 3 epochs (training) of Experiment 2 is shown in Panel A, and an example of the task used in the last 3 epochs (testing) of Experiment 2 is shown in Panel B. The target task was consistent throughout the task, a search for an upright two or an upright five stimulus. Panel C shows the contextual cueing effect as a function of epoch in Experiment 2. Significant transfer from training (stippled bars) to testing (shaded bars) was obtained despite the salient perceptual change in the distractor set. Error bars represent the standard error of the mean.

discriminability of one configuration versus another. The present experiment used monochromatic displays which were less discriminable from each other, providing a stronger test of the memory for context.

Methods

The methods were identical to that of Experiment 1 except where noted. Fourteen subjects searched through visual displays which contained either an upright two or an upright five. These two targets were mirror reflections of each other. The task was to press one of two response keys corresponding to which target was present. Stimulus–response mapping was counterbalanced across the observers. Half of the subjects pressed the ''z'' key if the digit ''2'' was present and the ''/'' key if the digit ''5'' was present. The other half of subjects were given the reverse stimulus–response mapping. A target was present on every trial. The distractors consisted of a roughly equal mixtures of rotated two and rotated five stimuli, adopted from Wang et al. (1994). Each display contained eight items which could appear within an array of 8 × 6 locations. See Fig. 3a for a sample display of the stimuli.

The distractor set was different for the first half and the second half of the experiment, to examine the specificity of the contextual cueing effect. In the first half (Blocks 1 through 12) of 24 blocks of trials, the distractors consisted of the novel shapes shown in Fig. 3a, adopted from Suzuki and Cavanagh (1993). In the second half (Blocks 13 through 24), the distractors were rotated two and five stimuli (Fig. 3b). Observers were informed of the distractor set switch at the beginning of Block 13, as well as in the instructions at the beginning of the session. It was stressed that the target task remained constant throughout the experiment. The background was gray. All items were black.

TABLE 2
Response Time as a Function of Configuration and Epoch in Experiment 2
(Standard Error in Parentheses; *t* Tests Two-Tailed)

	Epoch 1	Epoch 2	Epoch 3	Epoch 4	Epoch 5	Epoch 6
New	815.27	819.99	824.1	850.93	719.2	732.94
	(38)	(42)	(37)	(38)	(30)	(28)
Old	829.09	794.94	790.44	800.78	700.42	683.08
	(41)	(40)	(40)	(34)	(29)	(26)
$t(13)$	−0.57	1.08	1.54	2.09	1.10	2.61
p	.58	.30	.148	.057	.292	.022

The other change in procedure from Experiment 1 was the administration of a configuration recognition test at the end of the session. This was to systematically query whether subjects had noticed the configuration repetition manipulation and, if so, whether they had tried to memorize the spatial layouts of the display. In addition, regardless of whether the observer had noticed the repetition manipulation or not, every observer performed a yes/no recognition test for the configurations presented in that session. At the beginning of the experiment, subjects were not informed that a recognition test would be administered at the end of the session, although they were told that an extra 5-minute task would be administered after the visual search task was completed. At the end of the final block of the visual search task, the experimenter came into the room and described the following sequence of events to be presented on the computer. First, the computer presented a query on the computer screen asking, ''Did you notice whether certain configurations (spatial layout) of the stimuli were being repeated from block to block (press ''y'' or ''n'')?'' If the observer answered ''no,'' the computer proceeded on to the recognition test block. If the observer responded ''yes,'' then the computer asked two additional questions. The first was ''Around when do you think you started to notice repetitions? (Block 1–24)'' and subjects entered corresponding to approximately when they thought they began to notice the repetitions. Following this question, subjects were asked ''Did you explicitly try to memorize the patterns? (press ''y'' or ''n'')?'' After the subject responded to this query, the computer began the recognition test which was administered to every subject regardless of whether or not they had noticed the repetition manipulation. The recognition test was simply a standard block of visual search trials comprised of 12 configurations repeated throughout the experiment and 12 new patterns generated by the computer. But instead of searching for a target, subjects were instructed to respond ''yes'' if they thought they had seen this particular configuration in the earlier visual search blocks or ''no'' if they didn't recognize this configuration. Subjects entered responses at an unspeeded pace, using the ''y'' key for yes responses, and the ''n'' key for no responses.

Results and Discussion

Search task. The search task results are shown in Table 2 and Figure 3c. Significant contextual cueing was obtained in the testing phase of this experiment, pooled across Epochs 4–6 as in the previous Experiment. The magnitude of the difference between Old and New conditions was about 40 ms for these three epochs, $F(1,13) = 6.69$, $p < .03$. Analyzing the RT data across both distractor conditions (all epochs), there was a main effect of epoch, $F(5,65) = 6.79$, $p < .001$. The main effect of configuration did not reach significance, $F(1,13) = 3.01$, $p = .11$. The interaction between configuration and epoch approached significance, $F(5,65) = 2.09$, $p < .08$. A contrast examining only the first and last epoch (Epochs 1 and 6) revealed a significant interaction between Configuration X Epoch, $F(1,13) = 5.75$, $p < .04$. Distractor set was not tested as a variable as this covaried with the epoch variable and was not a focus of interest in this experiment. As in Experiment 1, subjects performed well in this task, averaging 98% correct performance in both Old and New configuration conditions.

The abrupt increase in RT at Epoch 4 was most likely due to the increased difficulty of the search task. The distractors used in the second half of the experiment were more similar to the targets, and this produces less efficient search (Duncan & Humphreys, 1989). It is unlikely that the contextual cueing effect obtained after the distractor switch is due to a selective jump in RT in the New condition. This is because target–distractor discriminability would have affected search efficiency in both Old and New conditions by an equal magnitude, if we assume distractor identity played no role in matching to instances in memory. In fact, if distractor identity played a role in memory retrieval, the distractor switch should have disrupted the Old patterns even more, contrary to what was obtained here. Thus, the significant difference between Old and New conditions cannot be due to the distractor switch, but must be due to contextual cueing alone.

Hence, the results replicated those of Experiment 1. Repeated exposure to an otherwise arbitrary configuration facilitates discrimination for targets appearing within a constant location within that configuration. This benefit was obtained even though the distractor set was different in the initial stages of training. Significant savings was observed for the set of configurations preserved throughout the experiment. This indicates that the configurational priming effect reflects an effect of global spatial layout rather than perceptual learning of the low-level image properties of the display.

We attempted to get a rough assessment of whether the magnitude of contextual cueing in the second half of this experiment was comparable to learning conditions in which a consistent distractor set was used throughout the session. We tested 12 subjects in a separate experiment which was identical to the present experiment except that the targets were presented among rotated 2 and 5 distractors throughout the session. This allowed for a between-group comparison of contextual cueing for Epochs 4–6. The magnitude of contextual cueing was 55 ms compared to the 40 ms obtained in this experiment, $F < 1$. Most compelling was that the magnitude of contextual cueing for Epoch 4 alone was comparable to the present study ($M = 43$ vs 50 ms, $F < 1$).

The results suggest that the perceptual identities of distractors were not encoded with much fidelity while global configurations were being learned, and this supports earlier proposals that coarse visual information is sufficient to drive perceptual schemas in scene perception (Biederman, 1981; Boyce et al., 1989). Our results are also consistent with the idea that visual processing for scenes comprised of objects progresses in a global-to-local, or low spatial frequency to high spatial frequency manner (Navon, 1977; Schyns & Oliva, 1994). Such a strategy may indeed be driving contextual cueing in the present study, but we caution against drawing general conclusions about global-to-local visual processing because this is dependent on both low-level factors such as the stimulus' spatial frequency spectrum (Kinchla & Wolfe, 1979) and high-level factors such as the diagnosticity of a particular spatial scale for a given scene categorization task (Oliva & Schyns, 1997). Moreover, although we believe coarse visual information is sufficient for our task, this does not imply that perceptual identity is never important. Clearly the spatial configuration of separate identities becomes important with increased expertise (as in memory for chesspiece configurations) and perhaps as the heterogeneity in content between scenes is increased (kitchen vs living room). The two distractor sets shared many basic visual features with each other and with the target. Introducing more heterogeneity should increase the contribution of perceptual identity in defining context. However, when the identity of the items does not effectively distinguish one exemplar from another, as in the present experiment, it seems likely that the distractors are simply being tagged as nontargets, distinguishing them from the target locations but not from other distractors. Such coarse coding would be more than adequate for the present task.

Our present results are consistent with proposals by Logan (1988; 1990) stating that the representations underlying automaticity reflect how the items were interpreted during the task. Thus in dot-counting tasks, learning transferred across changes in element identity and color groupings of items because these attributes were irrelevant to performance (Lassaline & Logan, 1993). An interesting difference between enumeration tasks and search tasks is that identity information distinguishing target and distractors is fundamental for search. We will demonstrate in Experiment 3 that the target/distractor distinction is indeed critical. However, the present experiment indicates that further detail (such as the exact identity of the distractors) in the instance-based representations is not relevant. In sum, the representation of instances which support automaticity or contextual cueing does not preserve all information present in the stimulus, but is constrained (optimized) by the nature of the task and by an ''attentional filter'' (Lassaline & Logan, 1993). Only information relevant to performing a task participates in the encoding and automatic retrieval of instance-based representations. In the present experiment, the instance-based representations of context appear to be limited to a global spatial layout of items with tags of individual elements grossly labeled as ''the target'' and ''nontargets.''

Explicit recognition task. The results of the recognition test and questioning support the hypothesis that contextual cueing is driven by incidental learning of implicit memory representations for configurations. Mean accuracy in the explicit recognition task was 52%. Subjects correctly classified Old patterns as old on 39.3% of the trials (hit rate), and this did not differ from their false alarm rate of 35.1%, $F(1,13) = 1.10$, $p > .31$. Only 3 of the 14 subjects reported that they noticed that certain configurations were being repeated. One reported noticing this at around the fifth block (Epoch 2) of the experiment; the other two reported noticing this in approximately the twelfth block (Epoch 4). All of these ''aware'' observers stated that they did not try to explicitly encode the patterns or configurations; their hit and false alarm rates in the recognition test were 41.7 and 50.0%, respectively ($F < 1$). The magnitude of contextual cueing (pooled across Epochs 4–6) for the Aware group was 53 ms, and for the Unaware group it was 36 ms, $F < 1$. The power of this test was low, but the results from another recognition test conducted in Experiment 5 further confirm that the magnitude of contextual cueing does not correlate with awareness of the repetition manipulation.

Hence, we conclude that contextual cueing is driven by implicit memory representations that were acquired incidentally. Observers were clearly not able to distinguish which patterns were repeated throughout the experiment, although the presence of contextual cueing indicates that their search performance benefited from repeated exposure. We have replicated this failure of explicit recognition in a separate experiment (Experiment 5). A recognition test was not administered to the subjects in our other experiments since it seemed sufficient to demonstrate that contextual cueing could be obtained in the absence of explicit strategy or awareness. One could argue that the distractor set switch in the present experiment would have reduced the strength of any memory representations for the stimuli arrays. However, the fact remains that significant contextual cueing was observed. Although it is always possible that a future population of observers may notice the repeated configuration manipulation and capitalize on some encoding strategy, explicit encoding is not a central factor nor a necessary condition for contextual cueing.

The implicit nature of contextual guidance appears to be a very useful property for vision since explicit recognition or conscious learning is a computationally expensive or capacity-limited process (Lewicki et al., 1988). Reber (1989) has argued that implicit learning is more robust than explicit learning. Note that we are not proposing that context memory must be implicit, nor do we believe that this is driven by a memory system which would be different from one that may support the explicit recognition of contexts. Other learning paradigms have demonstrated parallel effects in performance measures of implicit memory and recognition judgments (Logan, in press). For contextual cueing, an implicit/explicit memory distinction is an empirical issue that can only be addressed with other types of converging evidence, such as data from amnesic patients or functional imaging. And as noted earlier, we currently hypothesize that a single memory system exists for both implicit/explicit visual context information, which can be accessed in different ways through multiple cognitive (and perceptual) procedures which can be characterized as explicit or implicit (Roediger, 1990). The main conclusion here is that memory and learning of context does not have to be explicit. Furthermore, it is unclear whether explicit recognition or conscious learning strategies would confer significant benefit for contextual cueing. Pilot data from our lab suggests that it is very difficult to memorize the configurations while performing visual search. Explicit recognition depends on higher-level decision processes and other factors which, if anything, may retard any beneficial influences for on-line, covert processes such as search.

EXPERIMENT 3

There are several reasons to believe that contextual cueing is not a low-level repetition priming effect. First, target locations are cued rather than target identities or task responses. Stimulus and responses are typically correlated in most of the earlier studies that demonstrated repetition benefits or sequential learning (Lassaline & Logan, 1993; Lewicki et al., 1988; Nissen & Bullemer, 1987, though see Mayr, 1996, for a demonstration of spatial orienting learning independent of response requirements). Second, Experiment 2 showed that global spatial configurations were learned independent of surface features of the array. Yet it is still possible that the facilitation obtained in contextual cueing may represent a form of low-level repetition priming which facilitates perceptual processing of the learned displays. We pursue a different account in which contextual cueing represents the acquisition of associations between target locations and informative contexts. However, the data from the first two experiments are consistent with both accounts.

To distinguish the expertise account (low-level perceptual priming) versus the associative learning hypothesis, target locations were allowed to vary freely within configurations across repetitions in Experiment 3. Hence, the global configuration is no longer predictive of the target location. If observers are becoming more efficient in searching through repeated configurations, then a benefit should still be obtained for repeated arrays. However, if contextual cueing represents associative learning between target locations and contexts, little or no benefit should be obtained for repeated configurations in this experiment.

Method

The methods were identical to that of Experiment 2 except where noted.

Design and procedure. Ten subjects searched through displays for upright two or five stimuli targets as before. The distractors consisted of the novel shapes used in the first half of Experiment 2 (see Fig. 3a).

The main contrast with the previous two experiments is that targets were allowed to appear within any of the item locations within a particular configuration. Old configurations and distractor identities within those configurations were held constant and repeated from block to block, as in the previous experiments. Targets were allowed to rove in New configurations also. Relaxing target location constraints within the configurations led to unequal expected

TABLE 3
Response Time as a Function of Configuration and Epoch in Experiment 3 (Standard Error in Parentheses; *t* Tests Two-Tailed)

	Epoch 1	Epoch 2	Epoch 3	Epoch 4	Epoch 5	Epoch 6
New	857.36	802.76	780.44	771.67	771.09	764.78
	(65)	(70)	(63)	(56)	(48)	(50)
Old	866.98	809.53	773.93	774.99	794.14	769.16
	(61)	(60)	(64)	(60)	(67)	(52)
$t(9)$	−0.63	−0.36	0.37	−0.34	−1.00	−0.41
p	.545	.731	.722	.743	.343	.690

target location probabilities between Old and New configurations. In order to equate the probabilities, target locations were sampled evenly from all possible item locations within the 8 × 6 grid. The 48 possible item locations yielded 6 different mutually exclusive sets of 8 randomly chosen locations, yielding a total of 6 different configurations. For each configuration condition, this selection procedure was repeated twice to produce 12 different configurations. Hence, the probability of any target location's being selected on any given trial was equated across both Old and New configuration conditions.

Results and Discussion

A contextual cueing effect was *not* obtained in this experiment, suggesting that it depends on associations between configurations and target locations. The results are shown in Table 3 and Fig. 4. An ANOVA revealed no main effects of configuration, neither in the restricted analysis (Epochs 4–6) nor in the full analysis (all F's < 1); no main effects of configuration nor significant interactions with epoch were obtained (all F's < 1). There was a main effect

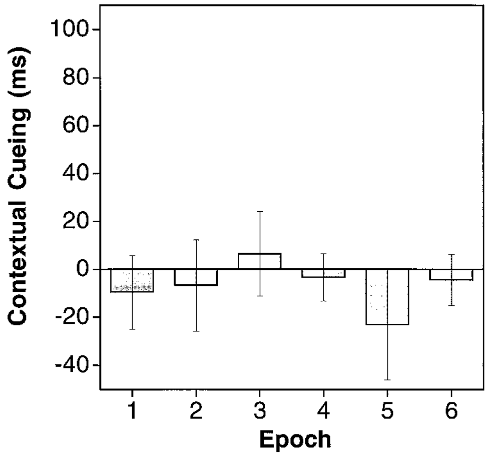

FIG. 4. Contextual cueing as a function of epoch in Experiment 3 using varied mapping. No benefit was obtained when the contexts were not predictive of target location.

of epoch, $F(5,45) = 10.35$, $p < .001$. An interaction between Configuration × Epoch was not obtained for the contrast between just Epochs 1 and 6 ($F < 1$). Overall accuracy was 98% in both configuration conditions.

The present results suggest that observers were not learning to search through repeated configurations more efficiently, but rather were learning where a target was most likely to appear given a predictive context. In other words, the contextual cueing effect obtained in Experiments 1 and 2 reflects the associative learning of configurations and target locations rather than automatic perceptual facilitation of repeated visual arrays, distinguishing our findings from common forms of low-level repetition priming.

Note, however, that contextual cueing can be considered a form of repetition priming if one construes the effects of repetition to prime associations between repeated stimuli and a critical task variable. Logan (1990) demonstrated that priming also depends on how repeated stimuli were interpreted within the context of a task, rather than on stimulus repetition per se. In the present experiment, the variable target locations minimized the formation of useful associations; hence, no benefit of repetition was obtained. Thus, our results cannot be explained in terms of low-level repetition priming, but they can be understood as a form of high-level priming which is contingent on the demands of a repeated task (Logan, 1990).

The lack of contextual cueing in this experiment fits in particularly nicely with a recent study by Wolfe et al. (1997), who showed that there was no benefit for repeating search arrays per se. In his study, arrays of different objects were repeated for several consecutive trials. Observers were required to search for a target which could be different from trial to trial. If subjects could learn which objects were present in the repeated displays, search performance should be facilitated with increased repetition. However, no such benefit was obtained. Wolfe proposed that once attention is drawn away from a visual object, the visual representation of that object reverts to its preattentive state, such that there is no memory for the attended object. At first glance, our contextual cueing findings appear to be at odds with his results: Wolfe and his colleagues obtained no benefit of repetition whereas we have in Experiments 1 and 2. Although there are a number of differences between the two paradigms, a critical difference is one of varied versus consistent mapping (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). In our experiments, each Old configuration was associated with a unique target location, producing a consistent mapping between the context and the target location (not the target identity or associated response). In their study, each of the repeated search arrays was associated with many targets (which could change from trial to trial) producing a varied mapping between the search array (context) and response variable (target presence). Hence, much more information needs to be learned for a benefit to emerge in Wolfe's paradigm. This points to an important aspect of visual processing. Rather than encoding all that information, the visual system opts to rely on the visual image itself as the memory (O'Regan, 1992; Rensink et al., 1997; Simons & Levin, 1997).

Although contextual cueing relies on consistent mapping to capitalize on useful invariances, the RT benefit in search does not necessarily reflect the gradual withdrawal of demands on attention with practice as proposed by Schneider and Shiffrin (1977; Shiffrin & Scheider, 1977). This classical view of automaticity corresponds to a perceptual priming account of our data in which items become processed and searched through more quickly. In contrast, instance theory proposes that performance improvements reflects the increased probability of a solution's being retrieved from memory over algorithm (Logan, 1988). Thus, rather than increasing the efficiency of processing, contextual cueing may be driven by interactions between memory and attention which guide the deployment of attention towards the target location. The cue validity of such interactions is increased by repeated exposure to a global spatial layout in which the target appears within a consistent location.

EXPERIMENT 4

The present experiment was designed to provide more direct empirical support for the assumption that context guides spatial attention towards the target. The standard measure of search efficiency is target detection RT slopes as a function of varied set size. As a search task becomes more efficient, its target slope will get smaller. If contextual cueing guides spatial attention, then we should observe a decrease in search slopes with increased training. This decrease should be greater for Old configurations. Furthermore, little difference is expected between the intercepts of Old and New configuration conditions. This is because we hypothesize that contextual cueing does not represent early facilitation of perceptual representations (operating over the entire visual display in parallel). This is also consistent with our view that contextual cueing does not represent priming of late motor responses. We test these predictions on search slopes and intercepts by examining contextual cueing and search performance across three different set sizes: 8, 12, or 16 items.

Method

The methods were identical to that of Experiment 1 except where noted.

Design and procedure. Thirty-four subjects searched through displays for rotated T targets among L distractors. These were identical to the ones used in Experiment 1, except that monochromatic stimuli were used in this experiment (white items on a gray background).

Three different set sizes were tested in this experiment (8, 12, 16), intermixed within blocks. The set-size factor was crossed with the configuration and epoch factors. This produced 4 configurations of each set size for each configuration type within each block. Items were

TABLE 4
Response Time as a Function of Configuration and Epoch in Experiment 4
(Standard Error in Parentheses; *t* Tests Two-Tailed)

	Epoch 1	Epoch 2	Epoch 3	Epoch 4	Epoch 5	Epoch 6
Set Size 8						
New	1094	947	907	833	839	819
	(39)	(29)	(36)	(25)	(27)	(27)
Old	1091	941	847	794	785	748
	(39)	(35)	(32)	(22)	(24)	(22)
$t(31)$	0.07	0.23	1.48	1.37	2.23	2.73
p	.943	.819	.149	.182	.033	.01
Set Size 12						
New	1340	1156	1095	1017	1033	989
	(38)	(37)	(38)	(43)	(41)	(36)
Old	1216	1066	966	929	908	863
	(39)	(36)	(33)	(32)	(39)	(30)
$t(31)$	3.01	1.89	3.32	2.19	2.94	3.35
p	.005	.068	.002	.036	.006	.002
Set Size 16						
New	1665	1387	1284	1192	1156	1100
	(51)	(50)	(40)	(52)	(43)	(39)
Old	1494	1319	1148	1052	1022	964
	(47)	(46)	(45)	(29)	(36)	(35)
$t(31)$	2.73	1.67	3.62	3.25	3.55	3.75
p	.010	.106	.001	.003	.001	.001

randomly positioned in cells of an invisible 12 × 8 matrix subtending roughly 54 × 37 degrees of visual angle.

Results

The data from two subjects were removed and replaced due to an excessively high error rate. The RT means of each configuration condition and epoch were calculated individually for each observer. The means of these means are presented in Table 4. Search slopes and intercepts were derived from each individual's mean data. These were averaged and the results are presented in Fig. 5. Figure 5a shows the slope data as a function of configuration condition and epoch, Fig. 5b shows the corresponding intercept data, and Fig. 5c shows the contextual cueing measure for each set size condition as a function of epoch. The data were analyzed using multivariate ANOVA with configuration (New vs Old), Epoch (1–6), and set size (8, 12, and 16) as factors.

First, a significant contextual cueing effect was obtained in the last three epochs, $F(1,31) = 26.85$, $p < .001$. This was significant for all three set sizes [$F(1,31) = 5.25$, 10.68, and 17.93; p's $< .03$, .003, and .001 for set sizes 8, 12, and 16, respectively]. Across the entire experiment, there were

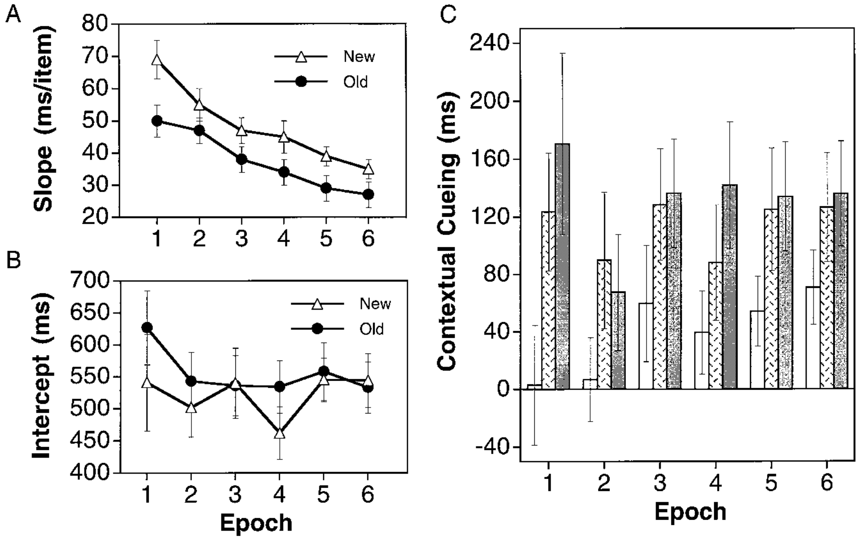

FIG. 5. Results of Experiment 4. Panel A shows average search slopes as a function of epoch for each configuration condition. These were significantly shallower for Old configurations. Panel B shows the corresponding intercept data. There was no significant difference between the two conditions. Panel C shows contextual cueing as a function of epoch, broken down by set size for each configuration condition. The scaling used for the Y axis is larger than in other figures. Error bars represent the standard error of the mean.

significant main effects of configuration, $F(1,31) = 28.01, p < .001$, epoch, $F(5,27) = 69.77, p < .001$, and set size, $F(2,30) = 213.07, p < .001$. Significant two-way interactions were obtained for Setsize × Configuration, $F(2,30) = 3.83, p < .04$, showing a greater benefit for larger set sizes, and Set Size × Epoch, $F(10,22) = 7.69, p < .001$, indicating more efficient search as the session progressed. The two-way interaction between Configuration × Epoch approached significance, $F(5,27) = 2.23, p = .08$. The three-way interaction between Configuration × Epoch × Set Size was not significant.

Analyzing the slope data, there was a significant main effect of configuration, $F(1,31) = 6.40, p < .02$, and epoch, $F(5,27) = 11.24, p < .001$. The interaction between Configuration × Epoch was not significant. This lack of an interaction is problematic, and a possible reason for it is that contextual cueing may have emerged early within the first epoch. We will explore this conjecture in the Discussion section. The intercepts revealed no significant main effects between configuration or epoch, nor interactions. This pattern was also obtained for an analysis restricted to the last three epochs.

Discussion

The main finding is that contextual cueing is supported by a reduction in target search slopes rather than a reduction in intercept times. Thus we can

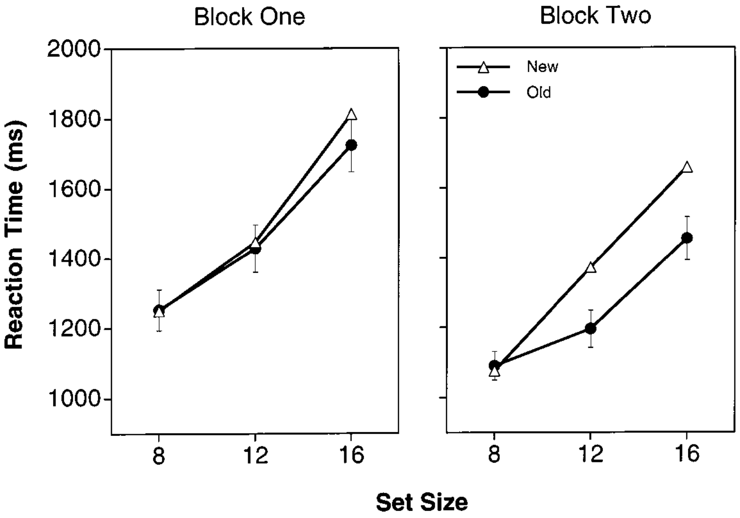

FIG. 6. Search RT plotted against set size for each configuration condition is shown for Block 1 and Block 2. This is to provide a more detailed analysis of contextual cueing which was significant for Epoch 1 unlike all of our other data. The reason for this appears to be rapid learning. Contextual cueing was not significant for Block 1, but became significant by Block 2. Error bars represent the standard error of the mean and are shown only for the Old condition. The New condition produced similar values.

conclude that contextual cueing allows for the context to guide attention towards the target location more efficiently rather than speeding up other search processes such as initial perceptual processing of the display or later decision processes involved in selecting a response.

One puzzling aspect of our results is the lack of a three-way interaction between Configuration × Epoch × Set Size for target discrimination RT (or equivalently a significant two-way interaction between Configuration × Epoch for slope measures). Significant interactions should have been obtained since contextual cueing should only emerge after implicit learning of associations between target locations and search configurations has been established in early epochs. Examination of Figs. 5a and 5c reveals that the problem is that contextual cueing is already significant at Epoch 1! This contrasts with our previous experiments in which contextual cueing was never significant for the first Epoch of trials. It is possible that the heterogeneous array of set sizes used in this experiment may have made the configurations more distinct in this experiment than in previous ones. If so, contextual cueing may be occurring earlier, perhaps within the first few blocks within the first epoch.

We analyzed the data as a function of block of Epoch 1. The RT data for Blocks 1 and 2 are plotted as a function of set size in Fig. 6. It is clear from this graph that contextual cueing emerges after just one cycle of presentations. Contextual cueing is not significant at any set size for Block 1 (all p's $> .41$), but is significant at both set sizes 12 and 16 in Block 2 (two-tailed $t(31) = 2.85$ and 2.76; $p = .008$ and .01, respectively). The two-way interaction between Configuration × Block (1 and 2) had a tendency towards significance, $F(1,31) = 2.89$, $p = .099$. The three-way interaction between Configuration × Block × Set Size was not significant. The lack of significant interactions may be due to lack of power (small N of trials within each block; median scores produced similar results). Nevertheless, contextual cueing was not significant in Block 1 and it was significant in Block 2. It appears that the set size of a trial may serve as an additional cue to further discriminate one configuration from another, making contextual cueing significant within a single repetition. This may benefit larger set sizes to a greater extent.

In sum, contextual cueing appears to increase the efficiency of search by guiding the deployment of visual attention toward target locations (reducing search slopes) rather than by facilitating early perceptual processing or late motor response selection and execution (intercepts did not differ between configuration conditions).

EXPERIMENT 5

For context to be of much benefit for on-line visual processes such as search, the influence of context should occur relatively soon after initial perceptual registration of the incoming image. Biederman (1982) argued that contextual scene coherency exerts its effects on target detection performance in early stages of visual processing, perhaps in concert with object recognition processes. In our experiments, contextual cueing was obtained for search tasks which were typically completed within 1 s, suggesting that contextual guidance occurs rather early, perhaps within the first few hundred ms of visual processing. Although it is not possible to determine the actual time course of contextual guidance using behavioral measures, we can further strengthen the plausibility of early guidance by limiting the duration of visual exposure. To the extent that flashing the displays reduces search performance (in comparison to when the search display is available until a response is made), we can infer that the internal representations of the search arrays were not available to search mechanisms for as long as prolonged displays were.

Flashed displays also allow us to examine another issue. Since we did not constrain eye movements in previous experiments, it is possible that the RT benefit reflected procedural learning of saccade patterns. By this account, contextual cueing reflects facilitation of the programming and execution of eye movements, making it a type of motor skill acquisition. The use of flashed displays disallows multiple eye movements from contributing to per-

TABLE 5

Response Time (Epochs 1–4) and Accuracy (Epochs 5 and 6) as a Function of Configuration and Epoch in Experiment 5 (Standard Error in Parentheses; *t* Tests Two-Tailed, Shown Only for Accuracy in Epochs 5 and 6)

	Epoch 1	Epoch 2	Epoch 3	Epoch 4	Epoch 5	Epoch 6
New	1329	1142	1067	1034	812 (25)	815 (34)
	(64)	(53)	(42)	(51)	.72 (.02)	.75 (.03)
Old	1316	1076	1010	958	801 (30)	800 (44)
	(64)	(51)	(39)	(44)	.78 (.02)	.79 (.03)
$t(17)$	0.32	2.62	2.72	2.40	2.81	1.85
p	.75	.018	.015	.028	.01	.08

formance, so contextual cueing in this experiment would suggest that it is not dependent on such overt motor skills.

Method

The methods were identical to that of Experiment 1 except where noted.

Design and procedure. Eighteen subjects searched through displays for rotated T targets among L distractors. These were identical to the ones used in Experiment 1, except that monochromatic stimuli were used in this experiment (white items on a gray background).

This experiment employed 20 blocks (4 epochs) of the speeded response visual search task as before. This constitutes the training phase of the experiment. The standard speeded search procedure (as opposed to flashed displays) produces more effective learning because the displays are present on the screen until the target is located. This allows target location and context associations to be acquired and strengthened on every trial.

After contextual cueing was established in the training phase, an accuracy version of the task was administered. This consisted of 10 blocks (2 epochs) of search trials which were identical to the speeded response task except that the search displays were flashed briefly for 200 ms. This manipulation precludes subjects from making additional eye movements and also reduces the effective duration of the visual array (Sperling, 1960), impairing target detection performance. Accuracy was stressed over speed in this task. We did not employ masks because search performance was already quite low without further disruption of the presentations, suggesting that internal representations of the displays had rapidly faded. Furthermore, the use of masks would not have ensured disruption of visual representations at higher stages of visual processing anyway. The two epochs of accuracy task trials were preceded by two blocks of practice in which the subjects were familiarized with the flashed display procedure. Only New configurations were presented in the practice blocks.

An explicit recognition test was administered to subjects in this experiment at the end of each session. The procedure for this was identical to that of Experiment 2.

Results

Search task. The search task results are shown in Table 5 and Fig. 7. A significant contextual cueing effect was obtained in the training phase of the experiment using the standard speeded response task (Epochs 1–4). There was an overall main effect of configuration, $F(1,17) = 5.07$, $p = .038$, and epoch, $F(3,51) = 65.06$, $p < .001$. The interaction between Configuration × Epoch was not significant, $F(3,51) = 1.76$, $p > .15$, although there was

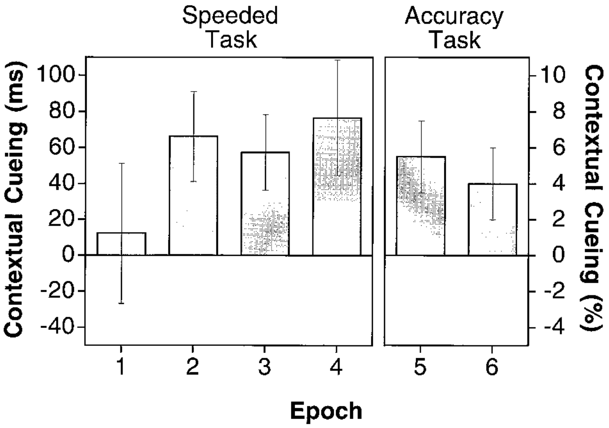

FIG. 7. Contextual cueing in Experiment 5, shown separately for each task. The RT differences are shown for Epochs 1–4, and the accuracy differences are shown for Epochs 5–6. The accuracy data were calculated by subtracting New configuration performance from Old configuration performance. Hence, the positive values indicate a benefit for Old configurations.

a trend toward significance for the contrast between the first and last epoch of the RT test (Epochs 1 and 4), $F(1,17) = 3.53$, $p < .08$. Overall accuracy was 99% correct in the speeded task.

A benefit in accuracy was also obtained for Old configurations in the testing phase of the experiment, as shown in Table 5 and Fig. 7 (Epochs 5 and 6).[2] Flashing the displays reduced the effective duration of the search arrays such that baseline target search performance dropped from 99% correct to around 74% correct. Yet significant contextual cueing was obtained as a benefit in accuracy for Old configurations versus New configurations. Pooled across Epochs 5 and 6, a significant main effect of configuration was obtained, $F(1,17) = 6.70$, $p < .02$. There was no main effect of epoch or interaction with configuration (p's $> .25$).

Explicit recognition test. The results of the recognition test and questioning replicated those obtained in Experiment 2, strengthening the claim that contextual cueing is driven by implicit representations. Mean accuracy in the explicit recognition task was 53%. Subjects correctly classified Old patterns as old on 47% of the trials (hit rate), and this did not differ from their false alarm rate of 42% ($p > .18$). Seven out the 18 subjects reported that they noticed that certain configurations were being repeated. On average, they reported noticing that repetitions were occurring around the 6th block into the session. None of these aware observers reported trying to explicitly encode the patterns or configurations. The hit rate and false alarm rates of

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[2] RT is also shown in Table 5. These did not differ significantly between conditions. Note that we informed our subjects that a speeded response was not required for the accuracy task.

aware subjects in the recognition test were 54 and 49%, respectively ($F < 1$). Interestingly, the aware group of observers produced an apparently smaller contextual cueing effect in the flashed display task [M = 1 versus 7% for the unaware group, $F(1,16) = 3.55$, $p = .08$]. This pattern mirrored their RT data. Pooled across Epochs 2–4, the magnitude of contextual cueing was only 14 ms for the Aware group compared to 94 ms for the Unaware group, $F(1,16) = 4.76$, $p < .05$. There was one outlier in the Aware group who showed a negative contextual cueing effect, and when this observer's data was removed, contextual cueing was 35 ms, $F(1,5) = 8.07$, $p = .04$ for the speeded response task, but remained at 1% for the flashed display task ($F < 1$).

Discussion

The results are consistent with models which propose that context may play a role in the first few hundred ms of visual processing (Biederman et al., 1982). This behavioral evidence is very indirect, and our lab is currently employing electrophysiological methods to obtain a more direct measure of the time course of contextual effects on visual search processes.

Our data from briefly flashed displays demonstrate that contextual cueing can be obtained without eye movements. This distinguishes contextual cueing from procedural learning of motor responses in serial reaction time tasks (Cohen et al., 1990; Lewicki et al., 1988; Nissen & Bullemer, 1987). But rather than focusing on a distinction, we believe that our findings can be integrated with the motor learning literature by conceptualizing the guidance of spatial attention as a form of *covert* procedural learning. Furthermore, we are not claiming that eye movements are not important. Indeed, the functional significance of contextual cueing is to guide attentional deployment whose primary function, in turn, is to guide eye movements.

Finally, we established that contextual cueing does not correlate with awareness of the repetition manipulation. Observers who reported that they noticed that certain configurations were being repeated did not perform beyond chance in the explicit recognition test replicating Experiment 2. Moreover, their contextual cueing effects were smaller than those obtained for the Unaware group for both RT measures in the speeded response task and accuracy measures in the flashed display task. We do not claim that there is a dissociation between performance and awareness because a smaller contextual cueing effect for the aware group was not obtained in Experiment 2. However, awareness of the repetition manipulation clearly does not confer any benefits for recognizing the patterns or search performance. Contextual cueing is driven by implicit representations which are acquired incidentally.

EXPERIMENT 6

In this experiment, we examined the robustness of contextual cueing across perturbations in the configurations and changes in target locations. In the previous experiments, contextual cueing was obtained for spatial configurations which were fully identical across repetitions. Items were jittered to prevent colinearities with other stimuli, but the magnitude and direction of jitter was preserved across repetitions for any given configuration. In the present experiment, we allowed items to jitter randomly within their cells across repetitions to provide an initial test of the robustness of learning. Using Logan and Lassaline's (1993) enumeration task of random dot configurations, Palmeri (1997) showed that automaticity effects (learning) generalized to new distorted exemplars of learned spatial configurations. The amount of generalization correlated with the degree of similarity between test and training exemplars. These types of results are useful for extending findings from automaticity paradigms to the rich literature on classification learning (Medin & Schaffer, 1978; Nosofsky & Palmeri, 1997; Posner & Keele, 1968). Although a detailed investigation is beyond the scope of the present article, significant contextual cueing in the present experiment will facilitate conceptual links between our paradigm and formal theories of perceptual classification.

Our second question was to examine whether contextual cueing would generalize to more than one target location for a given configuration. The utility of contextual guidance would be limited if it were restricted to a single location. We test whether learning allows the context to cue more than one target location. For any given configuration, the target is allowed to appear in one of two locations. These two modifications of the old configuration condition, jitter and two target locations, provide a stringent test of the robustness and generality of contextual cueing.

Finally, we also test performance for targets appearing in untrained nontarget locations. Slower RT's should be obtained for targets appearing in distractor locations after training. There are two different hypotheses which predict slowing for locating targets in distractor locations. One is an inhibition mechanism which actively inhibits distractor locations while allocating spatial attention to the learned target location. The other is a simple queuing account in which contextual cueing prioritizes target locations such that distractor locations receive attentional allocation at a later time. According to visual search models such as Guided Search, items in a search array are attended to according to a list of ''activations'' of decreasing strength (Cave & Wolfe, 1990; Chun & Wolfe, 1996; Wolfe, 1994a). It would be difficult to distinguish empirically between the inhibition and queing accounts. However, we can examine whether RT's to targets appearing in nontarget locations in learned configurations are faster than, comparable to, or slower than baseline performance defined by targets appearing in New configurations. It would be unlikely that targets in learned distractor locations would be faster than baseline, given that subjects do not appear to be searching through repeated displays more quickly (Experiment 3). Instead, RT's for targets in learned distractor locations would be slower or comparable to baseline if contextual cueing deprioritizes distractor locations. We test for this in the last epoch of each session after training has established significant contextual cueing for target locations.

Methods

The methods were identical to those of Experiment 1 except where noted. Sixteen observers participated in visual search tasks using white rotated T targets amongst rotated L distractors, as in Experiment 4. The main differences from previous experiments were that Old configurations were generated differently and Epoch 6 was a transfer session in which the targets appeared in previous distractor locations.

First, each Old configuration was associated with two target locations in this experiment instead of just one. From Blocks 1 to 20, the target was presented at one of the two locations in 10 randomly selected blocks, and it was presented at the other location in the other 10 blocks. Thus, targets appeared 10 times in each of these two locations throughout the experiment.

Second, the exact positions of items within Old configurations were allowed to jitter from repetition to repetition. These positions were randomized around the center of each cell, and the magnitude of the jitter was from −12 to 12 pixels from the center (a range of about 1.6 degrees of visual angle), with possible magnitude of −12, −8, −4, 0, 4, 8, 12 pixels in both horizontal and vertical directions.

Finally, in the testing session (Blocks 21–24), targets were presented in randomly selected distractor locations rather than previously trained locations. Presumably, if there were cueing effects in the first five epochs, subjects would attend to previously trained locations first. Since the target was located elsewhere, we predict that search performance would be equal to or worse than targets in New configurations where no locations were prioritized by learning. Significantly slower performance would be obtained if untrained locations in Old configurations were actively inhibited.

Results

The RT benefit measure is shown in Fig. 8 (see also Table 6). Restricting the analysis to Epochs 4 and 5 revealed a significant contextual cueing effect with a magnitude of 35 ms, $F(1,15) = 6.80$, $p = .02$. Across all epochs, the main effect of configuration was marginally significant, $F(1,15) = 4.12$, $p = .06$. The main effect of epoch was significant, $F(4, 60) = 55.63$, $p < .001$. The Configuration × Epoch interaction was not significant. However, comparing contextual cueing for Blocks 1 and 2 (M = −12 ms) versus Blocks 17 and 18 (M = 54 ms) revealed an increase which approached significance, $t(31) = 1.68$, $p < .06$, one-tailed. Overall accuracy was 98% for each configuration condition.

In the last testing epoch, targets always appeared in previous distractor locations in Old configurations. Responses in the Old condition were 17 ms slower than in the New condition, but this difference was not significant, $F < 1$. Although we cannot conclusively state that inhibition did not occur, a significant interaction of Configuration and Epoch for Epochs 5 and 6, $F(1,15) = 5.64$, $p = .03$, confirms that contextual cueing for target locations did not transfer to distractor locations.

Discussion

Significant contextual cueing was obtained even though items within configurations were allowed to jitter in location across repetitions (see Fig. 8).

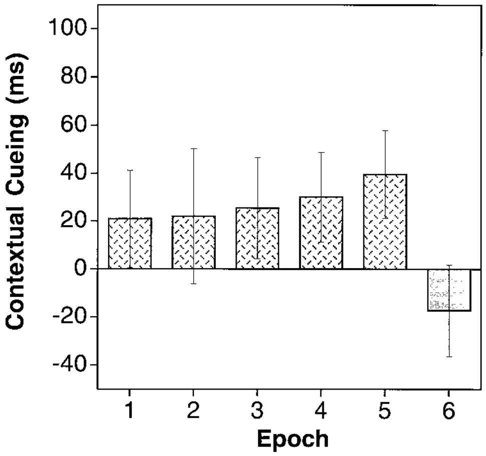

FIG. 8. Contextual cueing in Experiment 6. Targets appeared in one of two locations and the elements within configurations were allowed to jitter from repetition to repetition. A significant contextual cueing effect was obtained in this phase of the experiment (Epochs 1–5, stippled bars in the figure). In Epoch 6, the targets were presented in previous distractor locations. No significant benefit or cost was obtained.

We propose that contextual representations are instance-based (Logan, 1988), but it is important to remember that these representations support generalization to similar exemplars as well as to averaged prototypes (Medin & Schaffer, 1978; Nosofsky & Palmeri, 1997; Palmeri, 1997). The present results make it likely that these findings on classification learning or automaticity may apply directly to our contextual cueing paradigm. In other words, formal theories of perceptual classification may be applied toward understanding how categorical structure of contexts can be learned from exemplars and how these can be applied to new instances. Future efforts to integrate the two areas will benefit from the fact that contextual

TABLE 6

Response Time as a Function of Configuration and Epoch in Experiment 6. In Epoch 6, Targets Appear in Distractor Locations (Standard Error in Parentheses; *t* Tests Two-Tailed)

	Epoch 1	Epoch 2	Epoch 3	Epoch 4	Epoch 5	Epoch 6
New	1200	1048	975	927	883	844
	(39)	(39)	(30)	(24)	(27)	(18)
Old	1179	1026	950	897	844	861
	(45)	(39)	(33)	(24)	(29)	(27)
t(15)	1.02	.78	1.2	1.61	2.16	−.91
p	.322	.45	.248	.129	.048	.376

cueing is supported by the same type of novel item configuration displays used in classification learning studies (Palmeri, 1997; Posner & Keele, 1968).

The contextual cueing effect also generalized to two target locations. Although this is not much of an increase from one cued location, it is a useful demonstration that more than one location can be prioritized by context. We have also tried three target locations in our lab with somewhat weaker though significant cueing effects from a fixed amount of training. It appears that generalization of contextual cueing to multiple target locations will be dependent on the amount of training available, with increased training requiring a concomitant increase in the number of exposures to establish this. This, of course, simply reflects a continuum between varied and consistent mapping (Shiffrin & Schneider, 1977), for which the number of target locations associated with any given context can be viewed as the most critical variable. Further parametric work will be needed to establish whether a ceiling exists in the number of locations which can be cued for any given context. At this point, we speculate that this will be influenced by a large host of factors including the difficulty of the task, the number of trained exemplars, the distinctiveness of exemplars, and of course, the practical amount of training. The utility of contextual cueing is not totally hostage to such parametric factors, however. In our experiments, contextual cueing for one target location was usually established by the end of 5 cycles of training, or approximately 6–8 s of exposure to spatial layouts which were not readily discriminable from other exemplars in an explicit recognition test. This reveals a highly robust memory for context which could be more fully exploited in real-world interactions. Not only is the visual environment much more diverse and distinctive, but any implicit learning processes will benefit from the luxury of minutes, hours, perhaps even a lifetime's worth of visual experience.

Finally, this experiment provides further evidence that contextual cueing prioritizes target locations while decreasing the probability that distractor locations will be attended. Our data cannot determine whether this involves active inhibition or suppression of distractor locations. However, an explicit inhibition mechanism does not need to be invoked to account for the present results in which RT's to targets appearing in learned distractor locations were not slower than baseline.

GENERAL DISCUSSION

Contextual Cueing

This set of experiments demonstrates that the visual context of a target is incidentally learned during visual search, forming an implicit memory for context which guides attention toward target locations in subsequent encounters. This guidance is based on learned associations between the global context and target locations. Context was operationalized as the spatial configuration of the search array. Target localization and discrimination was facilitated for search configurations which were invariant throughout the experiment. We term this benefit the contextual cueing effect.

Context prioritizes aspects of a global image, hence optimizing critical visual processes such as attentional deployment. Contextual cueing represents a new factor in the guidance of attention. In addition to the many image-driven, bottom-up factors and knowledge-driven, top-down factors used to guide attention, the present demonstration of contextual guidance may be of high ecological value because most objects we encounter in the world appear within the context of other items. Global context is the source of complexity and the segmentation problem in vision, and the present results show how context also serves to facilitate processing rather than just complicate it.

The present findings also highlight the important role of implicit learning and memory mechanisms in visual processing. All of the contextual cueing effects obtained here were learned within the experimental session. Namely, search processes are sensitive to regularities in the visual input, and visual processing mechanisms automatically encode useful and predictive cues such as global layout to facilitate future interactions with a stimulus. This invariant information can be acquired incidentally, which is a useful property for a visual learning mechanism to have. The representations can affect performance without explicit awareness or recognition of the contextual cues. In sum, contextual cueing is driven by implicit memory representations tuned by past visual experience. This finding supports recent proposals which stressed the importance of understanding how visual memory influences attentional selection (Desimone & Duncan, 1995). In addition, our paradigm provides a platform for understanding how rich covarations and meaningful invariances in the complex visual environment can be acquired through implicit learning mechanisms (Berry & Dienes, 1993; Reber, 1989; Seger, 1994; Stadler & Frensch, 1994). The contextual cueing effect demonstrates that such learning helps optimize basic visual processes such as attentional deployment.

In the following sections, we provide further discussion on how contextual cueing relates to the existing literature as well as its implications for understanding visual processing and implicit learning. We will first consider what visual context is and how it facilitates search. Second, we describe the learning and memory mechanisms that support contextual cueing. Finally, we conclude with speculations on the broader implications and importance of considering interactions between memory and attention.

Visual Context and Attention

Contextual cueing illustrates how the visual system may rely on past experience to efficiently deploy visual attention to task-relevant aspects of a complex scene. Such prioritization processes are crucial for efficient selection. We propose that one role of visual context is to allow an incoming image to make contact with stored representations (memory) of past interactions with identical or similar instances. This matching process is likely to benefit from complexity and richness which increases the discriminability between global images. We introduce the notion of *context maps,* which simply refer to memory representations of visual context. We will discuss in further detail how context maps are learned and stored in a separate section. Here we discuss our definition of context maps and how these interface with attentional mechanisms to guide selection.

What is visual context? Visual context can be defined as the set of invariant, covariational visual information present in global images or scenes. In other words, visual context represents the rich informational structure present in the visual environment. In this study, we operationalized context as the spatial layout of the search array, and our cueing effects were driven by sensitivity to these configurations. It is clear that the visual world is relatively stable and that sensitivity to the layout of prominent objects and global surfaces would be useful. The content (identities of objects) of a scene is a critical factor not considered here, but one which certainly deserves further investigation using our learning paradigm. However, the immediate goal pursued in this study was to first establish an effect of global visual context on search, independent of meaning and semantic associations in existing background knowledge. The use of novel spatial configurations allowed us to rule out these semantic factors which have complicated the interpretation of previous studies of scene perception. Of course, we are not proposing that context in the real-world can be defined solely by layout. Spatial layout is only one form of contextual information that embodies a rich correlational structure which can be picked up and retained by implicit learning mechanisms to facilitate future interactions. We believe that semantic (identity) covariances in the stimulus input can also be acquired to facilitate search via the same implicit learning principles operating in this study. For instance, Logan and Etherton (1994) demonstrated sensitivity to the co-occurrences of word identities in an automaticity paradigm. We plan to extend this result such that contextual cueing will be obtained when the identity of search items becomes relevant and predictive of target location or identity.

How does context influence search? When an incoming image matches instances stored in memory, objects in the current image will become prioritized in a manner that they were in past encounters. In this study, these will be target locations which were reinforced through repeated searches through an array. Context maps contain weights that determine the importance or salience of component objects. Hence, the model determines where attention should be allocated, solving a serious problem for complex scenes which contain a multitude of objects competing for attention.

Generalization of contextual cueing to natural scenes seems very plausible. First, Wolfe (1994b) demonstrated that findings based on visual search experiments using isolated stimuli (such as those used here) can be extended to spatially continuous stimuli that approximate those of naturalistic images. This result makes it likely that contextual cueing would be obtained using more naturalistic real-world scenes. Second, target locations in artificial search tasks may correspond to ''regions of interest'' in real-world scenes. Rensink et al. (1997) have recently illustrated that changes in flickering images are detected more readily in ''regions of interest'' of natural scenes (such as a helicopter seen through the cockpit window of a plane). Our results support their suggestion that this may be mediated by rapid apprehension of the gist of a scene, which guides the allocation of focal attention.

Toward a formal theory of contextual guidance, context maps are hypothesized to have the following characteristics. First, context maps are memory representations which interface with knowledge-independent, general-purpose attentional mechanisms. The basic point here is that contextual cueing is based on interactions between memory and attention rather than facilitation in perceptual or attentional processes alone. Second, context maps are instance-based. This allows for discriminative matching to past experience as well as fine-tuned attentional guidance. In addition, such specific, instance-based representations still support generalization to similar exemplars or averaged prototypes (Palmeri, 1997). There is rich theoretical support for understanding how generalization from stored instances can be applied to novel inputs (Hintzman, 1986; Medin & Schaffer, 1978; Nosofsky & Palmeri, 1997). Thus, characterizing the representations as instance-based should not limit their potential functional utility in real-world visual processing. Third, we hypothesize that the memory for context maps is of high capacity, exceeding the already large capacity of explicit recognition memory for pictures (Nickerson, 1965; Shepard, 1967; Standing, 1973). This capitalizes the primary advantage of implicit learning mechanisms which is to allow more information to be retained than is possible through consciously mediated channels (Lewicki et al., 1988). Fourth, context maps are by no means absolute but rather are used to provide a default setting which can be subsequently modulated according to present stimulus characteristics or task demands. It is presumed to be automatic by default, but their impact on attentional selection is subject to volitional modulation or other factors. Fifth, the matching and prioritization process is hypothesized to occur rapidly and in parallel across the entire visual field. In other words, contextual knowledge is readily available to on-line visual processes, as opposed to being exerted in a slow fashion after multiple fixations (de Graef, Christiaens, & D'Ydewalle, 1990). This is consistent with evidence and proposals suggesting that the gist of a scene is available rather quickly to guide visual recognition and selection (Biederman, 1981; Boyce et al., 1989; Potter, 1975). In our study, search latencies were typically under 1 s, and contextual cueing was obtained for briefly flashed displays (Experiment 5). Finally, contextual influences appear to operate in a global-to-local manner and suggest high interactivity between top-down and bottom-up processes. Global-to-local precedence in visual processing occurs in certain visual tasks (Navon, 1977), and such mechanisms could also be operating in contextual cueing. Coarse-to-fine processing has also been implicated in natural scene recognition (Schyns & Oliva, 1994). The results of Experiment 2 suggest that coarse spatial information was sufficient to drive contextual cueing.

Current models of visual search do not include mechanisms for context to influence processing, but the notion of context maps introduced here provides a model-independent scheme for implementing contextual guidance. For example, Wolfe and his colleagues proposed the Guided Search model of visual search in which bottom-up visual information and top-down modulatory influences are combined to produce an activation (Cave & Wolfe, 1990; Wolfe, 1994a). This activation map dictates which spatial locations should be attended to. The proposed context map may be conceptualized as a type of top-down influence which can modulate the activity levels of the activation map in Guided Search (Wolfe, 1994a, Fig. 1), hence guiding the allocation of spatial attention. Treisman's Feature Integration Theory (1988) also proposes a Master Location Map used to deploy attention toward spatial locations, and the present context map may influence its activity in a similar fashion. Thus, although the specific mechanics of implementation will differ from model to model (Duncan & Humphreys, 1989; Grossberg, Mingolla, & Ross, 1994; Humphreys & Müeller, 1993; Logan, 1996; Treisman, 1988; Wolfe, 1994a), the notion of context maps represents a generic mechanism which can be convolved with any computational process that enforces top-down modulation of attentional guidance.

Instance-Based Memory and General-Purpose Attentional Mechanisms

Context maps are hypothesized to be rather specific, instance-based representations. These are instantiated and shaped by visual experience such that the acquisition and tuning of context maps relies on past encounters with scenes. The end result is optimization or automatization of target detection for a learned instance. Logan's instance theory of automatization (Logan, 1988) provides a theoretical framework to characterize the learning, storage, and retrieval of memory for visual context.

According to instance theory, specific traces are laid down whenever a particular instance is encountered. In turn, these traces are automatically retrieved when a similar or identical display is presented. Increased exposure to the instances results in a higher degree of automatization. In our task, specific traces of spatial layouts are laid down as the subject performs the search task, and these traces are automatically retrieved and reinforced for repeated configurations, facilitating performance for learned spatial layouts. This produces a progression from algorithmic processing to memory-based processing. Algorithmic processing refers to the random item-by-item search or unbiased parallel competition between visual items (these characterizations depend whether one adheres to a serial vs parallel model of search—a distinction not relevant here), while memory-based processing allows for the solution, the target location, to emerge quickly, based on past experience. Treisman et al. (1992) have also proposed that learning effects in visual search may be subserved by traces of the stimuli laid down in the course of training in accordance with Logan's instance theory.

Instance theory predicts that performance benefits are based on instance-based memory traces rather than general algorithmic improvements. Some aspects of improvement in search RT with increased training may reflect increased efficiency in algorithmic operations (performance improves for New configurations also), but contextual cueing (the increased benefit for Old versus New configurations) is driven primarily by memory traces interacting with attentional processes. This is true by definition since contextual cueing is instance-based, observed only for the contexts which were invariant throughout the experiment. Furthermore, contextual cueing can be distinguished from passive forms of perceptual facilitation (priming) because repetition benefits were not obtained when the context was not predictive of the target location (Experiment 3).

Second, instance theory states that the representations of instances reflect only those aspects of the stimuli input that are relevant to a task (Lassaline & Logan, 1993). This is the *attention hypothesis,* which states that attention determines how the input was interpreted while the task was performed and that only attended information is encoded into instance representations (Logan & Etherton, 1994). For instance, Lassaline and Logan demonstrated transfer of learning across changes in stimulus identity and color groupings because these attributes were not relevant to the enumeration task. Consistent with this, we demonstrated that contextual cueing transferred across perceptual surface feature changes in Experiment 2. One difference is that the identity-based distinction between targets and distractors is important in our search task. But further processing to encode the identities of each search element is not required to perform the task. Hence, preservation of global spatial layout was sufficient to cue target locations. The attention hypothesis is very important for understanding the nature of memory for visual context. This is critical because the amount of visual information in a typical scene context is extremely high, and some filtering is needed to maintain parsimony in the representations of visual context. The attention hypothesis states that a lean representation can be achieved by encoding only the information that is relevant to a task in the first place. Additional work in our lab further suggests that only attended visual information produces contextual cueing.

Although instance theory provides a framework for understanding contextual cueing, it does not explain whether learning was intentional or incidental and whether memory for context is explicit or implicit. Instance theory is considered to address primarily implicit memory (Logan, 1990, in press), but such distinctions between implicit/explicit learning or incidental/intentional learning are not necessarily important or relevant for the understanding of automaticity. This may also be the case for contextual cueing, but we argue that characterizing the learning and memory as implicit carries special significance for the domain of perceptual processing.

Implicit Visual Learning and Memory

Contextual cueing results from both implicit learning and implicit memory. The visual system naturally encodes useful, predictive information about complex structure in its input without conscious intention or explicit effort. Second, this knowledge can bias or guide processing in an implicit manner without conscious awareness of the underlying representations. But what's so useful about the explicit/implicit distinction in contextual cueing?

The main advantage of implicit learning is that it may allow cognitive systems to memorize ''more information about encountered stimuli than can be processed through consciously controlled channels'' (Lewicki et al., 1988, p. 35). By definition, incidental learning allows information about a complex environment to be acquired while releasing conscious, effortful processes to focus on performing primary tasks. Reber (1989) has argued that implicit learning mechanisms are phylogenetically older, making them more robust and resistant to insult. Seger's (1994) extensive review supports the view that implicit learning can mediate the acquisition of information that explicit processes have difficulty with. Thus, although contextual cueing does not have to be implicit, the literature and our findings clearly point to the numerous advantages afforded by implicit mechanisms for learning complex information.

Similar arguments can be marshaled for the utility of implicit memory representations which operate outside of awareness to influence and control behavior. Task performance can benefit from past experiences not accessible to conscious and deliberate retrieval (Schacter, 1987). This is especially the case when performance on a test benefits as a function of similarity in operations between ''learning'' and ''testing'' activities, as is the case in the present study. Contextual cueing may be examined as a form of such transfer-appropriate processing (Roediger, 1990) which would be afforded by the obligatory encoding and obligatory retrieval assumptions of instance theory (Logan, 1988; Logan, in press; Logan & Etherton, 1994).

An intelligent system without such learning mechanisms or memory for past interactions is bound to be maladaptive, yet most existing models of visual search and attentional processing are limited in this sense. This is an understandable shortcoming, but it may be useful now to consider how memory and attention interact. Desimone and Duncan (1995; Desimone, 1996) have argued that visual memory biases selection of an item participating in an interactive competition with other visual events for the control of behavior. We endorse this view, and offer contextual cueing as a paradigm for understanding how memory and attention interact to facilitate processes such as search.

Exciting findings are just beginning to emerge on the functional utility of memory-based guidance of spatial attention. A robust phenomenon termed priming of pop-out (PoP) demonstrates that focal visual attention is rapidly deployed to features and positions that were repeated within 15–30 s (Maljkovic & Nakayama, 1994, 1996). This short-term priming effect has recently been characterized as implicit, distinguishable from explicit memory in time course and the types of feature information it encodes (Maljkovic & Nakayama, 1997). Maljkovic and Nakayama proposed that such an implicit memory system is extremely beneficial for the efficient deployment of attention and control of eye movements. For instance, an analysis of eye movements in a visuo-motor task for copying block images revealed that observers make a rather large number of ‘‘checking’’ eye movements (Ballard, Hayhoe, & Pelz, 1995). Such extensive saccadic retrieval of visual information serves to minimize the demands on visual working memory (which Ballard et al. argue is computationally expensive). An implicit memory for recently examined visual features could optimize the rapid deployment of attention and eye movements in such task situations (Maljkovic & Nakayama, 1997; McPeek, Maljkovic, & Nakayama, 1998). Our results reinforce this proposal and further demonstrate that implicit memory for the entire context of a scene or image can be used to guide the deployment of attention.

A future extension of the present research will address the role of visual learning mechanisms in general object recognition. The ability to see and recognize a coherent world of discrete objects from continuous, natural images is in large part acquired through incidental learning over a lifetime's worth of experience and interactions with the visual environment. Implicit learning processes are tuned to invariant information in its input, and the role of spatial layout studied here is just one form of invariance. So in closing, our results revealed how the deployment of attention is tuned by visual experience. But it is not just about how search can be made more efficient. It also represents the beginning of a query into the broader issue of how perceivers internalize meaningful regularities and covarations between objects and events in the visual world. This important process occurs through implicit visual learning.

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(Accepted April 14, 1998)