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# Implicit Learning of Spatiotemporal Contingencies in Spatial Cueing

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We investigated the role of implicit spatiotemporal learning in the Posner spatial cueing of attention task. During initial training, the proportion of different trial types was altered to produce a complex pattern of spatiotemporal contingencies between cues and targets. For example, in the short invalid and long valid condition, targets reliably appeared either at an uncued location after a short stimulus onset asynchrony (SOA; 100 ms) or at a cued location after a long SOA (350 ms). As revealed by postexperiment questioning, most participants were unaware of these manipulations. Whereas prior studies have examined reaction times during training, the current study examined the long-term effect of training on subsequent testing that removed these contingencies. An initial experiment found training effects only for the long SOAs that typically produce inhibition of return (IOR) effects. For instance, after short invalid and long valid training, there was a benefit at long SOAs rather than an IOR effect. A 2nd experiment ruled out target–cue overlap as an explanation of the difference between learning for long versus short SOAs. Rather than a mix of perfectly predictable spatiotemporal contingencies, Experiment 3 used only short SOA trials during training with a probabilistic spatial contingency. There was a smaller but reliable training effect in subsequent testing. These results demonstrate that implicit learning for specific combinations of location and SOA can affect behavior in spatial cueing paradigms, which is a necessary result if more generally spatial cueing reflects learned spatiotemporal regularities.

*Keywords:* attention, perception, cueing, learning, inhibition of return

Imagine you are walking in the woods when a flash of motion grabs your attention. You quickly realize (e.g., within 350 ms) that the flash of motion was just blowing leaves rather than an animal. Soon your attention wanders to a new region of the environment that seems likely to contain something of interest. As this example makes clear, foraging the perceptual environment involves shifts of attention based on salient cues (Wolfe & Horowitz, 2004) as well as the maintenance of attention for a duration sufficient to identify anything of interest. The Posner cueing paradigm (e.g., Posner, Snyder, & Davidson, 1980) has provided a great deal of information regarding attentional capture and the dynamics of attentional shifts and maintenance. In a typical Posner cueing experiment, the participant is instructed to detect a target at one of two or more locations. Prior to the target's appearance, one of these locations is made salient using a cue, such as a flash, which may be valid (in the same location as the impending target) or invalid (at another location). In the current study, we investigated whether implicit learning of spatiotemporal contingencies can change the typical pattern of results found with this task.

There are two key results found with the Posner cueing paradigm, and they are differentiated by the stimulus onset asynchrony (SOA) between the onset of the cue and the onset of the target. If the SOA is short (e.g., 100 ms), reaction times (RTs) to a target appearing at a validly cued location are faster than to targets appearing at other locations (Posner et al., 1980). This constitutes a *positive cueing effect* and represents sensible foraging under the expectation that a "salient" location (e.g., as signified by an abrupt onset) is likely to contain important information (*importance* being defined in relation to the task that the organism is attempting to solve, such avoiding predators or finding food). However, for longer SOAs (e.g., 350 ms), RTs to targets at cued locations are often slower compared with targets appearing at uncued locations (Posner & Cohen, 1984). This second result is commonly termed *inhibition of return* (IOR), and has been extensively studied over the past several decades. Noting that this name presupposes a cause that has been discounted in the literature (Berlucchi, 2006), we nevertheless refer to the resulting behavioral effect as the *IOR effect* for consistency with prior work. In terms of foraging behavior, the IOR effect seems sensible: Once all the information has been gained from a salient location, there is no reason to expect anything new at that location in the immediate future.

The IOR effect has been found in a wide range of situations. It occurs with both saccadic eye movements (Rafal, Calabresi, Brennan, & Sciolto, 1989) and when the eyes remain fixated while spatial attention covertly shifts (Posner & Cohen, 1984). Not only is the IOR effect observed in simple detection tasks, but it can also occur with target discrimination tasks (Cheal, Chastain, & Lyon, 1998; Lupiáñez, Milán, Tornay, Madrid, & Tudela, 1997; Pratt, Kingstone, & Khoe, 1997). The IOR effect can be initiated by exogenous cues, such as a flash at a specific location, and also endogenous cues, such as central arrows or verbal cues in object-

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directed attention (Weger, Abrams, Law, & Pratt, 2008). Furthermore, the IOR effect can arise from an exogenous auditory cue to a visual target (Spence & Driver, 1998) and from an auditory cue to an auditory target (Mondor, Breau, & Milliken, 1998). The mechanisms of IOR effects across these different tasks likely differ depending on the nature of the cues and the motor effectors involved. For instance, the IOR effect has been differentiated into separate perceptual and motor components (Taylor & Klein, 2000). Others also have suggested that the wide variety of situations in which IOR can be observed and the difficulty isolating IOR to a specific mechanism imply that IOR is instantiated at multiple levels of processing, for example, through habituation (Dukewich, 2009). At a computational level of analysis (Marr, 1982), the ubiquitous nature of the IOR effect suggests that it arises from a common computational constraint related to information processing. In support of this claim, increasing the perceptual processing demands of the task by changing the task from detection to discrimination (Lupiáñez et al., 1997), or by increasing the difficulty of target detection (Castel, Pratt, Chasteen, & Scialfa, 2005), has been found to delay the onset of the IOR effect. Furthermore, in rapidly changing visual environments, IOR effects are not observed (Wang, Zhang, & Klein, 2010).

In terms of information processing in foraging behavior, shifts from positive cueing to IOR effects as a function of SOA between cue and target may reflect learned responses to the spatiotemporal contingencies of the typical visual environment. A salient cue indicates that something has just changed, signaling that there is something new to perceive at that location (i.e., positive cueing immediately following the cue). However, once the information at that location has been collected and processed, it may be unlikely that something new will subsequently appear (i.e., because nothing new is expected at the previously cued location, the IOR effect is observed). This follows if new objects appear infrequently at a given location. In contrast, if the world changed rapidly, with new objects appearing frequently at all locations (e.g., a new object at all locations every 200 ms), then it is rational to maintain attention at a given location because even after processing the current information at that location, there would likely be something new in the immediate future. On this account, whether an IOR effect is observed depends both on how long it takes to perceive the visual information at a given location (i.e., at a minimum, attention must be maintained until the relevant information is gathered) and how frequently visual objects change at a given location. This predicts that IOR will be delayed or absent in more difficult tasks such as discrimination (Lupiáñez et al., 1997), in contrast to simple tasks such as detection, because the cognitive system needs more time to initially process and reject a cued location as not containing relevant target information. While this initial processing at a cued location takes place, there can only be cueing benefits rather than deficits: It is only after this initial time period that a statistical regularity for infrequent change will exert its influence, making the system less likely to anticipate targets at the cued location.

We are not presently concerned with the mechanistic processes underlying spatial cueing, but rather the role of the visual environment in sculpting those processes. These ideas are similar to the *foraging facilitator hypothesis* (Klein, 2000; Maylor, 1985; Posner & Cohen, 1984; Taylor & Klein, 1998). The critical distinction between the conceptualization of IOR as a foraging facilitator and the ideas put forth here is that rather than positing IOR as a response to previous foraging behavior, we suppose that these attentional effects are a rational response to the statistical regularities of the visual environment. One sensible interpretation of the foraging facilitator hypothesis is that the learning of prior behaviors exists to satisfy the need for adaptation to environmental regularities. Therefore, we refer to our theory as the *rational forager hypothesis*. It is important to note that the rational forager hypothesis does not aim to specify the precise mechanism or algorithm (Marr, 1982) by which attentional shifts adapt to environmental contingencies, but simply posits a need for such an adaptation based on environmental regularities. According to the rational forager hypothesis, the IOR effect occurs for experimental conditions that are in general incongruent with the spatiotemporal contingencies that actually exist in the visual environment (e.g., a target appearing at a cued location after a relatively long SOA). In a typical spatial cueing experiment, the location and timing of the cue are fully counterbalanced such that all SOAs occur equally often for all locations. However, we hypothesized that the more typical visual environment changes more slowly than in spatial cueing experiments: In the everyday world, it is unlikely that there will be SOAs of only 350 ms between the appearance of one object (the cue) and a second object (the target) at a given location. This hypothesis is motivated by conceptualizations and demonstrations of the importance of spatiotemporal expectations in the IOR effect (Jefferies, Wright, & Di Lollo, 2005; Spalek, 2007; Spalek & Hammad, 2004, 2005). A rational forager uses spatiotemporal statistics from the past environment to create implicit expectations as to the location of salient information given recent perceptual history. The end result of these expectations, possibly instantiated at multiple independent levels of cognitive processing, is the IOR effect. Our proposition is motivated by the idea that the mind seeks to efficiently encode the statistical structure of the world (Attneave, 1954; Barlow, 1975), which successfully explains attributes of both low-level vision (e.g., Bell & Sejnowski, 1997; Olshausen & Field, 1996) and audition (Smith & Lewicki, 2006). The rational forager hypothesis is an extension of these ideas to spatiotemporal attention.

One requirement of this hypothesis is that each location of the everyday visual environment changes at a frequency that is lower than the frequency implied by the SOA that produces IOR effects. However, measuring the spatiotemporal properties of the world is nontrivial. Rather than measure the everyday visual environment, our approach was to manipulate the visual environment within the context of a spatial cueing experiment to examine whether spatiotemporal attention adapts to this novel environment and whether there are long-term consequences of this learning for spatial cueing as it is typically tested. According to the rational forager hypothesis, if the spatiotemporal contingencies of the visual environment change, then spatial cueing behavior will be similarly changed, assuming some degree of plasticity. To test this, we performed experiments that exposed participants to different spatiotemporal contingencies and then assessed whether learning generalized to spatial cueing in an unstructured environment (i.e., one in which all cues to SOAs are tested equally often). We did not inform participants of these manipulations, and most participants did not realize that the spatiotemporal contingencies were manipulated.

The rational forager hypothesis assumes that the spatiotemporal dynamics of visual attention reflect long-term learning for combinations of spatial position and temporal delay in the world. The assumption that visual attention can learn in such a manner is testable, although previous studies have not fully explored this assumption. There are prior studies of spatial cueing demonstrating sensitivity to newly learned spatial regularities by manipulating the proportion of trials that cue the correct position for a fixed SOA (e.g., Bartolomeo, Decaix, & Siéroff, 2007; Farrell, Ludwig, Ellis, & Gilchrist, 2010; Lambert, 1996; Lambert, Naikar, McLachlan, & Aitken, 1999; López-Ramón, Chica, Bartolomeo, & Lupiáñez, 2011; Ludwig, Farrell, Ellis, Hardwicke, & Gilchrist, 2012; Risko & Stolz, 2010; Warner, Juola, & Koshino, 1990; Wright & Richard, 2000). There are also prior studies demonstrating sensitivity to newly learned temporal regularities by manipulating the proportion of different SOAs (e.g., Gabay & Henik, 2008, 2010; Milliken, Lupiáñez, Roberts, & Stevanovski, 2003). However, joint manipulations of spatial position and delay have not been examined. Most important, these prior studies examined cueing behavior only in the ongoing presence of the newly learned temporal or spatial regularity, rather than examining whether learning generalizes to the typical testing situation that uses an equal mix of SOAs and spatial positions. This is a critical distinction because an effect of a newly learned contingency might reflect only the last few trials (i.e., a local short-term effect) if tested in the ongoing presence of that regularity. Indeed, last-trial effects are known to be large in spatial cueing (Dodd & Pratt, 2007). Thus, cueing behavior may appear to be globally adaptive because the last trial reflects the local statistics of the different trial types. If the rational forager hypothesis is correct, it must be demonstrated that there are long-term effects of previously learned spatiotemporal contingencies.

Several studies have demonstrated the existence of long-term learning effects with spatial cueing. For instance, IOR effects gradually decrease the longer participants are tested in an unstructured environment in which targets appeared equally often in all locations (Weaver, Lupiáñez, & Watson, 1998; but see Pratt & McAuliffe, 1999). However, this effect appears only in the absence of temporal uncertainty (Lupiáñez, Weaver, Tipper, & Madrid, 2001). Another example of long-term learning comes from an examination of reading direction. For English readers, the IOR effect is larger when the cue and target appear on the left of the screen, whereas for readers of Hebrew, the opposite is true (Spalek & Hammad, 2004, 2005). This is a compelling result, although it not clear whether this reflects the natural behavior of spatiotemporal attention, or whether it might instead reflect some process specific to reading that has been co-opted for the spatial attention task. To examine whether there are long-term learning effects based on experimental manipulations, Ludwig et al. (2012) used different contextual cues (the orientation of the cue) to examine whether people could simultaneously learn two different spatial contingencies in a saccadic IOR task over several sessions. In their third experiment, the contingencies were randomly interleaved such that on average there was no differential contingency based on the last trial. Nevertheless, the magnitude of the IOR effect was sensitive to the spatial contingency implied by the contextual cue, demonstrating that there are long-term effects of newly learned contingencies. However, as with all of the research reviewed above, this experiment did not examine combinations of spatial position and temporal delay.

The current experiment is the first to use spatiotemporal contingencies requiring combinations of location and SOA, followed by testing in which all target locations and SOAs were equally likely. An advantage of including SOAs appropriate to both positive cueing and the IOR effect is that it becomes difficult to explicitly detect that anything has been manipulated. By including both short and long SOAs with opposing contingencies, it becomes possible to run an experiment in which the target is equally likely to appear at the cued and uncued locations even though there is a specific spatiotemporal contingency that can be implicitly learned. In addition, testing with nondiagnostic cue–target relationships ensures that the results cannot be attributed to short-term effects based on the last few trials.

# Experiment 1

We trained three groups of participants in a spatial cueing task with each group receiving a different spatiotemporal contingency. All three contingencies entailed an equal proportion of valid and invalid cue trials (i.e., the target was equally likely to appear on the cued side as the uncued side throughout the experiment). During training, one group received only trials in which the target appeared either on the same side as the cue after a short SOA or on the opposite side from the cue after a long SOA (short valid/long invalid cues). Another group was trained with the opposite trial types: The target only appeared on either the opposite side from the cue after a short SOA or on the same side as the cue after a long SOA (short invalid/long valid cues). A third group was trained with equal proportions of all four trial types. Note that for all three training conditions, neither location nor timing was independently predictive of the target: Learning could occur only if spatial attention is sensitive to combinations of location and SOA. After training, generalization was tested in the same manner for all three groups, with equal proportions of valid and invalid trials at a range of SOAs, including both trained and untrained SOAs.

## Method

**Participants.** A total of 58 participants completed the experiment. Each participant was randomly assigned to one of three possible training conditions: 20 to the short invalid/long valid training, 19 to the short valid/long invalid training, and 19 to the all cueing conditions training. The study was approved by the University of California, San Diego, Institutional Review Board, and all participants gave informed consent.

**Stimuli and apparatus.** The experiment was conducted using computers with a 60-Hz refresh rate and 640 × 480 pixel display resolution. The background of the display was a neutral gray. The two potential target location boxes were defined by lighter gray 48 × 56 pixel regions located equally spaced from the center fixation point (separated by approximately 16 degrees of visual angle). Both the fixation and the two potential target location boxes were present for the entire trial. Cues were white rectangles (40 × 48 pixels) presented in the center of one of the potential target location boxes. Targets were black asterisks presented in the center of one the potential target location boxes.

**Procedure.** Figure 1 presents the basic trial sequence. Each trial started with a fixation point in the center of the screen. Participants were instructed to maintain their gaze at the fixation and to respond (press a key) as quickly as possible after an asterisk appeared on the screen. Prior to the target presentation, the cue

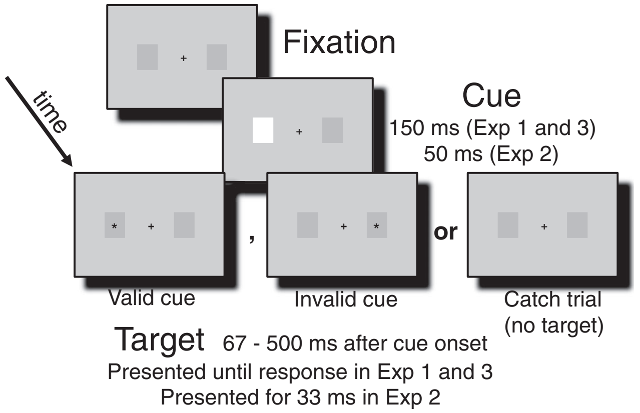

*Figure 1.* The basic trial sequence. For stimulus onset asynchronies (SOAs) that were longer than the cue duration, a display identical to the initial fixation screen was presented between the offset of the cue and the onset of the target. For SOAs that were shorter than the cue duration, the target appeared on top of the cue.

appeared at one of the potential target locations for 150 ms. Cues were equally likely appear at the right or left potential target location boxes. On each trial, there was a 50/50 chance that the cue validly indicated the target location, which also appeared at either the left or right location with equal probability. During final testing, the target followed the appearance of the cue after a SOA ranging from 67 to 500 ms. Note that for trials with 67- or 100-ms SOAs, the cue was still present when the target appeared such that the target appeared on top of the cue. To reduce anticipatory responses, on some trials no target was presented. Participants were instructed not to respond to these catch trials. Following each trial, accuracy and RT feedback was briefly reported to the participant to promote interest and motivation for the task. If the participant made a response prior to the target on a target-present trial, or responded on a target-absent trial, or if a response was not made within 1,500 ms of the target's appearance, the trial was recorded as incorrect and a brief message appeared on screen to encourage accuracy. Trials were divided into four blocks. The first two were training blocks, each consisting of 176 training trials. The second two blocks were testing blocks, each with 200 trials. Participants took 2-min video game breaks between blocks. Participants' correct RTs and target detection accuracy were the dependent measures. Participants were instructed to keep their eyes fixated on the center position, although eye movements were not monitored. We do not view this as serious limitation considering that the rational forager hypothesis supposes that implicit learning of spatiotemporal contingencies should occur for both covert shifts of attention and for shifts of attention that involve eye movements.

The experiment took place in two phases: a training phase and a test phase. This phase distinction was not disclosed to participants and, as reported in debriefing, was rarely noticed. There were three different randomly assigned groups of participants. The groups differed only in the types of trials occurring in the training phase. For all training groups, only 100- and 350-ms SOAs occurred during training. However, the proportion of valid and invalid cues at each SOA was manipulated between groups. Two experimental groups were trained in a fully deterministic spatiotemporal relationship between the validity of the cue and the SOA: a short valid/long invalid group and a short invalid/long valid group. For participants in the short invalid/long valid training group, training targets appeared at the uncued location after a short (100 ms) SOA or at the cued location after a long (350 ms) SOA. For participants in the short valid/long invalid training group, training targets appeared at the cued location after a short (100 ms) SOA or at the uncued location after a long (350 ms) SOA. The third training group served as a control. For this all-conditions training group, all four cueing conditions were equally likely (100-ms SOA valid cue, 100-ms SOA invalid cue, 350-ms SOA valid cue, or 350-ms SOA invalid cue). All trials were randomly ordered. Each training phase consisted of 288 target-present trials and 72 target-absent catch trials. The target present trials were divided evenly between the trained SOA and cueing conditions.

The testing phase was identical for all three training groups. Participants were tested with 67-, 100-, 200-, 350-, or 500-ms SOAs for both valid and invalid cues. In the testing phase, all SOA and cueing conditions were equally likely. There were 32 target-present trials at each combination of SOA and cue type (valid and invalid) and 80 target-absent trials. At the end of the experiment, participants were asked whether they noticed any relationship between the cue and the appearance of the target, and if so, to describe the relationship. Any participant who was able to describe any aspect of the training relationship or reported noticing a difference between the training and test phase of the experiment was eliminated from the analyses.

## Results

Trials with RTs of less than 100 ms were excluded from analysis (1.2% of trials over all participants). Furthermore, 11 participants were excluded because they either indicated insight into the nature of training ($n = 3$) or were low-accuracy outliers ($n = 8$). Outliers were designated by an average accuracy more than 1.5 times the interquartile range below the median across all groups. For Experiment 1, the cutoff accuracy rates were 0.946 on training trials and 0.915 on test trials. Including the data from these participants did not change the statistical conclusions. Data from 15 participants in the short invalid/long valid training, 15 in the short valid/long invalid training, and 17 trained with all cueing conditions remained. Before discussing the main results from the test portion of the experiment, we briefly report accuracy results and the data from training.

Accuracy was high and did not vary between training conditions. Participants responded incorrectly (i.e., before the appearance of the target or on target-absent trials) on an average of 1.9% of training trials and 2.8% of test trials. Incorrect anticipatory responses occurred more often for longer SOA trials. Given the high accuracy across conditions, accuracy data were arcsin transformed for analyses in all experiments. Comparing factors of SOA, training condition, and cue validity in an analysis of variance (ANOVA) for the test data, there was a main effect of SOA, $F(4, 176) = 70.64$, $p < .001$; accuracy was lower for 350-ms SOA as compared with shorter SOAs, $ts(93) > 5.19$, $p < .001$; and accuracy was lower for 500-ms SOA compared with all other SOAs, $ts(93) > 8.44$, $p < .001$. There were no differences in accuracy between training conditions, $F(2, 44) = 1.56$, $p = .22$, nor were there interactions with the training conditions, *F*s ≤ 1.75, *p* ≥ .089. Training RT data from each group could be compared only with the corresponding conditions of the all-conditions training group because the two experimental training conditions contained complementary cue validity and SOA conditions. Nevertheless, the pattern of mean RTs showed a similar pattern over the conditions as the test data, which are reported next.

Correct median RTs were averaged across participants and are presented in Figure 2. Statistical analysis with a repeated measures ANOVA examining the factors of training type, SOA, and target location resulted in a significant three-way interaction, *F*(8, 176) = 4.72, *p* < .001; a two-way interaction between cue validity and SOA, *F*(4, 176) = 57.81, *p* < .001; a two-way interaction between training and cue validity, *F*(2, 44) = 18.76, *p* < .001; and a main effect of SOA, *F*(4, 176) = 70.01, *p* < .001.

Considering the data at each SOA with separate repeated measures ANOVAs, including the factors of cue validity and training group, we found significant interactions between the training groups and cue validity for 200-, 350-, and 500-ms SOAs, *F*s(2, 44) ≥ 9.77, *p* < .001, but not at shorter SOAs of 67 ms, *F*(2, 44) = 1.15, *p* = .325, or 100 ms, *F*(2, 44) < 1. There were also main effects of cue validity at the two longest and two shortest SOAs, *F*s(1, 44) ≥ 15.70, *p* > .001. At 67- and 100-ms SOAs, there were no effects or interactions of the training group, although the typical valid cue benefit was observed, *t*s(46) ≥ 6.48, *p* < .001.

To understand the nature of the interaction between cue validity, SOA, and training condition, we analyzed the cueing effects for each training condition separately and then compared cueing effects between the training conditions. Results for participants in the all-conditions training replicate the typical positive cueing and IOR effects found in previous studies. Considering the factors of SOA and cue validity in an ANOVA for the all-conditions training group, there was an SOA by cue validity interaction, *F*(4, 64) = 34.12, *p* < .001. We used planned comparisons to test for the IOR effect at long SOAs (350 and 500 ms) and positive cueing at short SOAs (67 and 100 ms). Indicating the IOR effect, RT was faster to invalid cue trials at 350- and 500-ms SOAs: 350 ms, *t*(16) = −3.09, *p* = .007; 500 ms, *t*(16) = −5.74, *p* < .001. Positive cueing was found at 100- and 67-ms SOAs: 100 ms, *t*(16) = 3.92, *p* = .001; 67 ms, *t*(16) = 3.50, *p* = .003.

For both experimental groups, there were significant interactions between cue validity and SOA, *F*s(4, 56) ≥ 5.54, *p* ≤ .001. At long SOAs, these interactions were consistent with training. Participants in the short valid/long invalid training group were trained that following a long SOA, the location of the cue was likely to be an invalid indicator of the target location. Consistent with this training, the IOR effect was observed at 350- and 500-ms SOAs during the test phase: 350 ms, *t*(14) = −6.98, *p* < .001; 500 ms, *t*(14) = −7.75, *p* < .001. Unlike these results, participants in the short invalid/long valid training group displayed no significant IOR effects. In fact, at the 350-ms SOA, there was a significant positive cueing effect, *t*(14) = 2.76, *p* = .015. These positive cueing effects were also present at the 200-ms SOA, *t*(14) = 3.91, *p* = .002.

Comparisons between training groups of the size of the cueing effect (invalid cue RT – valid cue RT, so that larger numbers indicate a cueing RT benefit) revealed effects consistent with training for the longer SOA conditions. Cueing effects for the long invalid/short valid training group were significantly more negative than those for the all-conditions training group at 200 ms, *t*(27) = −2.39, *p* = .024, and 350 ms, *t*(27) = −2.53, *p* = .017, but not at 500 ms, *t*(30) = −0.73, *p* = .471, using Welch *t* tests. Cueing effects for the long valid/short invalid training group were more positive than those for the all-conditions group at 200 ms, *t*(29) = 2.22, *p* = .034, 350 ms, *t*(30) = 4.13, *p* < .001, and 500 ms, *t*(28) = 4.21, *p* < .001. At 67- and 100-ms SOAs, there were no differences in the cueing effect size between the control and training groups: all-conditions training compared with the short valid/long invalid at 67 ms, *t*(30) = −0.39, *p* = .701; 100 ms, *t*(28) = 0.92, *p* = .366; all-conditions training compared with the short invalid/long valid at 67 SOA, *t*(30) = 0.87, *p* = .392; 100 ms, *t*(28) = 1.52, *p* = .141.

## Discussion

In Experiment 1, participants learned spatiotemporal contingencies without explicit awareness, and this learning generalized to a subsequent testing session that removed these contingencies. Compared with participants trained with both valid and invalid cues at long SOAs, training with only invalid cues at long SOAs increased the size of the IOR effect. Conversely, participants trained with

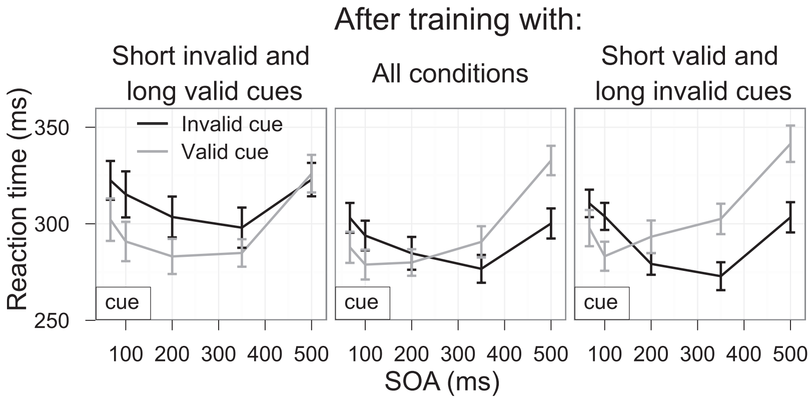

*Figure 2.* Average median correct reaction time (RT) across trial types for Experiment 1. These RTs are from the testing phase of the experiment, which was identical for each group. The box labeled “cue” in the lower left corner of each plot indicates the stimulus onset asynchronies (SOAs) for which the cue remained on screen during the presentation of the target. Error bars are ±1 standard error of the mean of participant medians.

only valid cues at long SOAs not only decreased the IOR effect but actually produced a reversal: A positive effect of cueing was observed at 350-ms SOAs. For both experimental training groups, the changes in behavior at the trained 350-ms SOAs generalized to other long SOAs. Unlike prior work that examined implicit learning of spatial cueing contingencies, these results cannot be explained by priming from the last few trials: Prior studies examined performance during training, whereas we examined generalization to subsequent testing that removed the spatiotemporal contingency.

The proportion of participants that explicitly noticed the contingencies during training was less than 10%, which leads us to believe that these long-term learning effects are implicit. In contrast, previous studies that manipulated spatial contingencies (Bartolomeo et al., 2007; López-Ramón et al., 2011) found that more than one third of the participants noticed the contingency. Experiment 1 used spatiotemporal contingencies rather than spatial contingencies at a fixed SOA, and this procedural difference might explain why participants did not notice the contingency in our experiment. It is possible that participants noticed the contingencies during training, but then forgot about them because the contingency was removed during testing. However, this implies that they did not contemplate the previously learned contingency during testing (otherwise, the contingency would not have been forgotten). If so, the effect of the learned contingency is still implicit (i.e., an implicit test of a previously learned contingency).

This generalization from training confirms a key assumption of the rational forager hypothesis, providing evidence that the local spatiotemporal cueing statistics of one environment can be learned and affect perceptual inference in a subsequent environment with different statistics. This is a necessary requirement for the claim that the typical pattern of results reflects adaptation to the everyday visual world. However, the results of Experiment 1 suggest that generalization from training exists for only long but not short SOAs. The next two experiments tested two potential explanations for this difference.

## Experiment 2

In Experiment 1, training effects were observed at long but not short SOAs. One difference between short and long SOAs is that for short SOAs, the cue overlapped with the presentation of the target. For valid cue trials, this overlap creates greater visual contrast for the target, enhancing sensory processing of targets. If targets are easier to detect at the cued locations for short SOAs, this might reduce the need for shifts of spatial attention because with higher visual contrast, spatial attention is less important for rapid target detection. If there is less demand for shifts of spatial attention, then there may be less learning of the cue contingency for short SOAs. To test this possibility, Experiment 2 replicated Experiment 1 using a shorter duration cue, such that the cue never overlapped with the target. Thus, there was no cue overlap for both short- and long-cue SOAs. Unlike Experiment 1, Experiment 2 did not test for generalization of training to other SOAs that did not appear during training. Instead, the question asked in Experiment 2 was whether training effects existed for both the trained short- and long-cue SOA when there was no cue overlap for either SOA. The SOAs used in Experiment 2 were chosen to represent a prototypical short and long SOA and were set at 83 and 400 ms, respectively.

### Method

The procedures and conditions used in Experiment 2 were identical to those of Experiment 1 except where stated otherwise.

**Participants.** A total of 30 participants completed the experiment. Each participant was randomly assigned to one of three training conditions: nine to the short invalid/long valid training, 11 to the short valid/long invalid training, and 10 to the all cueing conditions training.

**Procedure.** Experiment 2 used 50-ms cues and SOAs of 83 and 400 ms for both the three training conditions and testing. Furthermore, in Experiment 2, the target was a brief 33-ms flash. With these timings, the presentation of cue and target did not overlap. In total, 360 target-present training trials were divided into the two or four trial types, plus 72 target-absent trials. The testing phase of the experiment consisted of 40 trials of each of the four combinations of validity and SOA and 32 catch trials. To reduce the effects of anticipation with only two possible SOAs, we randomly jittered target presentations from the SOA condition by single screen refreshes (17 ms), so true SOAs varied from 67 to 100 ms and 383 to 417 ms. This was done during both the training trials as well as during test trials. The experiment was conducted in three blocks. The first two were training blocks of 144 trials, and the last consisted of 44 training trials followed by 192 trials in the testing phase.

### Results

As in Experiment 1, participants were deemed to be outliers and eliminated from further analyses if they were beyond 1.5 times the interquartile range from the median accuracy for either the training or test phase ($n = 5$, cutoffs of 0.900 and 0.916), or gave any indication of noticing the training manipulation ($n = 2$). This left 10 participants in all-conditions training, nine in the short valid/long invalid training, and five in the short invalid/long valid training. Overall error rates were 3.5% in the training phase and 2.6% in the test phase. Error rates were again higher for long SOAs compared with short SOAs: main effect of SOA in ANOVA with factors of SOA, cue validity, and training condition, $F(1, 20) = 24.97$, $p < .001$; $t$ test comparing long with short SOAs, $t(45) = 5.96$, $p < .001$.

Figure 3 presents the average of each participant's median RT for each condition during the test phase. In the testing phase of the experiment, there was a three-way interaction between training group, cue validity, and SOA in a repeated measures ANOVA with these three factors, $F(2, 20) = 14.94$, $p = .001$. There were also interactions between cue validity and SOA, $F(1, 20) = 114.70$, $p < .001$, training group and cue validity, $F(2, 20) = 12.00$, $p < .001$, and a main effect of cue validity, $F(1, 20) = 39.47$, $p = .001$. In an ANOVA for only the short SOA, with factors of cue validity and training group, there were no significant effects of the training group, $F(2, 20) < 1.00$, cue validity, $F(1, 20) = 1.47$, $p = .240$, or the interaction, $F(2, 20) < 1.00$. However, for the long SOA, there was an interaction between training condition and cue validity, $F(2, 20) = 24.84$, $p < .001$, and a main effect of cueing, $F(1, 20) = 119.66$, $p < .001$. The IOR effect was absent in the

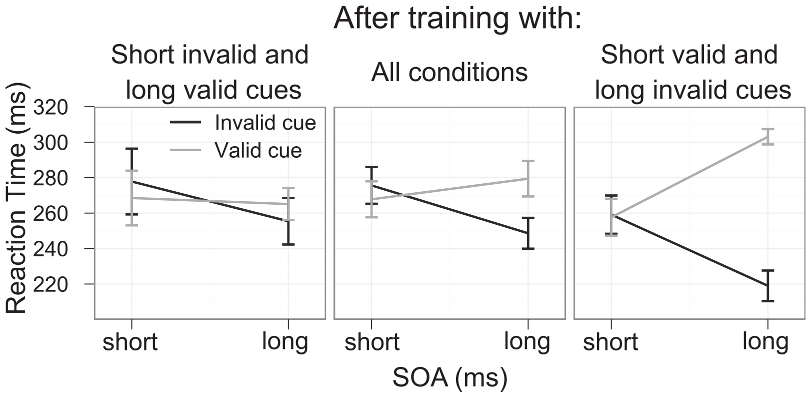

*Figure 3.* Average median correct reaction time (RT) for Experiment 2. These data are from the testing phase of the experiment, which was identical for each group. In this experiment, the cue and target never overlapped. Stimulus onset asynchronies (SOAs) were jittered between 67 and 100 ms for short SOAs, and between 383 and 417 for long SOAs. Error bars are ±1 standard error of the mean of participant medians.

short invalid/long valid training group, $t(4) = -1.05$, $p = .352$, but present for both the all-conditions training group, $t(9) = -5.24$, $p < .001$, and the short valid/long invalid training group, $t(7) = -11.64$, $p < .001$. Furthermore, the cueing deficit at the long SOA was larger for the short valid/long invalid training group than that for the all-conditions training group, $t(15) = -5.22$, $p < .001$. In turn, the IOR effect was larger for the all-conditions training group than that for the short invalid/long valid training group, $t(9) = 2.33$, $p = .046$.

## Discussion

Replicating Experiment 1, training effects were present only for the long SOA, indicating that the lack of a training effect for the short SOA in Experiment 1 was not a consequence of the temporal overlap between the target and cue for the short SOA.

There was one interesting difference between Experiment 1 and Experiment 2: Experiment 2, which eliminated overlap of the cue and target in the short SOA condition, failed to reveal any significant positive cueing effects for the short SOA condition. This result is not without precedent. Other studies have failed to find a facilitation effect at short SOAs (e.g., Tassinari, Aglioti, Chelazzi, Peru, & Berlucchi, 1994), and there is evidence that short SOA facilitation requires cues and targets that temporally overlap (Maruff, Yucel, Danckert, Stuart, & Currie, 1999) or highly salient cues (Lambert, Spencer, & Hockey, 1991). However, other experiments have demonstrated positive cueing effects for short SOAs in the absence of temporal overlap between the cue and target (McAuliffe & Pratt, 2005; Pratt, Hillis, & Gold, 2001). Besides eliminating temporal overlap, another procedural difference between the experiments is that the targets of Experiment 1 remained onscreen until a response was given, whereas the targets in Experiment 2 appeared only briefly. Regardless of the explanation for the failure to find a positive cueing effect for short SOAs in Experiment 2, it is clear that eliminating cue overlap failed to enable training effects for the short SOAs. An alternative explanation for the failure to observe training effects for short SOAs was tested in Experiment 3.

# Experiment 3

The failure to find training effects for short SOAs suggests that the automatic orienting response is incapable of learning. However, Warner et al. (1990) disconfirmed such an account, finding that subjects can learn new spatial regularities with short SOAs. For instance, participants in Warner et al.'s opposite condition produced faster responses to a target appearing at a position diametrically opposite to the cue as compared with a target appearing at the cued position. This reversal of the typical cueing benefit at short SOAs occurred with explicit instructions that the cue would likely indicate the opposite position on 80% of the trials. Furthermore, the reversal only emerged after several days of training. The failure to find a similar effect in Experiments 1 and 2 may reflect the smaller number of training trials used in those experiments. Nevertheless, it is puzzling that there was not even a hint of a trend in the expected direction in the short SOA data of Experiments 1 and 2 (in fact, the trend appeared to be in the opposite direction). There are many differences between the Warner et al. study and Experiments 1 and 2, but perhaps the most important difference is that the Warner et al. study involved training at only short SOAs. In contrast, Experiments 1 and 2 involved training at both short and long SOAs with opposing spatial regularities for short and long SOAs. As discussed next, this mixture of spatiotemporal contingencies might have made it selectively difficult to learn the short SOA contingency.

One possibility is that attention is sensitive to spatiotemporal contingencies for both short and long SOAs, but that it lacks the capacity to take advantage of these contingencies in a situation that presents both SOAs in an intermixed fashion. If participants are unable or unwilling to make two attention shifts during a trial (i.e., a first shift under the assumption that the trial is a short SOA trial, but then a second shift if the trial turns out to be a long SOA trial), then attention would be unable to use both the short and long SOA contingencies even if both were implicitly learned. If attention makes only one shift of attention, the optimal strategy is to wait until such time as it can be determined that the trial is a long SOA trial. In contrast, if that one shift is made as soon as the target appears, there is still a 50/50 chance that the trial will be valid versus invalid, depending on whether the SOA is short versus long. For the experimental training regimes of Experiments 1 and 2, if that one shift is made only after the short SOA has elapsed, then the shift can be made to the target location with greater certainty.

To test this account of the failure to find short SOA training effects in Experiments 1 and 2, Experiment 3 used training that included only short SOAs. Thus, if the system can implicitly learn spatiotemporal contingencies even for short SOAs, and if the participant experiences only short SOAs, the optimal strategy is to shift attention as soon as the cue appears. However, running such an experiment poses a problem: With only a single SOA, it is likely that participants will become explicitly aware of the trained contingency if that contingency is 100% reliable. Therefore, unlike Experiments 1 and 2, the validity of the spatiotemporal contingency in Experiment 3 was probabilistic rather than deterministic. This is likely to reduce the magnitude of any training effects, although this change is necessary to disguise the nature of the training. Analogous to Experiments 1 and 2, Experiment 3 trained participants that the cue was likely to be valid, likely to be invalid, or that both cue types were equally likely. Participants were then tested with equal proportions of valid and invalid cues at three short SOAs, including the trained SOA. At first glance, this may appear to be a replication of the Warner et al. (1990) study. However, unlike that study, (a) we did not explicitly inform participants about these contingencies, (b) we tested generalization of learning in a task without contingences, (c) the task was simple detection rather than discrimination, and (d) training was completed in a single session.

## Method

The procedures and conditions used in Experiment 3 were identical to those of Experiment 1 except where otherwise stated.

**Participants.** A total of 105 participants completed the experiment. Each participant was randomly assigned to one of three training conditions: 35 to invalid common training, 34 to valid common training, and 36 to all cueing conditions training.

**Procedure.** All target-present training trials in Experiment 3 used a 100-ms SOA. Participants in the all-conditions training group completed 192 valid cue trials, 192 invalid cue trials, and 96 target-absent trials. Unlike in Experiments 1 and 2, the other training groups experienced both valid and invalid cues during short SOA training; however, one of these conditions was much more common than the other. Therefore, we term these groups the *valid common* and *invalid common* training groups. The valid and invalid common training groups consisted of 336 trials of the common target location condition, 48 trials of the complementary target condition, and 96 target-absent trials. For example, a participant in the valid common condition completed 336 trials in which the target appeared at the same location as the cue, 48 trials in which the target appeared in the opposite location from the cue, and 96 trials with a cue but no target. Thus, 20% of trials contained a cue but no target, 10% of trials contained a cue that predicted the opposite location from that indicated by the spatial contingency (i.e., either the same or opposite position, depending on training group), and 70% of trials contained a cue that predicted the correct location based on the spatial contingency. When considering only target-present trials, the predictive strength of the cue was 87.5% rather than 70%. The testing phase of the experiment was identical for all groups and consisted of 48 target-absent trials and 32 trials at each of six conditions: SOAs of 67, 100, and 200 ms following either valid or invalid cue presentations. There were three blocks in the experiment, two training and one testing.

## Results

As in both previous experiments, participants were excluded if their median accuracy for either the training (0.920 training accuracy cutoff) or test blocks (0.863 cutoff) was below 1.5 times the interquartile range from the group median ($n = 14$) or if they gave any indication of noticing the spatial contingency ($n = 11$). This left a total of 31 participants in the all-conditions training group, 28 in the invalid common training group, and 32 in the valid common training group. On average, participants responded in the absence of the target on 2.8% on the training trials and 4.6% in the test trials. There was again a main effect of SOA on accuracy in the test block, $F(2, 154) = 6.14$, $p = .003$: Accuracy for the 200-ms SOA conditions was lower than either of the two shorter SOAs, $ts(159) \geq 3.00$, $p \leq .006$.

In Experiment 3, all three training groups received all conditions of training, but in different proportions. Thus, unlike Experiments 1 and 2, it was possible to analyze median RTs during training in a mixed ANOVA with factors of cue validity and training group. In addition to a main effect of cue validity, $F(1, 77) = 281.82$, $p < .001$, there was an interaction between training group and cue validity, $F(2, 77) = 45.85$, $p < .001$. There were significant positive cueing effects for the all-conditions training group, $t(58) = 4.01$, $p < .001$, and the valid common training group, $t(47) = 4.64$, $p < .001$. However, there was no significant cueing effect for the invalid common training group, $t(46) = 0.72$, $p = .476$.

Figure 4 presents the average median correct RT data from the test phase of this experiment, showing that probabilistic training had an effect on RT during subsequent testing. There was a three-way interaction between the factors of cue validity, training group, and SOA duration, $F(4, 154) = 2.47$, $p = .047$. In addition, there were interactions between cueing validity and SOA, $F(2, 154) = 25.14$, $p < .001$, and, critically, between training group and cue validity, $F(2, 77) = 8.36$, $p < .001$. Finally, there were main effects of SOA, $F(2, 154) = 129.60$, $p < .001$, and cue validity, $F(1, 77) = 48.35$, $p < .001$.

To examine the nature of the three-way interaction, we performed two-way ANOVAs at each SOA with the factors of training group and cue validity, finding significant interactions at all SOAs, $Fs(2, 77) \geq 3.24$, $p \leq .045$. At the 67- and 100-ms SOAs, there was a significant positive cueing effect for each training group: all conditions, $ts(30) \geq 4.36$, $p < .001$; valid common, $ts(24) \geq 6.12$, $p < .001$; invalid common, $ts(23) \geq 3.37$, $p \leq .003$. Notably, considering only the 67- and 100-ms SOAs, there was still a significant interaction between cue validity and training group, $F(2, 77) = 4.61$, $p = .006$. To determine the nature of the interactions between cue validity and training group, we compared the cueing effect sizes between training conditions for the 67- and 100-ms SOA conditions. The valid common training group had larger positive cueing effects than the all-conditions training group for the 67-ms, $t(48) = 2.09$, $p = .042$, and 100-ms SOA conditions, $t(47) = 2.22$, $p = .031$. In contrast, the cueing effect for the invalid common training condition was not significantly different

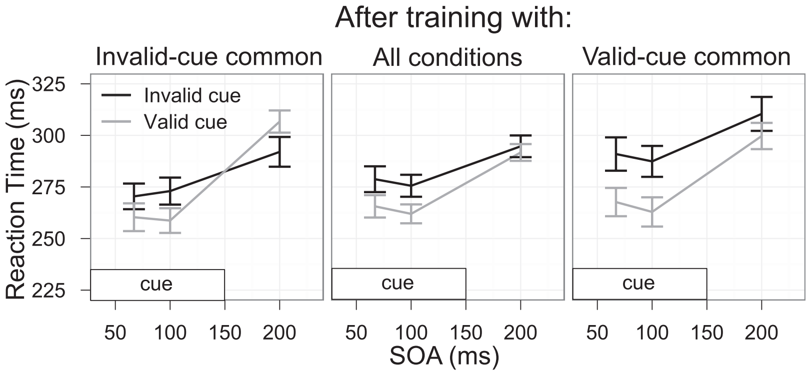

*Figure 4.* Average median correct reaction time (RT) for Experiment 3. These data are from the testing phase of the experiment, which was identical for each group. In this experiment, the diagnostic environment was probabilistic, and either valid or invalid cues were more common. The box labeled "cue" in the lower left corner of each plot indicates the stimulus onset asynchronies (SOAs) for which the cue remained on screen during the presentation of the target. Error bars are ±1 standard error of the mean of participant medians.

from the cueing effect in the all-conditions training for the 67-ms, $t(52) = -0.71$, $p = .478$, or 100-ms SOA condition, $t(51) = 0.16$, $p = .877$. At the 200-ms SOA, there was a qualitative change in the direction of cueing. There was a cueing benefit for the valid common group, $t(24) = 2.19$, $p = .038$, no cueing effect for the all-conditions group, $t(30) = 0.74$, $p = .465$, and a cueing deficit for the invalid common group, $t(23) = -2.89$, $p = .008$. Thus, for the 200-ms SOA condition, there was a full reversal from positive to negative cueing as a function of short SOA training. Notably, a similar reversal for the 200-ms SOA condition was also seen in Experiment 1. However, for Experiment 1, the reversal was that it tracked the learned regularities of the long SOA training trials, which were opposite those of short SOA training, whereas in the case of Experiment 3, this reversal tracked the learned regularities from short SOA training. In summary, the effect of short SOA training appears to be stronger for the 200-ms SOA conditions as compared with the 67-ms and 100-ms SOA conditions, although it is significant at all three SOAs.

## Discussion

Experiment 3 demonstrated that probabilistic training using only short SOAs produces training effects that generalize to subsequent testing during which all conditions appear equally often. Exposure to diagnostic contingencies with primarily valid cues resulted in larger positive cueing effects than training with equal proportions of valid and invalid cues. Exposure to primarily invalid cues also affected subsequent testing; however, this difference was smaller and seemed to be driven primarily by the longest SOA. Finally, when considering only the 200-ms SOA condition during testing, short SOA training produced a full reversal from positive to negative cueing. This demonstrates that implicit learning of short SOAs can affect subsequent testing; thus, the failure to find short SOA effects for Experiments 1 and 2 was presumably due to the random mixing of short SOA training with long SOA training that was opposite in nature. This supports the hypothesis that the attention system is capable of making or perhaps willing to make only one shift of attention following the cue, resulting in a failure to observe short SOA training effects for the training procedures used in Experiments 1 and 2.

Despite the significant results at short SOAs in Experiment 3, the training effects were noticeably smaller than what was observed for the long SOA training conditions of Experiments 1 and 2. However, the long SOA training trials in Experiments 1 and 2 were 100% diagnostic, whereas the short SOA training trials of Experiment 3 were only 87.5% diagnostic. This was done to ensure that the training manipulation was not noticed (i.e., implicit learning). As demonstrated by Warner et al. (1990), explicit training with short SOAs can eventually produce a reliable reversal of the usual positive cueing effects even for the shortest SOAs. The current results build on this finding by demonstrating that short SOA training effects occur even with implicit learning, and, furthermore, that short SOA training effects generalize to the typical testing situation that uses an equal mix of valid and invalid cueing conditions. The latter point is particularly important because the Warner et al. study examined performance only in the presence of ongoing short SOA training. As such, their findings might have reflected short-term (e.g., last trial) effects rather than long-term learning. The current results demonstrate that there are long-term consequences of learning short SOA contingencies.

## General Discussion

We report evidence that spatial attention implicitly adapts to contingencies that entail combinations of time and location, and, furthermore, that this training continues to affect subsequent performance in test trials without these spatiotemporal contingencies. To the best of our knowledge, this is the first study to examine combinations of time and location, rather than manipulating contingencies related only to SOA or only to spatial location. Generalization to subsequent testing demonstrates that there are long-term effects of implicitly learned spatiotemporal contingencies, ruling out explanations based on short-term effects (e.g., an influence of the last trial). Previous manipulations of spatial or temporal contingencies examined behavior in the ongoing presence of the contingency, and, as such, it was not clear whether the results reflected long-term or short-term processes.

The learning of these spatiotemporal contingencies occurred implicitly over the course of a single experimental session and generalized to blocks of nondiagnostic trials and untrained SOAs. At long SOAs, where the IOR effect is typically observed, the trained spatial contingencies readily affected RT behavior in the expected manner. For instance, in Experiment 1, training that targets were likely to appear at a cued location after a 350-ms SOA eliminated IOR effects at a 500-ms SOA and produced positive cueing effects during subsequent testing rather than the more typical IOR effects that are seen at long SOAs. For short SOAs, positive cueing was found in Experiment 1, but it was not influenced by training. However, in Experiment 1, short SOAs differed from long SOAs in that only for short SOAs did the cue visually overlap with the target. Experiment 2 used cues that never overlapped with targets and yet the same pattern of results was found (i.e., there were training effects only for long SOAs). This ruled out cue overlap as an explanation for the differential training effects at short and long SOAs. Experiment 3 tested whether the training difference between short versus long SOAs was due to the use of both SOAs in an intermixed fashion. Intermixed SOA contingencies necessitate two rapid shifts of attention to make full use of the spatiotemporal contingencies. In Experiment 3, only short SOAs were trained and tested, making it possible to take advantage of the trained contingency with a single shift of attention. With this change, training with short SOAs affected subsequent testing: For subsequent testing with 67- and 100-ms SOAs, the nature of this training effect was to modulate the magnitude of the cueing benefit, and for subsequent testing with 200-ms SOAs, the nature of this effect was to fully reverse the cueing benefit, producing cueing deficits following training that the cue was likely to indicate the invalid location with a short SOA.

These findings are consistent with the rational forager hypothesis, which posits that spatial cueing effects are the result of implicit learning of the statistical spatiotemporal regularities of the everyday visual world. On this account, salient cues (e.g., a flash of motion) are likely indicators of something of interest at the cued location, although if nothing has been identified within a brief period of time (e.g., 250 ms), that location is ruled out from subsequent foraging. In the rational forager hypothesis, the short durations typical of positive cueing effects reflect the minimum duration needed to identify (i.e., forage) anything of interest at a cued location, whereas the long durations typical of IOR effects reflect the assumption that objects of interest in the world tend to change location relatively slowly, such that a previously foraged location is unlikely to contain anything new in the immediate future. These assumptions dictate the spatiotemporal contingencies of the everyday visual world and the rational forager hypothesis assumes that long-term learning of these contingencies affects spatial cueing behavior in laboratory experiments even though the experiments eliminate these spatiotemporal contingencies by using an equal mix of SOAs and valid/invalid cues. A key assumption of this account is that the implicit learning of spatiotemporal contingencies is long lasting, and the current experiments confirmed this assumption. Whether the everyday visual world actually has the structure that corresponds to typical spatial cueing behavior awaits further study. Nevertheless, these experiments demonstrate that if the everyday environment has these properties, spatial attention should implicitly learn these regularities, and this learning should bias performance as typically tested in the lab.

Beyond spatial cueing, a number of nonspatial paradigms find that manipulations of exposure duration or delay between an initial presentation and a subsequent target produce a behavioral pattern that similarly changes from facilitation for compatible trials to a deficit for compatible trials. Furthermore, the time course of these transitions is strikingly similar to that found with spatial cueing. These paradigms include attentional blink (Raymond, Shapiro, & Arnell, 1992), immediate repetition priming (Huber, 2008; Huber, Shiffrin, Quach, & Lyle, 2002), repetition blindness (Kanwisher, 1987), and negative priming (Neill, 1977), which all show variants of this pattern. For the case of repetition priming, Huber and O'Reilly (2003) proposed that this dynamic time course is due to synaptic depression, which exists as a mechanism for parsing events in time to avoid source confusion between previously viewed objects versus the currently viewed object. If this same dynamic exists within a spatial attention map, it might explain the time course of spatial cueing. If this account is correct, the current results imply that synaptic depression readily adapts to capture different profiles for the rise and fall of spatial attention as dictated by environmental regularities. Further investigations may allow a unification of these paradigms as learned responses to diagnostic information, thus providing greater insight into domain general perceptual processing. For instance, an investigation of IOR effects and negative priming concluded that these two paradigms reflect the same underlying processes (Milliken, Tipper, Houghton, & Lupiáñez, 2000).

The similarity between spatial cueing and priming explained through synaptic depression fits well with the idea that IOR is the result of habituation of attentional capture (Dukewich, 2009). We consider the implicit learning of environmental regularities to be a computational-level explanation for IOR, which might be implemented cognitively through habituation and, in turn, physiologically through synaptic depression. From this perspective, it may well be that adaptation for the rate of habituation describes the specific nearly optimal adaptive mechanism that underlies the rational forager hypothesis. Critical for this connection is understanding how associative learning, like the implicit learning of spatiotemporal regularities, interacts with nonassociative habituation. One possibility is that parameters of habituation are modified to reflect long-term associations between a stimulus and reward or lack thereof. For instance, when trained that targets appear at the cued location with a short SOA or the uncued location with a long SOA, it is advantageous that spatial attention rapidly habituate, resulting in a shorter duration of maintained attention at the cued location. In the opposite type of training, the long SOA trials would be facilitated by slower habituation, such that attention is maintained at the cued location. Note, however, that this nonassociative type of learning fails to produce the optimal pattern of attention shifts for this condition, which would consist of quickly shifting attention to the uncued location, but then returning attention to the cued location in the event of a long SOA trial. The failure to engage in such a two-shift strategy is exactly what was observed. The current results do not prove that typical spatial cueing effects are due to learned spatiotemporal regularities; instead, they merely support a key assumption of this theory. However, there is evidence that appears to contradict this account. More specifically, there is evidence that typical spatial cueing is unaffected by learning/expectation manipulations such as manipulations of covert orienting (Berlucchi, Chelazzi, & Tassinari, 2000), manipulations of awareness for the likely position of targets (Bartolomeo et al., 2007; López-Ramón et al., 2011; Risko & Stolz, 2010), the inclusion of peripheral context cues that signal the likely location of the target (Chica, Lupiáñez, & Bartolomeo, 2006), and manipulations of spatial (but not temporal) regularities within an experiment that examined both short and long SOAs (Lupiáñez et al., 2004). In each case, these manipulations either failed to change spatial cueing or else produced effects that were additive with spatial cueing. However, the rational forager hypothesis does not claim that all spatial attention effects result from a single learning mechanism; instead, the rational forager hypothesis is agnostic regarding the mechanisms that support adaptation to the spatiotemporal regularities of the everyday visual world. If there are multiple mechanisms that influence spatial attention (e.g., long-term learning such as explored in the current study vs. last-trial short-term memory such as may underlie many of these other expectancy effects), then it is understandable that manipulations exist that selectively affect some of these mechanisms while leaving others unaffected. Instead, the key contribution of the rational forager hypothesis is the claim that the collective action of these mechanisms has been sculpted by the spatiotemporal regularities of the everyday visual world. Thus, a change in the spatiotemporal regularities should have a lasting effect on spatial cueing behavior, as was found in the current experiments.

Although the rational forager hypothesis is agnostic regarding the mechanisms that support spatial cueing, it does claim that these mechanisms can adapt to spatiotemporal regularities. To explore this issue in greater detail, a technique is needed that can determine whether the mechanisms that underlie the learning of spatiotemporal contingencies are the same mechanisms that underlie spatial cueing. One approach is to examine other attributes of choice behavior besides median correct RT. Providing evidence against the claim that the same mechanism underlies both phenomena, a study measuring saccadic RT in the presence of different spatial contingencies examined attributes of RT distributions from both correct and error trials as described by the linear ballistic accumulator RT model (Brown & Heathcote, 2008). This study found a dissociation in the attributes of perceptual decision making that best explained different cueing conditions versus those that best explained training effects. The IOR effect was best modeled as an increase in the rate of accumulation of evidence for invalid cue trials (Ludwig, Farrell, Ellis, & Gilchrist, 2009), but the effect of training was related to changes in the evidence threshold for responding (Farrell et al., 2010). In other words, the IOR effect was due to slower detection of the target, whereas training affected median RT by changing the bias to report targets. However, Farrell et al. (2010) used a single long SOA and the RT data came from blocks of trials while participants were still experiencing the spatial contingency. Thus, it is possible that the training effects in their study primarily reflected the short-term effect of the last few trials. For instance, it may be that the last trial affects the response threshold, but long-term learning, such as examined in the current experiments, affects the mean accumulation rate. To explore this issue in greater detail, the Appendix reports the results of applying the linear ballistic accumulator model to the data from Experiment 1. In contrast to the results of Farrell et al., both training effects and cueing effects were best accounted for by changes in the mean accumulation rate. For the long-lasting training effects examined here, we find support for the claim that a common mechanism underlies both cueing effects in general as well as implicit learning of spatiotemporal relationships. It should be noted that there are several important differences between the experimental and the model-fitting procedures that might explain this apparent discrepancy with Farrell et al. (2010): (a) saccadic IOR versus manual responses, (b) examination of learning effects while still experiencing the new contingency versus generalization to subsequent testing without the contingency, and (c) model results based on a full model with all parameters freely varying versus nested model comparison. Additional work is needed to determine which of these underlies this discrepancy.

The current study provides additional evidence that our perceptual and attentional systems are not fixed and can change in fundamental ways after just a brief training session. This implies that attempts to exploit the spatiotemporal properties of attention, (e.g., centralized brake lights; Kahane & Hertz, 1998) may ultimately be futile as attention adapts and updates based on recent experience. Our results may also be relevant to patient populations. For instance, patients with Alzheimer's disease (Faust & Balota, 1997) and patients with schizophrenia require longer SOAs between cues and targets than typical individuals to find IOR effects (Gouzoulis-Mayfrank et al., 2004; Larrison-Faucher, Briand, & Sereno, 2002). Rather than attributing this to a deterioration of spatial attention, the rational forager hypothesis offers a different account: It may be that these patients require longer to identify (forage) a given spatial location, and that the observed delay in the onset of the IOR effect reflects learning of spatiotemporal attention to accommodate slowed perceptual abilities. A similar explanation may underlie changes in IOR with aging (Castel, Chasteen, Scialfa, & Pratt, 2003; McCrae & Abrams, 2001). Compared with older individuals, the young may not need as long to identify whether there is anything of interest at a cued location, resulting in a more rapid onset of the IOR effect.

In conclusion, these experiments demonstrated that participants implicitly and rapidly adapt to novel spatiotemporal contingencies in spatial cueing, and this adaptation generalizes to both untrained SOAs and to the typical testing situation that uses all combinations of SOA and cueing equally. These results do not prove the rational forager hypothesis, which proposes that typical spatial cueing effects reflect the statistical regularities of the everyday visual world. However, they support several of its necessary assumptions. The rational forager hypothesis assumes that spatial attention implicitly adapts to spatiotemporal regularities, that this learning is sufficiently long lasting, and that it generalizes to the typical testing situation. The current experiments verified these assumptions.

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(*Appendix follows*)

# Appendix

## Computational Modeling of Experiment 1 Results

Here, we present fits of the results from Experiment 1 using the linear ballistic accumulator (LBA) model of RT (Brown & Heathcote, 2008). The LBA model fits RT distributions using five parameters: *b*, the response threshold; *v*, the mean accumulation rate; *s*, the standard deviation of the accumulation rate; *A,* the upper limit of the starting point; and $T_{er}$, the nondecision time. RT of a single trial is modeled as an accumulation process with a response occurring when the accumulator reaches the threshold, *b*. The accumulation starts at a random point between zero and *A,* and increases linearly at a rate randomly drawn from a Gaussian distribution with mean *v* and standard deviation *s*. A fixed time for nondecision processes ($T_{er}$) is also added. Figure A1 provides a graphical representation of this process. The parametric nature of the model allows for analytic solutions, making it easier to apply the model as compared with similar sequential processing models (Ratcliff, 1978).

The LBA model usually consists of separate accumulators for each possible competing response and models accuracy as the response crossing the threshold first. However, in the current application, we have only one response, and therefore we used only one accumulator to model RT. The model was fit to the data as follows. We first computed five quantiles of the cumulative RT distribution at 10%, 30%, 50%, 70%, and 90%. The cumulative distribution of the LBA accumulator was evaluated at these five RTs and one corresponding to the response deadline of 1,500 ms. The LBA cumulative proportions at these RTs were compared with the observed quantile proportions (0.1, 0.3, 0.5, 0.7, 0.9, and 1.0) with two measures of fit, $G^2$ and Akaike information criterion (AIC):

$$G^2 = 2\sum_i \left( N_i \sum_j p_{ij} \log\left(\frac{p_{ij}}{\hat{p}_{ij}}\right)\right),$$

$$AIC = G^2 + 2(n_{params}).$$

The index variable *i* increments over conditions, and *j* increments over quantiles. $N_i$ is the number of data points for condition *i*, $p_{ij}$ is the true quantile proportion, $\hat{p}_{ij}$ is the estimated quantile proportion from the model, and $n_{params}$ is the number of parameters. Best-fit parameters were selected by minimizing $G^2$ with numerical optimization.

Given the large space of possible mappings of the five model parameters onto the five levels of SOA and valid/invalid cueing conditions, we used a nested modeling procedure to determine which factors are best fit by which parameters. Figure A2 presents an illustration of this process. More complex models (i.e., models with more free parameters) appear at the top and less complex models are at the bottom. We started by fitting all conditions with a single set of parameters (i.e., the "base model" at the bottom of the figure). In this model, the parameters *s, A, v,* and $T_{er}$ were allowed to take on any value to maximize the likelihood of the observed data across all conditions, whereas *b* was fixed at 1 (fitting all parameters results in an underconstrained model; Donkin, Brown, & Heathcote, 2009). In other words, for this base model, all conditions were fit with the same parameters as if there were no differences between conditions. Moving up in the nested model hierarchy on the left-hand side in the figure, we next fit each participant's data allowing one of the parameters to take on different values (i.e., an "open" parameter) for each of the 10 conditions (or nine in the case of *b*), and the other parameters were forced to take on the same value for all conditions similar to the base model. This results in a fit with 13 total parameters for each participant. This was repeated for each parameter, resulting in five separate model fits of 13 parameters, one with each parameter open to vary over all conditions. Moving up the hierarchy from this point, there were two options for more complex models by allowing another parameter to vary over either the five SOA conditions or the valid and invalid cueing conditions, for a total of 17 or 14 parameters, respectively. Nested above these two points in the hierarchy were models with one parameter open across all conditions, one parameter open for SOA, and a third parameter open for the cueing conditions. These models had 18 parameters to fit the six quantiles for each of the 10 conditions. Finally, we allowed all parameters (with the exception of *b*, which was fixed to 1 across all conditions) to vary openly for each condition, for a total of 40 parameters. For additional comparisons, we also fit models with one parameter free over SOA conditions and another over valid and invalid cueing conditions (nine parameters, as seen in the lower right-hand portion of the figure). After fitting each individual's data, the fit statistics were summed over individuals and evaluated by AIC.

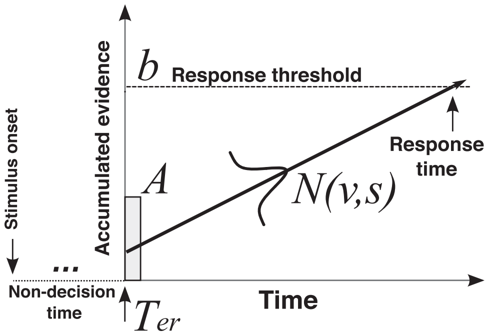
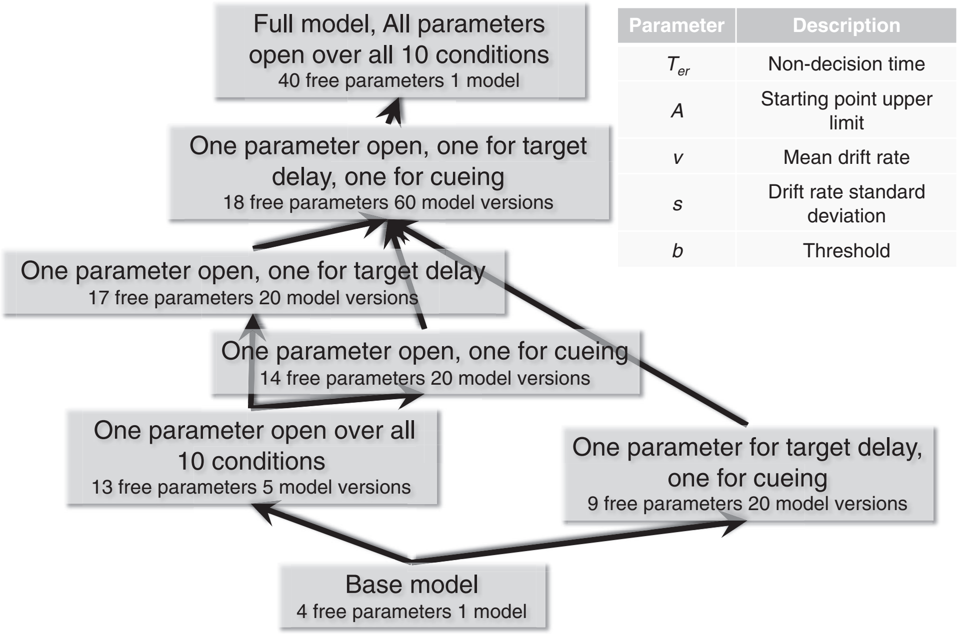


*Figure A1.* Mechanics and parameters of the linear ballistic accumulator model. After stimulus onset, there is a fixed duration unrelated to the decision process (nondecision time, $T_{er}$). After this time, an accumulator starts accruing evidence linearly (the dark line pointing to the upper right) from a starting point randomly chosen from a uniform distribution between zero and the parameter *A*. Evidence accumulates linearly with a slope randomly drawn from a normal distribution with mean *v* and standard deviation *s*, until reaching a response threshold, *b*. The time the threshold is reached is the model's reaction time.

(*Appendix continues*)



| Parameter | Description |
|---|---|
| $T_{er}$ | Non-decision time |
| $A$ | Starting point upper limit |
| $v$ | Mean drift rate |
| $s$ | Drift rate standard deviation |
| $b$ | Threshold |

*Figure A2.* The nested modeling procedure. Each model type was fit for each possible combination of different parameters to make a number of different model versions. The base value of the threshold parameter was fixed to 1.

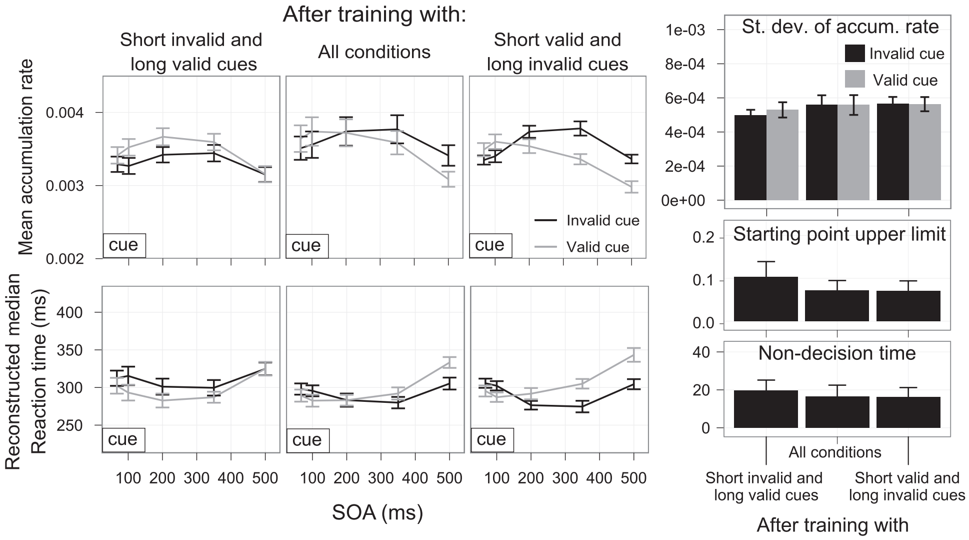


*Figure A3.* Linear ballistic accumulator model fitting results. For the best-fitting model, the mean accumulation rate was allowed to vary between all conditions and the standard deviation of the accumulation rate was allowed to vary between cueing conditions. The other parameters took on the same value for the cueing and stimulus onset asynchrony (SOA) conditions and the threshold was fixed at 1 for all conditions. The three graphs in the lower left present the reconstructed data from the best-fit model. To reconstruct the average data, we used the parameters for each participant's data to obtain a median reaction time from the fit model, which was then averaged across participants. Error bars are ±1 standard error of the mean.

(*Appendix continues*)

The best-fit model as evaluated by AIC allowed $v$, the mean accumulation rate, to vary openly over the 10 conditions, and varied $s$, the accumulation rate standard deviation, between valid and invalid cue conditions. The best-fit parameters and average reconstructed data are presented in Figure A3. The reconstructed data consist of the median of the fit distributions for each condition, averaged over the fit for each participant. As can be seen in the figure, changes in the mean accumulation rate capture both the effect of training: three-way interaction between training, cueing, and SOA, $F(8, 188) = 5.62$, $p = .009$; and the cueing effects: two-way interaction between SOA and cueing, $F(4, 188) = 37.34$, $p < .001$. Neither the standard deviation of the accumulation rate nor the other parameters varied between training or cueing conditions ($F\text{s} \leq 1.17$). Based on this model fit, which includes data across spatial and temporal manipulations of cueing, both cueing effects and training are the result of changes in mean accumulation rate.

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