

Intertrial Temporal Contextual Cuing: Association Across Successive Visual Search Trials Guides Spatial Attention

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Contextual cuing refers to the facilitation of performance in visual search due to the repetition of the same displays. Whereas previous studies have focused on contextual cuing within single-search trials, this study tested whether 1 trial facilitates visual search of the next trial. Participants searched for a T among Ls. In the training phase, the spatial layout on trial $N-1$ was predictive of the target location on trial N . In the testing phase, the predictive value was removed. Results revealed an intertrial temporal contextual cuing effect: Search speed became progressively shorter in the training phase, but it significantly lengthened during testing. The authors conclude that the visual system is capable of retaining spatial contextual memory established earlier to facilitate perception.

Keywords: intertrial association, contextual cuing, visual attention, visual search, implicit memory

Human visual processing is extremely powerful in many respects: We can recognize an object or an animal within complex scenes with a single glimpse (Thorpe, Fixe, & Marlot, 1996) and redirect our gaze to different regions of a display several times in a second (Yarbus, 1967). Yet in other respects we are surprisingly limited: We often miss large-scale changes in natural viewing and social interactions (Levin & Simons, 1997; Rensink, O'Regan, & Clark, 1997; Simons & Levin, 1998), and we cannot hold more than four visual objects in working memory (Luck & Vogel, 1997). The severe limitations in visual attention and working memory place significant pressure on humans to selectively process relevant information. This study focuses on one important factor that optimizes selective attention: learning of consistent spatial context.

A typical visual scene contains a complex array of visual objects. Despite this complexity, natural scenes that humans encounter every day often stay remarkably stable. The appearance of one visual object is accompanied by others that provide consistent contextual information. Such stability affords us ample opportunities to learn from previous encounters of the same scene. In his pioneering study, Biederman (1972) showed that visual search performance is better in intact natural scenes than in jumbled

scenes. Although recent studies have debated whether the facilitation reflects a change in response bias or sensitivity (Biederman, Mezzanotte, & Rabinowitz, 1982; Hollingworth & Henderson, 1998), it is widely accepted that the visual system is highly sensitive to repeated information (Schacter & Buckner, 1998) and consistent statistical associations (Chun & Jiang, 1999; Fiser & Aslin, 2001).

To test how good humans are at learning complex visual contexts, Chun and Jiang (1998) showed participants displays containing several Ls and one T. Such displays were obviously simpler than natural scenes, but they were complex and abstract, allowing researchers to control for participants' prior knowledge. Participants were asked to search for a T and report whether it was pointing to the left or to the right. The distractors surrounding the target defined the spatial context within which the target was presented. Participants were tested in two conditions: repeated and nonrepeated. In the repeated condition, a certain display was presented in Block 1, and it was again shown in Block 2, Block 3, and so on. In the nonrepeated condition, the target was at a repeated location across blocks, but the distractors were randomly positioned, so each time the target was seen, it was within a different spatial context. Chun and Jiang (1998) found that participants were faster at searching from repeated displays, even though they were unable to recognize the repeated displays explicitly. The significant facilitation of the repeated compared with the nonrepeated displays was called *contextual cuing*. It is as if the repeated spatial context cued spatial attention to the position of the target.

Using this paradigm, recent studies have revealed that the visual system is capable of quickly acquiring consistent associations in 3-D as well as in 2-D spatial layouts (Chua & Chun, 2003), object identities (Chun & Jiang, 1999; Fiser & Aslin, 2001), motion trajectories (Chun & Jiang, 1999), and a temporal sequence of letters (Olson & Chun, 2001). The ubiquity of contextual cuing

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may compensate for humans' severe limits in visual working memory.

Surprisingly, previous studies have focused primarily on contextual learning from a single visual search trial, often involving one search display or a temporal series of letters. They have not addressed whether spatial context acquired on one trial can influence the detection of target events on the next trial. Because cognitive operations in everyday life consist of a chain of relevant events, one following the other, it is of functional significance for the visual system to carry contextual information across events. For example, visual search for a cup may serve as a cue to guide visual search for a kettle, from which hot water is poured into the cup. This study is our first broad attempt to investigate conditions under which intertrial temporal contextual cuing is observed.

Current Study

In this study, we investigated whether contextual cuing is observed when the spatial layout presented on trial $N-1$ is predictive of the target location on trial N . Participants took part in a training phase, during which the search display formed on trial $N-1$ was reliably followed by a specific target location on trial N . The targets on trial $N-1$ and on trial N were at different locations. Participants were then tested in a testing phase, in which the pairing between trial $N-1$ and trial N was disrupted, removing the predictive value. We measured whether reaction time (RT) in searching for the target on trial N improved during the training phase and whether such improvement terminated when the association across trials was removed. To assess participants' explicit knowledge of the manipulation, we also tested participants in a recognition phase. Two hypotheses make opposite predictions about the effect of intertrial temporal contextual cuing.

According to the *ubiquitous statistical learning* account, the visual system is sensitive to all kinds of statistical consistency and will make use of predictive information, whether it is presented in a single trial or across trials. This account receives support from the contextual cuing literature reviewed earlier, which has repeatedly revealed new types of statistical learning. Given the unflinching demonstrations of contextual cuing with various types of associations, one might say that failure to show learning is as informative as success in showing learning.

Cases of failed contextual cuing are shown when the spatial context on a given trial is ignored. For example, when participants are told to search for a red target among a display of red and green distractors, contextual cuing is not observed if the green distractors—the ignored distractor set—are predictive of the target's location (Jiang & Chun, 2001). Similarly, when participants are told to search for a target from one depth plane, contextual cuing is not observed if distractors on an ignored depth plane are predictive of the target (Kawahara, 2003). Attending to the repeated spatial context thus appears to be a requirement for contextual cuing (but see Jiang & Leung, 2005).

Intertrial association is particularly interesting to examine in terms of the limits of contextual cuing. Context presented on trial $N-1$ is clearly attended during that trial, but it then becomes ignored once the trial is terminated. By the time trial N is presented, participants are no longer attending to the context from a previous trial. Thus, an *attention-dependent learning* account predicts that no intertrial temporal contextual cuing should be ob-

served, given that the spatial context from trial $N-1$ is no longer attended on trial N .

When succeeding trials contain the predictive and the predicted information separately, the availability of that information differs in the above two accounts. The ubiquitous statistical learning view hypothesizes that people can access both predictive and predicted information, so learning is possible. In contrast, the attention-dependent learning view hypothesizes that because the predictive information is not currently attended, it should not be available to promote learning.

Experiment 1: Intertrial Temporal Contextual Cuing

In this experiment we introduced the basic paradigm to study intertrial contextual cuing. In Experiment 1A, we used an "inconsistent transfer" procedure. Participants took part in a training phase (Epochs 1–5), which involved a consistent association between trial $N-1$'s display and trial N 's target location, and a testing phase (Epoch 6), in which the association was removed. If learning from the training phase no longer transfers to the testing phase, such that RT in Epoch 6 is longer than RT in Epoch 5, then this would suggest the existence of an intertrial temporal contextual cuing effect. In Experiment 1B, we used a "consistent transfer" procedure as a control. This procedure was similar to that used in Experiment 1A in providing consistent association during training. However, the consistent association was preserved during testing as well. Experiment 1B was included to control for the possibility that fatigue might account for longer RT in Epoch 6 than in Epoch 5.

Method

Participants. Twenty-eight students (14 each for Experiments 1A and 1B) from Hiroshima University volunteered for course credit or for payment. New participants from the same pool were recruited for Experiments 2–6. All participants reported having normal or corrected-to-normal visual acuity. They were naive to the purpose of this study.

Apparatus. Stimuli were displayed on a CRT monitor controlled by a PC/AT compatible computer equipped with a frame store (VSG 2/5, Cambridge Research Systems). The viewing distance was approximately 60 cm.

Stimuli. Each display contained one target, T, and 11 distractors, Ls, each subtending $1.3^\circ \times 1.3^\circ$. The T was rotated 90° to the left or to the right, and the Ls were randomly presented in four possible orientations (0° , 90° , 180° , and 270°). Items were presented within randomly selected locations from an invisible 8×6 grid matrix that subtended approximately $25.0^\circ \times 18.5^\circ$; collinearity between items was prevented by placing each item slightly off center in each cell.

Items were presented on a gray background; they were in red, yellow, blue, and green. There were three items in each color, randomly assigned. When a configuration was repeated, items at a given location also maintained their colors.

Experimental design and procedure. Each participant was tested in three phases, in the following order: training, testing, and recognition. There were 25 blocks in the training phase and 5 blocks in the testing phase. We binned 5 blocks into one epoch to increase statistical power. Thus, the main variable of the experiment was epoch (1–6): Epochs 1–5 were in the training phase, and Epoch 6 was in the testing phase. Training and testing were run continuously, without special instructions in between.

Training. Each block contained 18 trials, divided evenly into three types of displays: *trial N-1*, *trial N*, and *filler* trials (6 trials per condition). Trial $N-1$ was a visual search display created at the beginning of the

experiment (there were 6 trials, and each of the 6 trials involved a different pattern of display), and it was presented once per block. Thus, the entire search display—including the distractor locations and the target location—was repeated 25 times during the training phase. The order of all trials in each block was randomized except that trial *N* was always preceded by trial *N*–1. In other words, the filler trial never appeared after trial *N*–1. Unlike in trial *N*–1, distractors for a given trial were presented at randomly chosen locations, but the target location for trial *N*–1 was determined at the beginning of the experiment (each of the 6 trials involved a different target location), and it was presented once per block. Thus, for the pair of trial *N*–1 and trial *N*, a repeated trial *N*–1 was predictive of the next trial’s target location. Filler trials were randomly generated from block to block; they were included so that there would not be any intertrial association from one pair of trial *N*–1 and trial *N* to another pair. The same training phase was used in Experiments 1A and 1B.

Testing. The two experiments differed in the testing phase. In Experiment 1A, we shuffled the six pairs that were previously trained, such that although trial *N*–1 was again repeated and trial *N*’s target location was again repeated, their consistent association was destroyed. If there had been any intertrial temporal contextual cuing, it should not have transferred to Epoch 6; as a result, RT in Epoch 6 should be longer than RT in Epoch 5. In Experiment 1B, we maintained the consistent association, so RT in Epoch 6 should be as short as (or shorter than) RT in Epoch 5. Figure 1 illustrates the design of sample trials for all experiments.

Recognition. After the testing phase, participants were tested in a recognition phase in which the previously presented trial *N*–1 (6 trials) and trial *N* (6 trials) were randomly intermixed with 12 new trials. The layouts for trial *N*–1 and trial *N* were identical to those used in the last block of the testing phase (Block 30). The new layouts were randomly generated during the recognition phase. Participants pressed one of two keys to report whether they had previously seen a display. The response was not speeded.

At the end of the session, the participants were asked whether they had noticed consistent intertrial pairings.

Trial sequence. Participants initiated each epoch by pressing the spacebar. On each trial, a small fixation dot was presented at the center of the screen for 1,000 ms, followed by a search display that stayed on the screen until a response was made. After a pause of 1,000 ms, the next search display was presented. Participants were allowed to have a rest after each epoch. Then they were given 18 warm-up trials, in which new configurations were used. Participants were not informed of the repetition of displays or any association between one trial and the next.

Results

In this and all other experiments, accuracy for the visual search task was high (ranging from 93% to 100% across epochs) and was not statistically affected by epoch (all *F*s < 1). We report only mean RT data from correct trials here.

We calculated mean RT for correct trials on trial *N* for each participant. The group mean, shown separately for Experiments 1A and 1B and for the six epochs, are displayed in Figure 2. Note that Epochs 1–5 came from training, and Epoch 6 came from testing.

Experiment 1A: Inconsistent association during testing. A repeated measures analysis of variance (ANOVA) on RT in the training phase revealed a significant main effect of epoch, $F(4, 52) = 3.42, p < .05$. Planned contrast between Epochs 5 and 6 showed that Epoch 6 was significantly longer than Epoch 5, $t(13) = 3.33, p < .01$.

Mean accuracy in the recognition phase was 50.5%. Participants correctly identified trial *N*–1 and trial *N* as old layouts on 44% of trials (hit) and mistook new trials as old on 43% of trials (false alarm). These two values were not statistically different, $t(13) < 1$ (*ns*). Mean accuracy in the recognition for trial *N*–1 and for trial *N* were not statistically different, $t(13) < 1$ (*ns*).

Experiment 1B: Consistent association during testing. An ANOVA on search RT using epoch as the within-subject factor showed a significant main effect of epoch, $F(4, 52) = 7.54, p < .01$. Unlike Experiment 1A, which showed a significant lengthening of RT in Epoch 6, Experiment 1B demonstrated a significant shortening of RT in Epoch 6 compared with Epoch 5, $t(13) = 2.47, p < .05$.

Mean accuracy in the recognition phase was 52.9%: The hit rate was 53.5%, which was not statistically different from the false-alarm rate of 47.6%, $t(13) < 1$ (*ns*). Mean accuracy in the recognition for trial *N*–1 and for trial *N* were not statistically different, $t(13) < 1$ (*ns*). Because participants were unable to recognize the repeated displays, they could not have used such repetition to explicitly guide attentional deployment on trial *N*. Similarly, in Experiments 2–6 we did not observe any evidence for explicit recognition. In all experiments, the hit rate was not statistically different from the false-alarm rate (all *p*s > .31). We thus no longer report recognition performance in full in later experiments. None of the participants reported that he or she had noticed that certain intertrial pairings were repeated. We believe that the intertrial cuing effect occurred largely as a result of implicit learning.

Experiment 1A versus 1B. To identify the specific effect of removing consistent intertrial associations, we conducted a two-way ANOVA on search RT, with epoch (Epoch 5 vs. Epoch 6) as the within-subject factor and consistency (Experiment 1A vs. 1B) as the between-subjects factor. This analysis found no effect of

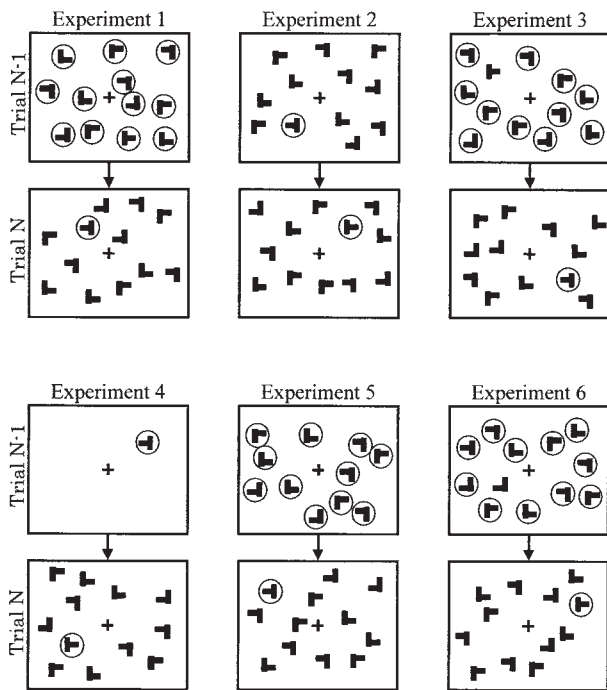


Figure 1. Schematic example of the stimuli used in the present study. The upper row indicates display in trial *N*–1; the lower row indicates the display in trial *N*. Circles indicate letters presented at repeated locations when they appeared. The circles were not shown in the actual display.

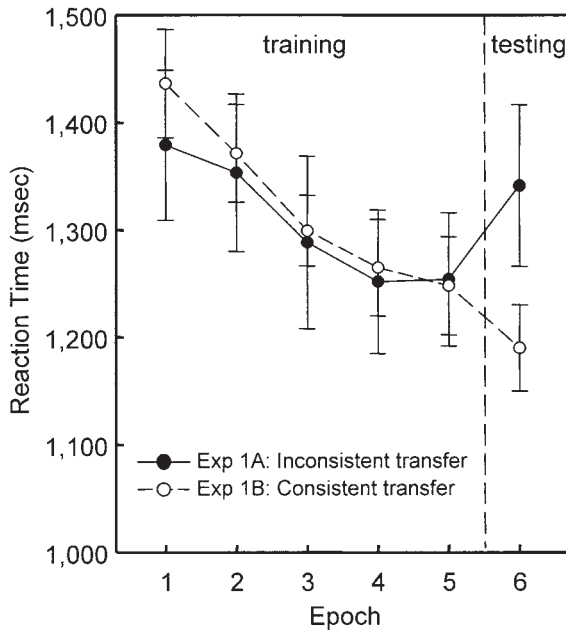


Figure 2. Mean correct reaction times as a function of epoch for Experiments (Exp) 1A and 1B. Filled symbols indicate the means in Experiment 1A, and open symbols indicate the means in Experiment 1B. The training phase comprised the first five epochs; the testing phase comprised the sixth. Error bars represent the standard error of the mean.

consistency ($F < 1$), suggesting that the overall RTs in the two experiments were comparable. There was also no main effect of epoch ($F < 1$). However, the interaction between consistency and epoch was highly significant, $F(1, 26) = 17.12$, $p < .01$. This confirms that whereas RT became shorter from Epoch 5 to Epoch 6 when the intertrial association was preserved, it became longer when the intertrial association was removed.

Conventional contextual cuing in trial $N-1$. To examine whether the conventional contextual cuing effect was obtained, we compared the RT on trial $N-1$ with that on filler trials in the training phase (Epochs 1–5). The average RTs across in the training phase for Experiment 1A were 1,236 ms on trial $N-1$, 1,305 ms on trial N , and 1,307 ms on filler trials. The RTs for Experiment 1B were 1,242 ms on trial $N-1$, 1,324 ms on trial N , and 1,320 ms on filler trials. Statistical comparison showed that the RT on trial $N-1$ was shorter than that on filler trials for both Experiments 1A and 1B, $F_s(1, 13) = 4.72$ and 6.62, respectively, $p_s < .05$. These results suggest that there was a conventional contextual cuing effect in trial $N-1$.

Discussion

We have shown, for the first time, the presence of an intertrial temporal contextual cuing effect. When a visual search display on trial $N-1$ was repeated, and when this display was predictive of where the target would be on trial N , RT on trial N improved over time. Once the association between the two trials was eliminated, RT on trial N was significantly longer. These results suggest that spatial context acquired on one trial carries predictive value with it. It can then be used by the visual system to anticipate the target

location on trial N . This finding is consistent with the ubiquitous statistical learning account, according to which the visual system is highly sensitive to predictive association across trials as well as within a trial. Even though selective attention is withdrawn from trial $N-1$ by the time trial N is presented, the spatial context of trial $N-1$ continues to guide attention on trial N . In this sense, our results are inconsistent with the attention-dependent cuing account. We return to the relationship between attention and contextual cuing in the General Discussion section.

The demonstration of intertrial temporal contextual cuing, although a novel finding, was expected within the framework of the ubiquitous statistical learning account. However, because several pieces of information were repeated on trial $N-1$, including its target location and distractor locations, it was unclear which was the critical association: that between trial $N-1$'s target and trial N 's target or that between trial $N-1$'s distractor layout and trial N 's target, or both. The following experiments were designed to find out which cue was important and to delineate conditions under which intertrial temporal contextual cuing was disrupted.

Experiment 2: Trial $N-1$ (Repeated Target and Random Distractors)

In this experiment we tested whether the association between the target locations on trial $N-1$ and trial N was sufficient for the intertrial temporal contextual cuing effect.

Method

All aspects of this experiment were the same as those in Experiment 1A except that distractors on trial $N-1$ were presented at randomly selected locations from block to block. Thus, in the training phase (Epochs 1–5), only the target location on trial $N-1$ predicted the target location on trial N . In the testing phase (Epoch 6), the association across trials was removed. Given that the target received the most attention on a given trial, one might expect that the association in target locations would be sufficient for an intertrial cuing effect. We also tested, as a control condition, Experiment 2B, which was identical to Experiment 2A except that the association was preserved during the testing phase. Thus, we expected RT to continue improving from Epoch 5 to Epoch 6 in Experiment 2B. The question of interest was whether RT would lengthen in Epoch 6 for Experiment 2A. We tested 24 participants (12 in each experiment).

Results and Discussion

Experiment 2A: Inconsistent association during testing. Figure 3 illustrates mean RT as a function of epoch in Experiments 2A and 2B. An ANOVA on training epoch (1–5) revealed a significant main effect of epoch, $F(4, 44) = 3.49$, $p < .05$. However, unlike in Experiment 1A, RT in Epoch 6 was significantly shorter than that in Epoch 5, $t(11) = 2.47$, $p < .05$.

Experiment 2B: Consistent association during testing. An ANOVA on training epoch revealed a significant main effect of epoch, $F(4, 44) = 7.43$, $p < .01$. Reaction time in Epoch 6 was significantly shorter than that in Epoch 5, $t(11) = 4.97$, $p < .05$.

Experiment 2A versus 2B. To compare the effect of consistent transfer, we conducted a two-way ANOVA on RT, with a between-subjects factor (experiment: 2A vs. 2B) and a within-subject factor (epoch: 5 vs. 6). This analysis revealed a significant main effect of epoch, $F(1, 22) = 10.48$, $p < .01$. There was no

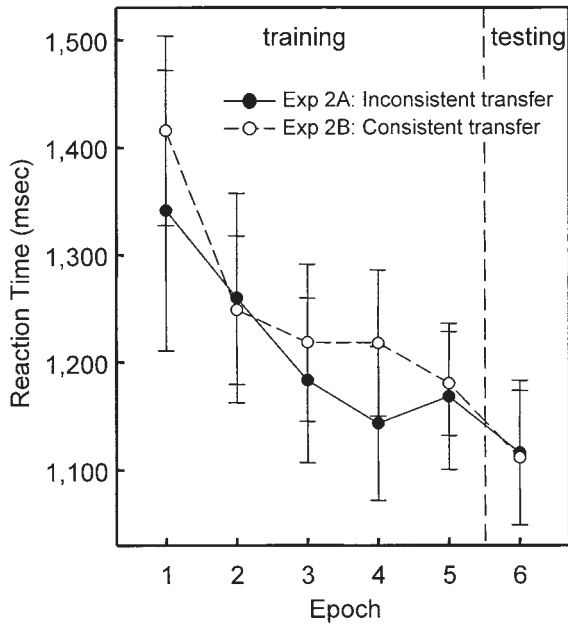


Figure 3. Mean correct reaction times as a function of epoch for Experiments (Exp) 2A and 2B. Filled symbols indicate the means in Experiment 2A, and open symbols indicate the means in Experiment 2B. The training phase comprised the first five epochs; the testing phase comprised the sixth. Error bars represent the standard error of the mean.

main effect of experiment ($F < 1$). The interaction between experiment and epoch was not significant ($F < 1$). This confirms that the lack of a lengthening of RT from Epochs 5 to 6 was due to a lack of contextual learning.

Thus, with a procedure in which the distractors on trial $N-1$ were randomly positioned, we were unable to obtain an intertrial temporal contextual cuing effect, even though the target location on trial $N-1$ was predictive of the target's location on trial N . This suggests that consistent association between trial $N-1$'s distractor layout and trial N 's target was important. These results also place a boundary condition on the ubiquitous statistical learning account, which predicts a significant intertrial temporal contextual cuing in the current experiment. We give a full assessment of this account after presenting data from the other experiments.

Experiment 3: Trial $N-1$ (Repeated Distractors and Nonrepeated Target)

This experiment used the opposite manipulation to that used in Experiment 2: We repeated distractor locations presented on trial $N-1$, which were predictive of the target's location on trial N .

Method

All aspects of this experiment were the same as those in Experiment 1A except that the target on trial $N-1$ was presented at randomly selected locations from block to block. Specifically, in the training phase (Epochs 1-5), the layout formed by distractors on trial $N-1$ was repeated and was always predictive of a specific target location on trial N . The target on trial $N-1$ was presented at randomly selected locations, and the distractors on trial N were presented at random locations. In the testing phase (Epoch 6),

the correlation between distractors on trial $N-1$ and the target on trial N was removed. If the association between the distractor configuration on trial $N-1$ and the next trial's target location was sufficient to produce intertrial temporal contextual cuing, then RT in Epoch 6 should be longer than that in Epoch 5. Experiment 3B was the same as Experiment 3A except that the association across trials was maintained during the testing phase (Epoch 6). We tested 24 participants (12 in each experiment).

Results and Discussion

Experiment 3A: Inconsistent association during testing. Figure 4 illustrates mean RT as a function of epoch in Experiments 3A and 3B. An ANOVA on training epoch (1-5) revealed a significant main effect of epoch, $F(4, 44) = 3.49, p < .05$. Reaction time in Epoch 6 was significantly shorter than that in Epoch 5, $t(11) = 2.55, p < .05$.

Experiment 3B: Consistent association during testing. An ANOVA on training epoch revealed a significant main effect of epoch, $F(4, 44) = 7.43, p < .01$. Reaction time in Epoch 6 was significantly shorter than that in Epoch 5, $t(11) = 2.96, p < .05$.

Experiment 3A vs. 3B. To compare the effect of consistent transfer, we conducted a two-way ANOVA on RT, with a between-subjects factor (experiment: 3a vs. 3b) and a within-subject factor (epoch: 5 vs. 6). This analysis revealed a significant main effect of epoch, $F(1, 22) = 14.84, p < .01$. There was no main effect of experiment ($F < 1$). The interaction between experiment and epoch was not significant ($F < 1$). This confirms that the lack of a lengthening of RT from Epochs 5 to 6 was due to a lack of contextual learning.

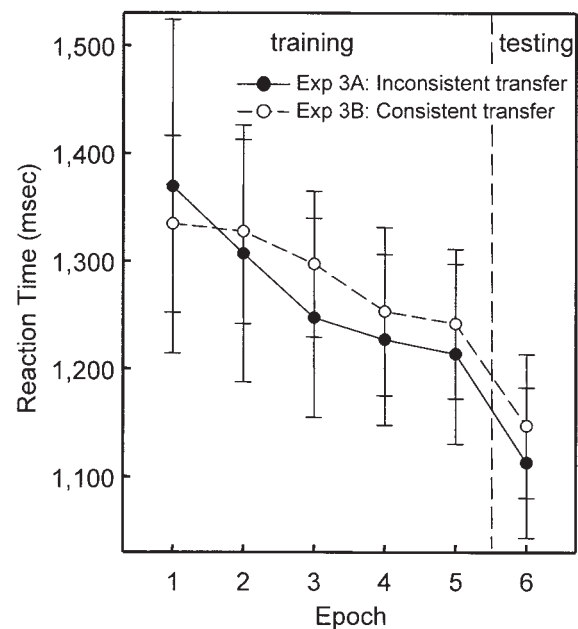


Figure 4. Mean correct reaction times as a function of epoch for Experiments (Exp) 3A and 3B. Filled symbols indicate the means in Experiment 3A, and open symbols indicate the means in Experiment 3B. The training phase comprised the first five epochs; the testing phase comprised the sixth. Error bars represent the standard error of the mean.

Experiment 4: Trial $N-1$ (Repeated Target, No Distractors)

The first three experiments showed a paradoxical pattern of results: When all items were repeated on trial $N-1$, their association with trial N 's target led to a significant intertrial temporal contextual cuing effect; but when only the target or only the distractors repeated on trial $N-1$, their association with trial N 's target led to no effect.

There are two possibilities that may explain why we failed to find cuing effects in Experiments 2 and 3. One is that the presence of random distractor layouts (in Experiment 2) or random target location (in Experiment 3) interfered with learning a consistent association in the other cue. According to this account, if the random variation on trial $N-1$ is removed by presenting only the target or only the distractors, intertrial temporal contextual cuing should be obtained again. An alternative account is that the repetition of a single association is insufficient for the intertrial cuing effect. Specifically, a single association between the target in trial $N-1$ and the target in trial N or between the distractors in trial $N-1$ and the target in trial N may not be strong enough to affect learning. Experiments 4–5 were designed to test these competing hypotheses.

Method

To test whether a repeating target alone on trial $N-1$ was sufficient for intertrial temporal contextual cuing, in Experiment 4A we removed the randomly varying distractors on trial $N-1$. That is, only the target was presented in trial $N-1$. This experiment was otherwise identical to Experiment 2 (which failed to show a cuing effect). That is, in Epochs 1–5, trial $N-1$'s target was repeated once per block, and it was predictive of trial N 's target location. In Epoch 6, the association was removed.

Experiment 4B was the same as Experiment 4A except that the association across trials was maintained during the testing phase (Epoch 6). We tested 32 participants (16 in each experiment).

Results and Discussion

Experiment 4A: Inconsistent association during testing. Figure 5 illustrates the mean RT as a function of epoch for Experiments 4A and 4B. An ANOVA on RT showed a significant main effect of training epoch (1–5), $F(4, 60) = 9.17, p < .01$. As in Experiment 1A, RT in Epoch 6 was significantly longer than that in Epoch 5, $t(15) = 2.19, p < .05$. Thus, the improvement we saw during training reflected elements of intertrial temporal contextual cuing. When the consistent association was removed, RT was delayed.

Experiment 4B: Consistent association during testing. An ANOVA on epoch revealed a significant main effect in training RT, $F(4, 60) = 4.34, p < .01$. Unlike in Experiment 4A, RT in Epoch 6 was not statistically different from RT in Epoch 5, $t(15) = 1.56, p > .13$.

Experiment 4A versus 4B. To compare the effect of consistent transfer, we conducted a two-way ANOVA on RT, with a between-subjects factor (experiment: 4A vs. 4B) and a within-subject factor (epoch: 5 vs. 6). This analysis revealed no main effects of experiment or epoch ($F_s < 1$), but there was a significant interaction between experiment and epoch, $F(1, 30) = 7.87, p < .01$, further confirming that the significant lengthening of RT seen

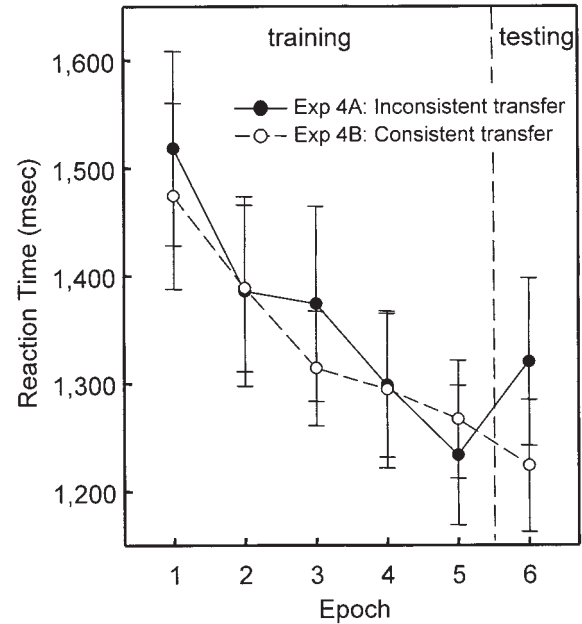


Figure 5. Mean correct reaction times as a function of epoch for Experiments (Exp) 4A and 4B. Filled symbols indicate the means in Experiment 4A, and open symbols indicate the means in Experiment 4B. The training phase comprised the first five epochs; the testing phase comprised the sixth. Error bars represent the standard error of the mean.

during the testing phase of Experiment 4A was due to the removal of intertrial association.

Thus, a significant intertrial temporal contextual cuing effect was observed when trial $N-1$'s target location was predictive of trial N 's target location. This result can be contrasted with that of Experiment 2, in which no cuing effect was observed when trial $N-1$'s target was repeated but its distractors were random. The lack of a cuing effect in Experiment 2 should be interpreted as a disruption effect from random distractor locations on trial $N-1$. The presence of a cuing effect in Experiment 4A suggests that the target-to-target association was sufficient for intertrial cuing as long as distractors on trial $N-1$ were removed.

Experiment 5: Trial $N-1$ (Repeated Distractors, No Target)

The contrast between Experiments 2 and 4 suggests that the presence of random variation in trial $N-1$'s layout was disruptive. For the same reason, the lack of a cuing effect seen in Experiment 3 may be a result of random target locations presented on trial $N-1$. To find out whether repeated distractor layout alone on trial $N-1$ could lead to intertrial temporal contextual cuing, we removed the target on trial $N-1$ in Experiment 5A. We also tested participants in Experiment 5B as a control.

Method

All aspects of Experiment 5A were the same as those of Experiment 3 except that the target T was removed from trial $N-1$. That is, there were only 11 distractors in trial $N-1$. Participants were told to withhold their response when a target was not found. The trial $N-1$ display remained on

for 1,200 ms and then disappeared. The layout shown on trial $N-1$ was predictive of trial N 's target location in Epochs 1–5, but the association was removed in Epoch 6. Experiment 5B was the same as Experiment 5A except that the association across trials was maintained during the testing phase (Epoch 6).

The recognition phase of Experiments 5A and 5B consisted of trial $N-1$ and new trials (six trials each); neither trial $N-1$ nor the new trials had targets in them. Displays tested on trial $N-1$ were identical to those used in Block 30, whereas new displays were newly generated and contained no target. We tested 30 participants (15 each in Experiments 5A and 5B).

Results and Discussion

Experiment 5A: Inconsistent association during testing. Figure 6 illustrates mean RT as a function of epoch in Experiments 5A and 5B. In Experiment 5A, there was a significant main effect of training epoch, $F(4, 56) = 17.48, p < .01$. As in Experiment 1A, RT in Epoch 6 was significantly longer than RT in Epoch 5, $t(14) = 2.46, p < .05$, showing intertrial temporal contextual cuing.

Experiment 5B: Consistent association during testing. As in Experiment 5A, participants improved significantly during training. The main effect of epoch (1–5) was significant, $F(4, 56) = 8.66, p < .01$. Unlike in Experiment 5A, though, RT in Epoch 6 was significantly shorter than that in Epoch 5, $t(14) = 2.59, p < .05$.

Experiment 5A versus 5B. A two-way ANOVA on experiment (5A vs. 5B) and epoch (5 vs. 6) revealed a significant interaction effect, $F(1, 30) = 12.78, p < .01$. This suggests that the lengthening of RT that we observed during the testing phase of Experiment 5A was specific to the lack of a consistent intertrial effect.

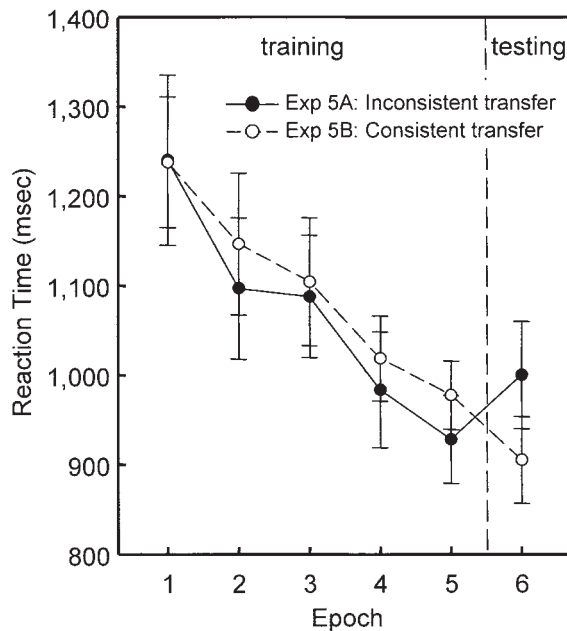


Figure 6. Mean correct reaction times as a function of epoch for Experiments (Exp) 5A and 5B. Filled symbols indicate the means in Experiment 5A, and open symbols indicate the means in Experiment 5B. The training phase comprises the first five epochs; the testing phase comprises the sixth. Error bars represent the standard error of the mean.

As in Experiment 4, Experiment 5 demonstrated that the removal of a randomly varying cue—in this case, trial $N-1$'s target location—was sufficient to restore an intertrial temporal contextual cuing effect. When trial $N-1$ did not contain any target location and when its distractor locations were predictive of the next trial's target location, a significant cuing effect was observed. This can be contrasted with Experiment 3, in which the presence of a random target location on trial $N-1$ eliminated learning of the association between trial $N-1$'s distractors and trial N 's target.

Experiment 6: Effects of a Random Distractor on Trial $N-1$

The previous experiments showed that although it was possible to observe the intertrial temporal contextual cuing effect, learning was sensitive to random variations on trial $N-1$. In particular, randomly changing trial $N-1$'s target location or its distractor locations disrupted the intertrial cuing effect. This raises the question of how robust the intertrial cuing effect was to fluctuations of trial $N-1$'s display.

To find out whether any fluctuation on trial $N-1$ would disrupt the intertrial cuing effect, we carried out Experiment 6, in which one distractor location on trial $N-1$ was randomly positioned from block to block. That distractor was randomly chosen at the beginning of the experiment. The target and other distractor locations were repeated and were predictive of the next trial's target location. Peterson and Kramer (2001a) found that contextual cuing still occurred when a single distractor was moved to a random location on each repetition. The difference between their study and ours was that we presented the predictive and the predicted information in successive trials, whereas Peterson and Kramer (2001a) presented them in a single trial. We tested 12 new participants.

Results and Discussion

Search RT data are presented in Figure 7. An ANOVA on training epoch in RT revealed a significant main effect of epoch, $F(4, 44) = 8.31, p < .01$. As in Experiment 1A, RT in Epoch 6 was significantly longer than it was in Epoch 5, $t(11) = 2.55, p < .05$. Thus, a significant intertrial temporal contextual cuing effect was observed, even though one distractor location on trial $N-1$ was randomly changing from block to block.

The persistence of intertrial temporal contextual cuing in the presence of a random distractor on trial $N-1$ suggests that the effect was not easily disrupted by any variation of trial $N-1$. It also suggests that in this paradigm, having a consistently predictive target is more important than having one consistently predictive distractor location. This fits with the observation that more attention is devoted to a target than to a distractor in visual search (see, e.g., Duncan, 1980).

General Discussion

Although previous studies on the learning of spatial context have examined learning effects within a single trial, we have shown here, for the first time, evidence for intertrial contextual memory. When a search display presented on one trial is predictive of the target's location on the next trial, RT for the next trial is improved. Removal of the consistent association between trials

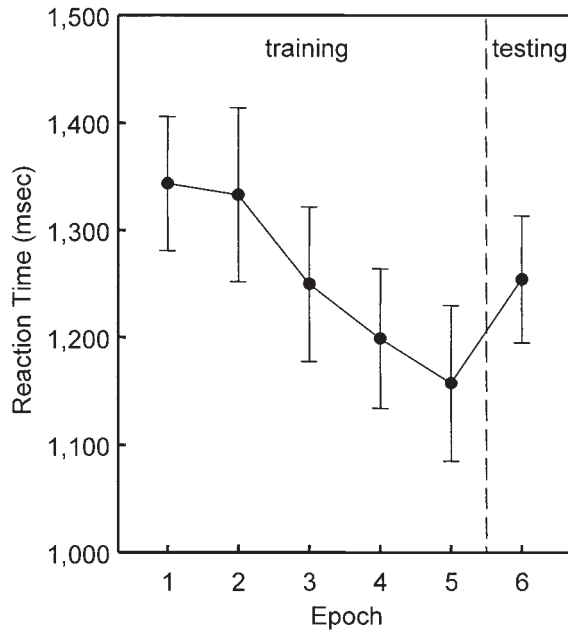


Figure 7. Mean correct reaction times as a function of epoch for Experiment 6. The training phase comprised the first five epochs; the testing phase comprised the sixth. Error bars represent the standard error of the mean.

produces a significant delay. Such learning is implicit, as participants are unable to explicitly recognize the repeated displays. This observation is consistent with the ubiquitous statistical learning account, according to which the visual system is sensitive to any statistical consistency, whether that occurs within a trial or across trials.

The Ubiquity of Statistical Learning in Vision

Experiments 2–6 provided important boundary conditions to the ubiquity of statistical learning. Experiments 2 and 3 showed that if the target (or the distractor layout) on trial $N-1$ was randomly changing from block to block, the presence of a consistent association between trial $N-1$'s distractor layout (or target location) and trial N 's target location was insufficient for contextual cuing. By presenting only the target (or only the distractor layout) on trial $N-1$, Experiments 4 and 5 clarified that the lack of learning should be attributed to the disruptive effects produced by the random variation. When the random variation on trial $N-1$ was removed, a significant intertrial temporal contextual cuing was observed, even though only one aspect of trial $N-1$ (e.g., either its target or its distractor layout) was predictive of the next trial. These findings suggest that the visual system is sensitive to statistical noise as well as to consistency. Whether a consistent association will facilitate performance depends on both the strength of the association and the strength of the noise (i.e., the strength of factors that are inconsistent).

This revised view, that the value of consistent association is affected by the relative strength between signal (consistent statistics) and noise (inconsistent statistics), receives support from all experiments of the current study. Experiment 1 produced the highest signal-to-noise ratio, in that the entire display on trial $N-1$

was predictive of trial N . Experiments 2 and 3 contained reduced signal (only the target or the distractor layout was predictive) and increased noise (the other cue was random), so learning was insignificant. Experiments 4 and 5 contained reduced signal (one cue was predictive) but no noise (the other cue was absent), leading to significant learning. Finally, Experiment 6 contained a strong signal (target and most distractors were predictive) against weak noise (one distractor was randomly positioned), leading to an intertrial cuing effect. These results led us to a revised view of the ubiquity of statistical learning, according to which the visual system is capable of extracting consistent association, but the efficiency depends on the amount of co-occurring noise. This is the *noise-sensitive statistical learning* account.

The noise-sensitive account also receives support from within-trial contextual cuing studies. When half of the items on a display repeat and are predictive of the target on that trial, contextual cuing is weakened, compared with when all items on the display repeat (Chun & Jiang, 1998). In addition, if items near the target are randomly positioned, items far away from the target produce no contextual cuing; but when the near items are removed, consistent far items can produce a cuing effect (Olson & Chun, 2002). In statistical learning of object pairs, participants are able to calculate conditional probability, such that learning is greater when two shapes appear together 10 times and never appear otherwise than when two shapes appear together 10 times and also appear independently 10 other times (Fiser & Aslin, 2001). In this respect, the visual system is not just sensitive to predictive statistics; it is also sensitive to random variations.

Effects of Attention on Contextual Learning

Extensive evidence from cognitive psychology has suggested that conscious perception and explicit memory are attention-dependent. Changes in natural scenes are better detected when they fall in attended regions (Rensink et al., 1997). In addition, when overlapping shapes are presented, one attended and the other ignored, subsequent recognition memory for the attended shape is much better than that for the ignored shape (Rock & Gutman, 1981).

Although attention may be the gateway to explicit learning and memory, recent studies show that unattended objects often leave implicit traces that can be revealed indirectly. Ignored shapes can produce a negative priming effect, such that RT is longer when ignored shapes later become targets (DeSchepper & Treisman, 1996). In addition, in the serial RT task, implicit learning of a repeated sequence of key presses is largely preserved when attention is taken away by a secondary task (Cohen, Ivry, & Keele, 1990; Frensch, Wenke, & Runger, 1999; Stadler, 1995; but see Nissen & Bullemer, 1987).

Contextual cuing provides an exception to the independence of implicit learning from attention. Distractor layout that can be quickly rejected because they form a different perceptual group from the target does not lead to contextual cuing (Jiang & Chun, 2001; Kawahara, 2003). However, although a repeated spatial layout does not lead to cuing when it is ignored, a significant cuing effect is immediately seen when a previously ignored context is now attended. Conversely, when a previously learned and attended context is now ignored, no cuing is observed (Jiang & Leung, 2005). This suggests that latent learning of spatial context does not depend on attention, but the expression of learning is attention-dependent.

Although previous studies have treated attention as an all-or-none phenomenon, the amount of attention across trials falls within an intermediate gray area. Yet this amount of reduced attention is sufficient for the learning and expression of intertrial temporal contextual cuing. This finding suggests that the predictive information and the predicted information need not be attended together in a single event. Residual attention for one event is sufficient to bridge across separate events, even though participants have no explicit knowledge that these events are related.

Future Directions

The demonstration of intertrial temporal contextual cuing leaves several questions unanswered with respect to how successive events are connected together. In particular, when does intertrial temporal contextual cuing occur, on trial $N-1$, during the intertrial interval (ITI), or on trial N ? Cuing could occur on trial $N-1$, such that attention is already directed to the future trial N 's target location and lingers there. Cuing could also occur during the ITI, anticipating trial N 's target location. Or it could occur after the presentation of trial N , during which memory of trial $N-1$ cues attention to the current trial's target location. The answer to this question has implications in terms of the cost and benefit of intertrial associative learning. If cuing already occurs on trial $N-1$, with attention directed to the next trial's target location, this should occur at the cost of the current trial's attentional deployment. If cuing occurs during the ITI and decays as the ITI lengthens, then intertrial temporal contextual cuing should be reduced as the ITI increases. Finally, cuing could be a retroactive process, in which case processing on trial $N-1$ should be unaltered, and the ITI may not have a significant effect. The current study did not manipulate necessary factors such as ITI to tease apart these possibilities. We leave it to future studies to determine the exact time course of an intertrial temporal contextual cuing effect.¹

Although it is not yet clear exactly when during the pair of trials the cuing effect occurred, the presence of intertrial temporal contextual cuing suggests that this mechanism may allow humans to bridge across temporally discrete events that lack spatiotemporal continuity. Such events are often considered as separate by the visual system, with the more recently presented display pushing a previous one outside of visual working memory (Jiang & Kumar, 2004). Intertrial temporal contextual cuing supplies a mechanism by which such separate events are still connected together.

In summary, the present study has highlighted the robustness and flexibility of implicit visual learning. We have shown that the association across successive visual search displays significantly facilitates search. Such intertrial temporal contextual cuing is sensitive not only to the presence of consistent association but also to random noise, such that cuing is reduced when the signal-to-noise ratio is reduced. We conclude that such cuing may help humans bridge across temporally discrete events.

¹ In a related study examining when the conventional contextual cuing effect takes place, Peterson and Kramer (2001b) included an abrupt-onset distractor in a contextual cuing experiment and found that the abrupt onset did not reduce the contextual cuing effect. They suggested that the effect of a preliminary attentional shift to the target location did not contribute to the cuing effect.

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