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More Power to the Unconscious: Conscious, but Not Unconscious, Exogenous Attention Requires Location Variation

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Abstract

Substantial evidence suggests that unconscious processing can be characterized as a lesser or weaker version of conscious processing. To test this notion, we designed a novel repeated-cuing procedure based on exogenous attention: The location of the attentional cue was first fixed across blocks (fixed-cue blocks), and then the cue was removed in subsequent blocks (no-cue blocks). The visibility of the cue was also manipulated. We found that when the cue was invisible, the response to a prespecified stimulus in the fixed-cue blocks was faster if the stimulus was at the cued location than if it was at the uncued location. But when the cue was visible, this cuing effect was abolished, potentially because of an awareness-dependent, location-based inhibition mechanism, as revealed by an attentional bias against the previously cued location in the no-cue blocks. We call this bias *negative attentional aftereffect*. These results provide novel evidence against the weaker-version characterization of unconscious effects, highlighting dissociable components of orienting and inhibition in exogenous cuing through awareness and temporal dynamics.

Keywords

repeated cuing, attentional aftereffect, consciousness, unconscious processing, exogenous attention

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Visual inputs hidden from conscious awareness nevertheless can activate early visual cortex (and, to a lesser degree, higher visual cortex and parietal-frontal cortex) and alter perception, attention, and behavior. Unconscious behavioral effects are occasionally found to be as strong as conscious effects, particularly for the processing of low-level features such as orientation, but more often they are weaker or just absent. These observations have led to a characterization of unconscious processing as a lesser or weaker version of conscious processing (Kouider & Dehaene, 2007; Lin & He, 2009; Lin & Murray, 2013, 2014b; van Gaal & Lamme, 2012).

For example, a large body of research has revealed an important parallel between unconscious and conscious visual attention: An invisible cue can capture attention to its location (e.g., Hsieh, Colas, & Kanwisher, 2011; Y. Jiang, Costello, Fang, Huang, & He, 2006; Mulckhuyse, Talsma, & Theeuwes, 2007; Zhaoping, 2008), just as a visible one does (Posner, 1980); this unconscious cuing effect can go beyond the cued location and manifest itself at a remote location when the initial cue location is perceived to have moved to this remote location (Lin & Murray, 2013), just as conscious cuing does (e.g., Lin, 2013).

But whether and how unconscious and conscious attention may be dissociated remains largely unexplored. It has been suggested that task-irrelevant background motion disrupts performance in a foveal task, more when the motion is subthreshold than suprathreshold (Tsushima, Sasaki, & Watanabe, 2006). Here, we asked whether an unconscious cuing effect can occur when there is no conscious cuing effect. Can a cue facilitate performance at the cued location relative to the uncued location only when it is invisible?

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To address this question, we designed a repeated-cuing procedure: A cue repeatedly appeared at a fixed location across trials (fixed-cue blocks), and then it was completely removed in subsequent trials (no-cue blocks). Cues were made either salient (visible-cue group) or nonsalient (invisible-cue group) by presenting them in red or black, respectively. We observed a robust facilitation effect in the fixed-cue blocks—but only for the invisible cue. The absence of a conscious cuing effect appeared to be due to an inhibition mechanism that manifested well after the fixed-cue blocks had ended, as revealed by an attentional bias against the previously cued location in the no-cue blocks—an effect we call *negative attentional aftereffect*.

Experiment 1

Method

Participants and apparatus. Sixty participants with normal or corrected-to-normal vision were recruited. They were separated into three groups, each with 20 participants: (a) the visible-cue group (mean age = 19.1 years; 65% female, 35% male), (b) the 33.3-ms-invisible-cue group (mean age = 19.5 years; 70% female, 30% male), and (c) the 16.7-ms-invisible-cue group (mean age = 19.7 years; 35% female, 65% male). The sample size was predetermined on the basis of a recent study using a similar paradigm (Lin & Murray, 2013). The experiment was approved by the University of Washington Institutional Review Board.

The stimuli were presented on a 19-in. CRT monitor (ViewSonic G90fB, refresh rate = 60 Hz; resolution = 1,024 × 768 pixels). Participants sat approximately 50 cm from the monitor with their heads positioned in a chin rest in an almost dark room (no lighting except from the computer and the monitor).

Procedure. The experiment involved two main phases: an exogenous cuing task followed by a cue-location-discrimination task.

Exogenous cuing. Participants were trained to maintain proper fixation first (as in, e.g., Lin & Murray, 2013). In this 2-min training session, a square patch of black-and-white noise flickered in counterphase on the screen, with each pixel alternating between black and white across frames. Participants perceived a flash each time they moved their eyes away from the central fixation dot, and they were asked to use this flash as feedback to maintain stable fixation (Guzman-Martinez, Leung, Franconeri, Grabowecky, & Suzuki, 2009).

After this fixation training, participants took part in an exogenous cuing task that consisted of 12 practice trials and 840 experimental trials (40 trials × 21 blocks). Each trial consisted of three events: the fixation display, the cue display, and the target display (Fig. 1).

The fixation point was a combination of a bull's-eye and crosshairs (diameter of inner annulus = 0.23°; diameter of outer annulus = 0.69°; luminance = 49.2 cd/m^2 for crosshairs, 0.14 cd/m^2 for bull's-eye), presented for 1,000 ms in the center of a gray background (luminance = 12.0 cd/m^2). Participants were asked to fixate on this mark, which was followed by a blank screen for 200 ms.

The cue—an abrupt-onset annulus (diameter = 3°, width = 0.25°)—appeared after the blank screen at the location of either the subsequent left-hand annulus or subsequent right-hand annulus (see the next paragraph). For the visible-cue group, the cue had a duration of 33.3 ms and was colored red (luminance = 10.8 cd/m^2; x = .600, y = .326, u' = .420, v' = .514). For the two invisible-cue groups, the cue was black (luminance = 0.14 cd/m^2); its duration was 33.3 ms for one group—as for the visible-cue group—but 16.7 ms for the other group. This difference allowed us to assess the robustness of the unconscious effect. Critically, for all three groups, the cue location was also manipulated. In the first 12 blocks, the cue appeared at a fixed location: always on the left or always on the right (distance from fixation = 6°), counterbalanced across participants. In the next 3 blocks, no cue was presented (i.e., the background remained blank during the cue interval). In the final 6 blocks, the cue appeared randomly on the left or on the right in each trial.

For the visible-cue group, the red cue was not masked by the appearance of three subsequent black annuli (e.g., Breitmeyer & Ogmen, 2000). For the invisible-cue groups, the black cue was strongly masked by the three black annuli. The annuli were the same size as the cue, and they appeared one each on the left, center, and right of the screen for 283.3 ms. On 80% of the trials, a target dot (diameter = 1.9°; luminance = 0.14 cd/m^2) appeared at the same time as the three annuli, randomly within either the cued annulus (valid trials) or the uncued annulus (invalid trials) for 83.3 ms. The target dot then disappeared, but the three annuli remained onscreen for the remaining 200 ms. The stimulus onset asynchrony (SOA) between the cue and the target was therefore equal to the duration of the cue. On the remaining 20% of the trials, no dot was presented. Participants were informed about the probability of the dot occurrence. They were asked to press a button as quickly as possible when the dot appeared but to refrain from response when the dot did not appear. The trial ended as soon as a response was made or 1 s after the offset of the annuli, whichever was earlier. To provide an incentive against false alarms, we followed each incorrect response with two tones (each lasting 200 ms with a 5-ms interval in between) and a 5-s time-out (blank background).

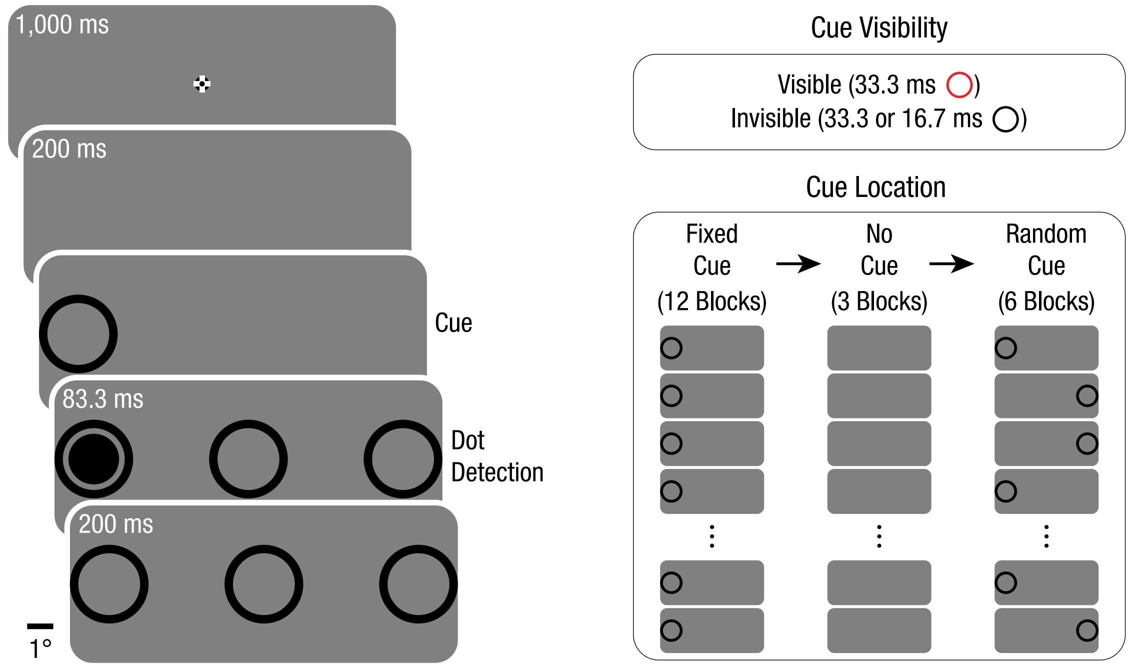

Fig. 1. Sample trial sequence (left) and design (right) of Experiment 1. On each trial, a cue appeared briefly after a fixation point and a blank screen. The cue was followed by three annuli. On 80% of the trials, a target dot also briefly appeared, randomly within the cued annulus (valid trials) or the uncued annulus (invalid trials); on the remaining 20% of the trials, no dot was presented. Participants were asked to press a button as quickly as possible when the dot appeared, but refrain from response when no dot appeared. Cue visibility was manipulated between participants: The color of the cues was either different from or the same as the annuli. The presentation time of the cue was different in one of the three groups. Cue location was manipulated within participants: In the first 12 blocks, the cue appeared at a fixed location (i.e., always on the left or on the right, counterbalanced across participants); in the next 3 blocks, no cue was presented; and in the final 6 blocks, the cue appeared randomly on the left or on the right. To assess the visibility of the cue, we also asked participants at the end of the experiment to complete a cue-location-discrimination task (not shown here).

Cue-location discrimination. To check cue visibility, we asked participants to take part in a cue-location-discrimination task immediately after the cuing task. The procedure was identical to the random-cue blocks in the cuing task, except for the task: Participants indicated whether the annulus cue appeared on the left or on the right by respectively left-clicking or right-clicking the mouse. Once a response was made, that trial ended. There were 5 practice trials and one block of 80 experimental trials (to increase statistical power for the 16.7-ms-invisible-cue group, we increased the number of trials to 10 practice trials and 120 experimental trials).

For this task, participants were told that "a red circle will appear either on the left or the right" (for the visible-cue group) or that "at the very beginning either the left or right circle will appear an instant earlier [than the three annuli]" (for the two invisible-cue groups)—the "circle" refers to the annulus cue. They were asked to "attend to the circle, not the dot, while fixating at the center." They were informed that "response time is not important" and told to "respond as accurately as possible." By directing their attention to the cue, this test provided a conservative measure of awareness (Vermeiren & Cleeremans, 2012).

Data analysis. Reaction times (RTs) for the cuing task were calculated as the time between the target onset and the button press. False alarms occurred when no target was presented but the button was pressed (Table 1), and these trials were excluded from the RT analysis—we counted only the trials with hits (i.e., those on which the button was correctly pressed in response to a target). Anticipatory responses (i.e., RTs < 100 ms) were rare (< 1%) and were excluded from analysis (Lin & Murray, 2014a)—counting RTs less than 200 ms as anticipatory responses yielded the same pattern of results (see the Supplemental Material available online). No other trimming of RTs was applied (excluding data outside of 3 standard deviations in each condition did not change the results). Effects that are not reported were not significant.

Table 1. Taxonomy of Responses for the Cuing Task

Target stimulus and response	Categorization
Present at the cued or old location	
"Yes"	Valid or old
"No"	Miss
Present at the uncued or new location	
"Yes"	Invalid or new
"No"	Miss
Absent	
"Yes"	False alarm
"No"	Correct rejection

Results

To ensure that the visible cue was visible and the invisible cue invisible, we first examined the results from the cue-location-discrimination task. Accuracy in this task—the percentage of correct responses—served as an index of conscious awareness of the cue location. The criterion for awareness versus unawareness was based on the binomial test: Participants with *p*s greater than .05 (one-tailed) were deemed unaware, whereas those with *p*s of .05 or lower were deemed aware.

For the visible cue, location discrimination was at ceiling (M = 97.8% correct, SD = 3.1%, range = 88.8–100%); this confirms that the cue was visible. For the invisible cue, 10 participants performed at chance for the 33.3-ms cue, and 14 performed at chance for the 16.7-ms cue; because the pattern of the attentional-cuing results was the same for the two groups (as detailed in the following paragraphs), their data were combined. Combined group performance in cue-location discrimination also did not differ significantly from chance (M = 49.30% correct, SD = 4.59%), $t(23) = -0.75$, $p = .46$ (two-tailed), which suggests that participants in the invisible-cue groups were unable to discern the location of the cue.

To address the role of location variation in conscious and unconscious cuing, we next examined the results from the cuing task (Fig. 2). We first looked at the visible-cue group. The cuing effect was measured by the RT difference scores (mean RT on invalid trials – mean RT on valid trials). In the fixed-cue blocks, there was no cuing effect (mean RT difference = 2.1 ms), $t(19) = 0.85$, $p = .407$, $d = 0.19$, which suggests that conscious exogenous attention requires location variation. Notably, there was also no evidence for a cuing effect even in the first few blocks (e.g., mean RT difference = 1.0 ms, −2.7 ms, and 0.3 ms for the first, second, and third blocks, respectively, all ps > .6), which suggests that the lack of the cuing effect was not due to an early cuing effect being diluted when averaged across all 12 blocks. In the subsequent no-cue blocks, we measured the *location-bias effect*, which was indexed by the mean RT for targets at the previously uncued location (the new location) minus the mean RT for targets at the previously cued location (the old location). Performance was slower at the old location than at the new location (mean RT difference = −12.2 ms), $t(19) = -3.78$, $p = .001$, $d = -0.85$; this suggests that attention was biased against the repeatedly cued location, even when the cue no longer appeared, which may reflect an inhibition mechanism. This negative attentional bias was relatively long-lived and consistent across the three blocks, as revealed by the lack of an interaction effect between location (old vs. new) and block number (1 vs. 2 vs. 3), $F(2, 38) = 0.83$, $p = .443$, $\eta_p^2 = .04$. In the random-cue blocks—when the cue was reintroduced and appeared at a random location—the cuing effect emerged (mean RT difference = 14.2 ms), $t(19) = 4.57$, $p < .001$, $d = 1.02$, which suggests that the lack of a cuing effect in the fixed-cue blocks was not due to the cue itself being impotent.

We next looked at the invisible-cue groups, restricting our data analysis to participants who were objectively unaware of the cue location. The patterns in the fixed-cue and no-cue blocks contrasted the patterns in those blocks following the visible cue. First, in the fixed-cue blocks, the cuing effect was readily observed (mean RT difference = 15.7 ms; for the 33.3-ms cue: 14.7 ms, for the 16.7-ms cue: 16.4 ms), $t(23) = 5.96$, $p < .001$, $d = 1.22$; this suggests that, in contrast to conscious exogenous attention, unconscious exogenous attention does not require location variation. Second, in the no-cue blocks, performance was similar for targets appearing at the old location and the new location (mean RT difference = 1.6 ms; for the 33.3-ms cue: 4.7 ms, for the 16.7-ms cue: −0.6 ms), $t(23) = 0.50$, $p = .621$, $d = 0.10$, which suggests that repeatedly cuing a fixed location does not generate an attentional aftereffect when the cue does not enter awareness. Finally, in the random-cue blocks, the cuing effect emerged (mean RT difference = 14.9 ms; for the 33.3-ms cue: 15.4 ms, for the 16.7-ms cue: 14.6 ms), $t(23) = 8.49$, $p < .001$, $d = 1.73$; this reveals an otherwise similar cuing effect for the visible and invisible cues.

The fundamentally distinct patterns between the visible- and invisible-cue groups in the fixed-cue and no-cue blocks were further supported by interaction effects. Specifically, the finding that the cuing effect without location variation (i.e., in the fixed-cue blocks) occurred only for the invisible cue, but not for the visible cue, was supported by a significant interaction effect between cue validity (valid vs. invalid) and cue visibility (visible vs. invisible), $F(1, 42) = 14.00$, $p = .001$, $\eta_p^2 = .25$. Likewise, the finding that repeatedly cuing a fixed location subsequently generates a negative attentional aftereffect (i.e., in the no-cue blocks) only when the cue is consciously perceived was bolstered by a significant interaction effect between location (old vs. new) and cue visibility (visible vs. invisible), $F(1, 42) = 9.17$, $p = .004$, $\eta_p^2 = .18$.

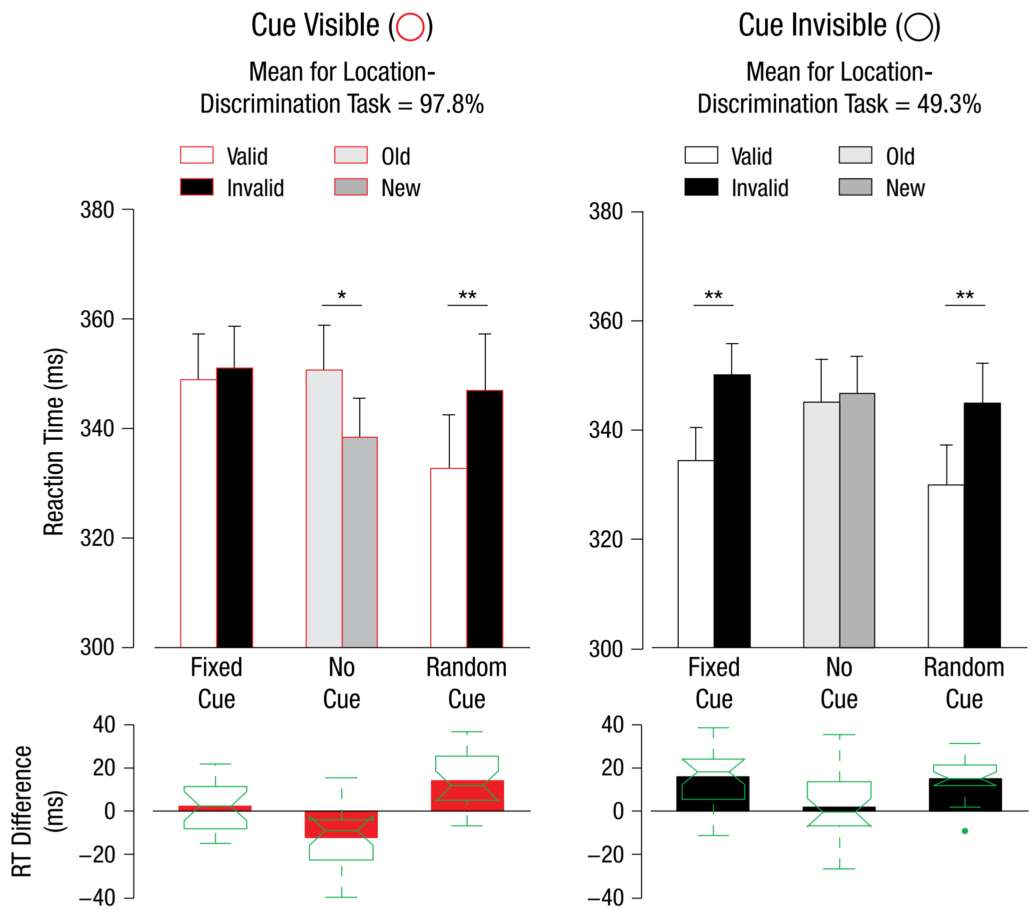

Fig. 2. Results from Experiment 1 for the visible-cue group and the invisible-cue group in the cuing task. The graphs in the top row show mean reaction time (RT) as a function of cue location and trial type (valid vs. invalid for fixed- and random-cue trials; old vs. new for no-cue trials). Error bars show standard errors of the mean. The box-and-whisker plots in the bottom row show median RT differences between each trial type for each cue location. RT differences were calculated by subtracting the mean RT for valid trials from the mean RT for invalid trials (fixed- and random-cue trials) or the mean RT for old trials from the mean RT for new trials (no-cue trials). In the plots, the horizontal center lines indicate medians; the top and bottom edges of the side notches mark 95% confidence intervals for the medians; the top and bottom edges of the boxes designate the 25th and 75th percentiles, respectively; whiskers delimit 1.5 times the interquartile range from the 25th and 75th percentiles (the ends of the whiskers are plotted at the actual data points closest to those limits); and the dot indicates an outlier. Asterisks indicate significant differences between trial types (* $p < .005$; ** $p < .001$).

These results regarding the effect of the invisible cue were from participants who were objectively unaware of the cue location. What about the other participants, who performed above chance in discriminating the location of the strongly masked cue (accuracy: M = 72.28% correct, SD = 11.82%, range = 58.3–92.5%) even though they generally reported being unable to see it? This group is conceivably more heterogeneous in cue awareness because forced-choice performance could have been above chance for two distinct reasons (Lin & Murray, 2014a): conscious cue processing and unconscious cue processing. Therefore, although we had no a priori prediction regarding this group, given their heterogeneity in awareness and given the distinct cuing effects for visible and invisible cues in both the fixed- and no-cue blocks (but not in the random-cue blocks), a reasonable expectation was that (a) in the fixed- and no-cue blocks, the respective cuing and location-bias effects from this heterogeneous group would be likely to fall in between the effects from visible and invisible cues, and (b) in the random-cue blocks, the cuing effect should be similar to the effects from visible and invisible cues. This appears to have been the case: In the fixed-cue blocks, the cuing effect was 8.5 ms, $t(15) = 2.44$, $p = .028$, $d = 0.61$; in the no-cue blocks, the location-bias effect was −7.5 ms, $t(15) = −1.52$, $p = .149$, $d = −0.38$; in the random-cue blocks, the cuing effect was 17.7 ms, $t(15) = 6.52$, $p < .001$, $d = 1.63$.

Table 2. Results From Analyses of Miss Rates and False Alarm Rates

Experiment and block type	Miss rate: Mean rate for valid and old trials (%)	Mean rate for invalid and new trials (%)	Difference between conditions	Mean false alarm rate (%)	d'	c
Experiment 1: visible						
Fixed cue	0.8	0.7	$t(19) = 0.54$, $p = .595$, $d = 0.12$	24.7	3.31	−0.91
No cue	0.2	0.4	$t(19) = -0.97$, $p = .343$, $d = -0.22$	18.3	4.04	−0.89
Random cue	0.4	0.8	$t(19) = -1.00$, $p = .33$, $d = -0.22$	31.4	3.19	−1.04
Experiment 1: invisible						
Fixed cue	0.3	0.6	$t(23) = -0.30$, $p =$ **.006**, $d = -0.61$	16.6	3.80	−0.83
No cue	1.0	0.7	$t(23) = 0.17$, $p = .867$, $d = 0.03$	18.2	3.83	−0.77
Random cue	1.0	0.9	$t(23) = 0.6$, $p = .555$, $d = 0.12$	20.2	3.61	−0.81
Experiment 2						
Fixed cue	0.4	0.3	$t(12) = 0.35$, $p = .735$, $d = 0.1$	11.7	4.32	−0.64
No cue	0.3	0.3	$t(12) = 0.01$, $p = .999$, $d = 0.01$	14.1	4.63	−0.61
Random cue	0.9	1.1	$t(13) = -0.23$, $p = .819$, $d = -0.06$	16.4	3.89	−0.56
Experiment 3						
Fixed cue	1.0	0.9	$t(19) = 0.59$, $p = .564$, $d = 0.13$	31.7	3.11	−1.02

Note: Comparisons in the fixed-cue and random-cue blocks were made between valid and invalid trials; comparisons in the no-cue blocks were between old and new trials. The measure of d' was calculated as follows: $z(1 - \text{miss}) - z(\text{false alarm})$. The criterion ($c$) measure was calculated as follows: $-(z(1 - \text{miss}) + z(\text{false alarm}))/2$. Boldface indicates a significant result.

Misses were rare (< 1%) and generally did not differ between the valid and invalid conditions or between the old and new conditions (see Table 2), except between the valid and invalid conditions in the fixed-cue blocks for the invisible-cue group—in this case, the valid condition had a lower miss rate than the invalid condition.

Two control experiments

Following Experiment 1, we conducted two control experiments. The first one (Experiment 2) examined the unconscious effects in Experiment 1. In the location-discrimination task of the first experiment, we had assessed visual awareness using 80 trials for the 33.3-ms cue and 120 trials for the 16.7-ms cue—less than the 840 trials in the cuing task. Although it is almost universal in studies of unconscious processing to have fewer trials in an awareness test than in the main test, such a mismatch nevertheless could pose some methodological concerns (Lin & Murray, 2014a). For instance, a shorter awareness test may show a weaker learning effect or have less power in quantifying awareness—which could lead to underestimates of visual awareness. Relatedly, in Experiment 1, we measured awareness in the random-cue blocks but not in the fixed-cue blocks. Although cue awareness in the random-cue blocks provided a reasonably good surrogate for cue awareness in the fixed-cue blocks, the two conceivably could differ. We addressed these issues in Experiment 2, in which trials for both the exogenous cuing task and the cue-location-discrimination task were identical; this meant that both the total number of trials and the sequence of trials for the two tasks were matched.

The second control experiment (Experiment 3) concerned the lack of a conscious cuing effect in the fixed-cue blocks in Experiment 1. In the first experiment, the cue-to-target SOA was 33.3 ms, whereas in discrimination tasks, peak cuing effects have been observed at 83 to 100 ms (Cheal & Lyon, 1991) and 70 to 150 ms (Nakayama & Mackeben, 1989). This raises the question whether a conscious cuing effect might appear in the fixed-cue blocks if the SOA was lengthened. Evidently the SOA of 33.3 ms was sufficient to induce a robust conscious cuing effect in the random-cue blocks in Experiment 1, which suggests that this short SOA was effective in our task. Nevertheless, we directly addressed this question in Experiment 3 by employing a longer SOA of 100 ms and examining whether a conscious cuing effect appeared in the fixed-cue blocks. An added benefit of using this longer SOA was that it would weaken any potential forward-masking effect from the cue on the target and thus provide a better chance to detect the cuing effect, should it exist.

Experiment 2

Method

The design of Experiment 2 was the same as that of the 16.7-ms-invisible-cue condition in Experiment 1, except for two changes. First, both the exogenous cuing task and the cue-location-discrimination task had 12 practice trials and 420 experimental trials. The 420 trials—including their order—were the same in the two tasks, which consisted of seven blocks (60 trials each): four fixed-cue blocks, one no-cue block, and two random-cue blocks. Including the fixed-cue blocks in the cue-location-discrimination task allowed us to directly test the visibility of the cue when its location was fixed—which may have differed from the visibility of the cue when its location was random. Second, in the cue-location-discrimination task, to ensure that participants knew what to expect from the cue (Lin & Murray, 2014a), we increased the cue duration in the 12 practice trials from 16.7 ms to 100 ms.

There were 20 participants in this experiment (mean age = 19.2 years; 50% female, 50% male). Anticipatory responses were rare (0.47%) and excluded from analysis. All participants performed above chance in the practice session of the cue-location-discrimination task (M = 95.4% correct, SD = 8.3%, range = 75.0–100%).

Results

As in Experiment 1, accuracy in the cue-location-discrimination task served as an index of conscious awareness of the cue location. Accuracy was submitted to the binomial test: Participants with ps greater than .05 (one-tailed) were deemed unaware, whereas those with ps of .05 or lower were deemed aware. Unlike in Experiment 1, awareness for the fixed-location cue was directly tested in the fixed-cue blocks (rather than in the random-cue blocks).

We first examined the unconscious cuing effect in the fixed-cue blocks and its aftereffect in the no-cue block. Thirteen participants performed at chance; group performance for these 13 participants also did not differ from chance (accuracy: M = 49.39% correct, SD = 9.48%), $t(12) = -0.61$, $p = .55$ (two-tailed), which suggests that these participants were unable to discern the location of the cue. Replicating Experiment 1, results showed that when the cue location was fixed, the invisible cue induced an unconscious cuing effect (mean RT difference between valid and invalid trials = 15.6 ms), $t(12) = 4.13$, $p = .001$, $d = 1.15$. When there was no cue, there was no attentional aftereffect at the location where the previous cue repeatedly appeared (mean RT difference = −2.1 ms), $t(12) = -0.41$, $p = .692$, $d = -0.11$.

We next looked at the effect in the random-cue blocks. Fourteen participants performed at chance; group performance for these 14 participants also did not differ from chance (accuracy: M = 50.48%, SD = 5.36%), $t(13) = 0.33$, $p = .74$. As in Experiment 1, a cuing effect was observed in these random-cue blocks (mean RT difference = 20.5 ms), $t(13) = 5.10$, $p < .001$, $d = 1.36$. Misses were rare (< 1%) and did not differ between the valid and invalid conditions or between the old and new conditions (see Table 2).

Hence, with all the trials (and their sequence) completely matched between the cuing task and the location-discrimination task, we found, as in Experiment 1, a cuing effect in the fixed-cue blocks, no aftereffect in the no-cue block, and a cuing effect in the random-cue blocks. This pattern persisted even for participants who performed at chance in both the no-cue blocks and the random-cue blocks—fixed-cue blocks: mean RT difference = 16.9 ms, $t(5) = 2.33$, $p = .067$, $d = 0.95$; no-cue blocks: mean RT difference = −3.7 ms, $t(5) = -0.77$, $p = .476$, $d = -0.31$; random-cue blocks: mean RT difference = 21.0 ms, $t(5) = 2.66$, $p = .045$, $d = 1.09$.

Experiment 3

Method

The design of Experiment 3 was the same as that of the visible-cue condition in Experiment 1, except for two changes. First, there were 12 blocks, all with the cue location fixed. Second, in each trial, a 66.67-ms blank period was inserted between the offset of the cue and the onset of the target—this brought the cue-to-target SOA to 100 ms.

There were 22 participants in this experiment (mean age = 20.6 years; 82% female, 18% male). Anticipatory responses were rare (0.2%) and excluded from analysis. Data from 2 participants were discarded because of chance-level performance in the location-discrimination task (50% and 58% correct responses, respectively—compared with near-ceiling performance for the other participants: M = 98.5% correct, SD = 2.1%, range = 91.3–100%).

Results

The results replicated those in the visible-cue condition of Experiment 1: With the cue location fixed, there was no cuing effect (mean RT difference = −2.9 ms), $t(19) = -1.03$, $p = .317$, $d = -0.23$; there was also no evidence for a cuing effect in the first few blocks (e.g., mean RT difference = −5.1 ms, 2.7 ms, and −6.3 ms for the first, second, and third blocks, respectively, all ps > .2). Misses were rare (< 1%) and did not differ between the valid and invalid conditions (see Table 2). Therefore, the lack of a conscious cuing effect in the fixed-cue blocks was robust, and it was unlikely to be explained by suboptimal SOAs or by forward masking from the cue.

Individual Differences in the False Alarm Rate

As Table 2 shows, for all three experiments, the miss rate was exceedingly low and generally did not differ significantly between the valid and invalid conditions or between the old and new conditions. In contrast, the false alarm rate was much higher, consistent with previous reports using a similar task (e.g., Lin & Murray, 2013). False alarms, however, could in no way contaminate the critical comparisons (valid vs. invalid trials, old vs. new trials): False alarm trials, by definition, were those on which targets were absent; in contrast, trials in the valid, invalid, old, and new conditions were those on which targets were present. In other words, since trials in our critical comparisons (invalid – valid; old – new) were all hit trials that were randomly mixed with the false alarm trials within each block, such a design precludes accounts based on changes in either sensitivity (d', calculated as z(hit) – z(false alarm)) or criterion (c, calculated as –(z(hit) + z(false alarm))/2; see Table 2).

Nevertheless there was considerable individual variation in the false alarm rate, which raises the questions whether and how the false alarm rate might correlate with the critical difference effects in RTs. To address these questions, we examined the correlation between the false alarm rate and three variables: (a) the cuing effect (invalid trials – valid trials) for the fixed-cue blocks and the random-cue blocks, (b) the location-bias effect (new trials – old trials) for the no-cue blocks, and (c) the mean RTs, that is, (invalid trials + valid trials)/2 for the fixed-cue and random-cue blocks and (new trials + old trials)/2 for the no-cue blocks.

Figure 3 shows the results. First, in no case did the false alarm rate correlate with the difference effects in RTs, whether the cue was visible or invisible. Indeed, the correlation was rather weak and ran in both positive and negative directions, which suggests that the cuing effect and the location-bias effect were insensitive to the false alarm rate. Second, the false alarm rate strongly correlated with the mean RTs: Participants who tended to press the button indiscriminately (higher false alarms) also tended to respond earlier than others (faster RTs). Taken together, these results show that although higher false alarm rates were associated with faster RTs, false alarms did not play a major role in determining the cuing effect or the location-bias effect.

Discussion

Using a repeated-cuing paradigm, we uncovered two main results. First, repeatedly cuing the same location can facilitate performance at the cued location relative to the uncued location, but only when the cue is invisible—not when it is visible. Second, such repeated cuing results in a relatively long-term consequence (at least 120 trials), that is, an attentional bias against the previously cued location, but only when the cue is visible—not when it is invisible. These results show that in repeated cuing, conscious awareness comes with two costs with regard to attention: Not only does conscious awareness eliminate the cuing effect, but it also reduces the subsequent priority of the cued location.

These results suggest that an exogenous cue elicits two opposing effects that together determine the behavioral cuing effect: an awareness-independent orienting effect and an awareness-dependent inhibition effect. In addition, the orienting component is a transient and relatively automatic effect, whereas the inhibition component is a sustained and controlled effect. Accordingly, when the location of a visible cue is fixed and thereby rendered predictable, inhibition of the cue location is facilitated, which can effectively cancel out the orienting component—thus explaining the lack of a conscious cuing effect in fixed-cue blocks. This conscious-inhibition effect may arise from a need to suppress task-irrelevant information (e.g., the cue) in order to extract the task-relevant information (e.g., the target)—particularly when the two are spatially and temporally close. This notion is consistent with the observation that task-irrelevant dynamic random dots on the background are subject to effective inhibitory control when they are suprathreshold, but not when they are subthreshold (Tsushima et al., 2006).

That the negative attentional bias was observed in blocks in which the cue was removed is perhaps surprising. Such an effect mimics traditional perceptual aftereffects such as motion aftereffects—in which exposure to a moving stimulus causes a subsequent static image to be perceived as moving in the opposite direction (e.g., Lin & He, 2012; Mather, Verstraten, & Anstis, 1998)—and hence could be referred to as an *attentional aftereffect*. Unlike low-level perceptual aftereffects, which typically do not require awareness (Lin & He, 2009), the attentional aftereffect here depends critically on awareness, which implies that it has a cognitive origin (Huber, 2008).

Persisting attentional bias has been documented previously. For example, the tendency to attend to locations that are likely to contain the target lingers even when such a bias is no longer warranted—when the target appears equally likely at all locations (Y. V. Jiang, Swallow, Rosenbaum, & Herzig, 2013). This positive attentional bias contrasts with the negative attentional aftereffect observed here. In addition, whereas the positive attentional bias is claimed to be implicit (Y. V. Jiang et al., 2013), the negative attentional aftereffect apparently requires explicit awareness of the cue. These distinctions highlight fundamental differences between attentional biases arising from manipulating target locations and from manipulating exogenous cue locations.

The novel demonstration of a cuing effect confined only to invisible cues also has an important implication for unconscious perception and cognition. Unconscious

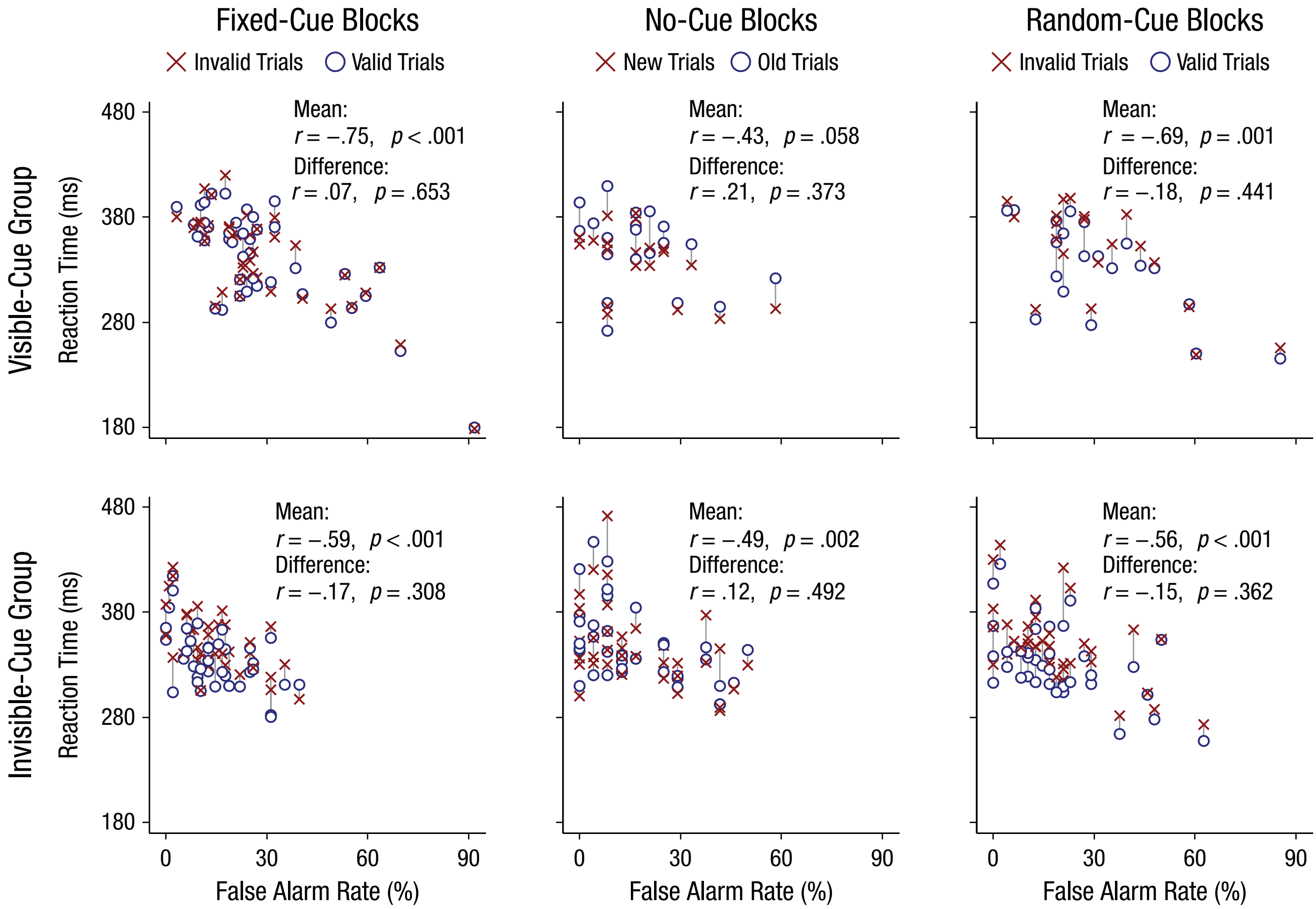

Fig. 3. Results from the three experiments: scatter plots showing mean reaction time (RT) as a function of false alarm rate and trial type (valid vs. invalid for fixed- and random-cue blocks; old vs. new for no-cue blocks). Plots are shown separately for each block type for the visible- and invisible-cue groups. Lines between circles and crosses connect the RTs of the two critical conditions in each individual participant. The correlations shown are between false alarm rate and mean RT (calculated as (invalid trials + valid trials)/2 or (new trials + old trials)/2) and between false alarm rate and the difference in mean RTs (calculated as invalid trials − valid trials or new trials − old trials). The data from Experiments 1 and 3 were pooled for the visible-cue group (for the fixed-cue blocks only, as Experiment 3 did not include the no-cue or random-cue blocks), whereas the data for the invisible-cue group were pooled from Experiments 1 and 2.

effects are routinely demonstrated to be weaker than conscious effects (Kouider & Dehaene, 2007; Lin & He, 2009; Lin & Murray, 2013, 2014b; van Gaal & Lamme, 2012). This characteristic of unconscious effects poses a serious challenge for the study of unconscious processing itself: Because of the notorious difficulty of proving the absolute invisibility of a stimulus, a so-called unconscious effect could be due to partial awareness in a number of trials, a number of participants, or both, particularly when the visibility test is inappropriate (for recent demonstrations, see Lin & Murray, 2014a, in press). Here, we demonstrated a robust unconscious effect and an essentially absent conscious effect in the fixed-cue blocks. These results are difficult to explain by residual awareness—if this were the explanation, the unconscious cuing effect would have been weaker than the conscious cuing effect. Thus, together with studies showing distinct conscious and unconscious effects (Barbot & Kouider, 2012; Eimer & Schlaghecken, 1998; Merikle & Joordens, 1997; Sumner, Tsai, Yu, & Nachev, 2006), our results provide novel evidence against the weaker characterization of unconscious effects. They also highlight orienting and inhibition as distinct components in exogenous cuing—these components differ in their dependence on visual awareness and in their timescale.

Author Contributions

Z. Lin conceived, designed, and conducted the research. Z. Lin and S. O. Murray wrote the manuscript.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Supplemental Material

Additional supporting information can be found at http://pss.sagepub.com/content/by/supplemental-data

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