Visible propagation from invisible exogenous cueing

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Perception and performance is affected not just by what we see but also by what we do not see—inputs that escape our awareness. While conscious processing and unconscious processing have been assumed to be separate and independent, here we report the propagation of unconscious exogenous cueing as determined by conscious motion perception. In a paradigm combining masked exogenous cueing and apparent motion, we show that, when an onset cue was rendered invisible, the unconscious exogenous cueing effect traveled, manifesting at uncued locations (4° apart) in accordance with conscious perception of visual motion; the effect diminished when the cue-to-target distance was 8° apart. In contrast, conscious exogenous cueing manifested in both distances. Further evidence reveals that the unconscious and conscious nonretinotopic effects could not be explained by an attentional gradient, nor by bottom-up, energy-based motion mechanisms, but rather they were subserved by top-down, tracking-based motion mechanisms. We thus term these effects *mobile cueing*. Taken together, unconscious mobile cueing effects (a) demonstrate a previously unknown degree of flexibility of unconscious exogenous attention; (b) embody a simultaneous dissociation and association of attention and consciousness, in which exogenous attention can occur without cue awareness ("dissociation"), yet at the same time its effect is contingent on conscious motion tracking ("association"); and (c) underscore the interaction of conscious and unconscious processing, providing evidence for an unconscious effect that is not automatic but controlled.

Introduction

The human brain processes incoming visual information in two distinct modes: one available to conscious perception and the other hidden from awareness. Although both unconscious and conscious processing are known to affect behavior (Kouider & Dehaene, 2007; Lin & He, 2009; Lin & Murray, in press), it is unknown whether they are fundamentally separate or interactive, and if they interact, how they might be coordinated.

We explore this issue using unconscious exogenous cueing, in which bottom-up, saliency-driven attention is oriented toward a visual stimulus that is outside of conscious awareness—an invisible cue. Unconscious exogenous cueing has been demonstrated with several techniques that render the cue invisible, including interocular suppression (Jiang, Costello, Fang, Huang, & He, 2006), visual masking (Mulckhuyse, Talsma, & Theeuwes, 2007), and eye of origin (Zhaoping, 2008), revealing that attention is captured at the location of the invisible cue.

But here we ask whether unconscious exogenous attention travels to affect performance at locations other than the cued location, based on one's conscious perception of visual motion direction. Such flexibility of unconscious exogenous cueing has not been previously suspected, with unconscious processing generally thought to be "dumb" (Greenwald, 1992; Loftus & Klinger, 1992) and unconscious exogenous cueing "automatic" and "bottom-up" (Fuchs, Theeuwes, & Ansorge, 2012). Indeed, even for conscious exogenous cueing, attention is routinely found to be attracted to the retinotopic location of the cue (Posner & Cohen, 1984), unless apparent motion is introduced (Lin, 2013).

In a new paradigm combining masked unconscious cueing (Mulckhuyse et al., 2007) and apparent motion (Lin, 2013), here we show that (a) when the cue was rendered invisible, exogenous cueing could travel to affect performance at uncued locations—an effect referred to as *unconscious mobile cueing*; (b) unconscious mobile cueing could not be attributed to an attentional gradient or bottom-up, energy-based motion mechanisms; rather it relied on top-down, tracking-based motion mechanisms. Unconscious mobile

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cueing therefore demonstrates a surprising degree of flexibility of unconscious exogenous attention, revealing an interaction of unconscious processing (exogenous cueing) and conscious processing (motion perception). These findings support a simultaneous dissociation and association of attention and consciousness: Exogenous attention can occur without cue awareness ("dissociation"), yet at the same time its effect is contingent on conscious motion tracking ("association").

Experiment 1: The role of awareness in the mobility of exogenous cueing

Method

Observers and apparatus

Thirty-one human subjects (nine males; average age = 19.0) with normal or corrected-to-normal vision participated in accordance with the IRB approved by the University of Washington.

The stimuli were presented on a black-framed 21-in. CRT monitor (Sony G520 at 60 Hz and 1024 × 768 pixels). Observers sat approximately 80 cm from the monitor with their heads positioned in a chin rest in an almost dark room.

Structure of the experiment

The experiment consisted of three sequential phases: fixation training, attention cueing test, and cue awareness test. In the fixation training session, for 2 min, subjects continuously viewed a square patch of black and white noise that flickered in counterphase, with each pixel alternating between black and white across frames; each eye movement during the viewing would lead to perception of a flash. Subjects were asked to minimize the perception of flashes, thereby training to maintain stable fixation. The fixation training was followed by an attention cueing task and then a cue awareness test.

Stimuli and procedure in the attention cueing test

Figure 1 illustrates the procedure of the cueing task, consisting of three events: fixation, cue display and target display.

(a) Fixation: A central fixation mark was first presented for 1000 ms against a gray background (luminance = 24.4 cd/m^2), followed by a blank screen for 200 ms. The fixation mark was a combination of a bulls eye and cross hairs (diameter of inner circle = 0.16°; diameter of outer circle = 0.50°; luminance = 106.0 cd/m^2 for cross hairs and 0.1 cd/m^2 for bulls eye). Subjects were told to fixate on the fixation mark.

(b) Cue display: A circle cue (diameter = 3°; luminance = 0.1 cd/m^2) was then randomly flashed on the left or right side (horizontal displacement = ±6°) for 16.7 ms or 50 ms, with a vertical displacement of 0°, ±2°, or ±4°. The cue was immediately masked by three circles of the same size and with the same vertical displacement as the cue for 16.7 ms, each on the left, center, and right of the screen. Subjects were informed of the presence of the cue before starting the experiment as they saw a written schematic diagram of the procedure; at the same time, they were informed that they probably would not be aware of the cue.

(c) Target display: The cue and the mask display was then followed by a target display that consisted of the same three circles for 283.3 ms. Thus, the cue to target stimulus onset asynchrony (SOA) was 33.4 ms (for the 16.7 ms cue) or 66.7 ms (for the 50 ms cue). The target display either appeared at the same locations as the mask circles ("retinotopic") or shifted downward/upward to the opposite vertical position ("nonretinotopic")—for example, from 2° to −2°—thereby evoking apparent motion from the cue circles to the target circles. On 80% of the trials, a target dot (diameter = 1.91°; luminance = 0.1 cd/m^2) appeared randomly within either the left or the right circle during the beginning of the target display for 83.3 ms; on the remaining 20% of the trials, no dot was presented. Subjects were asked to press a button as quickly as possible when the target appeared, but refrain from response when the target did not appear. The trial ended as soon as a response was made or 1 s after the offset of the target circles, whichever was earlier. To provide incentive against false alarm, each incorrect response was followed by two tones (each lasting 200 ms and separated by 5 ms), plus a subsequent 10 s timeout (blank screen).

In total, there were 720 experimental trials (in 18 blocks), preceded by 12 practice trials (in one block, in which the circle-to-fixation distance was randomized). Before proceeding to the main experiment, subjects were asked to describe their perception of the apparent motion displays as in the main experiment and were trained until they were able to see apparent motion.

Design in the attention cueing test

There were two main factors in the cue task: cue validity and cue–target relative vertical position. Specifically, when the cue-to-fixation vertical distance was 0°, the target display always overlapped the cue

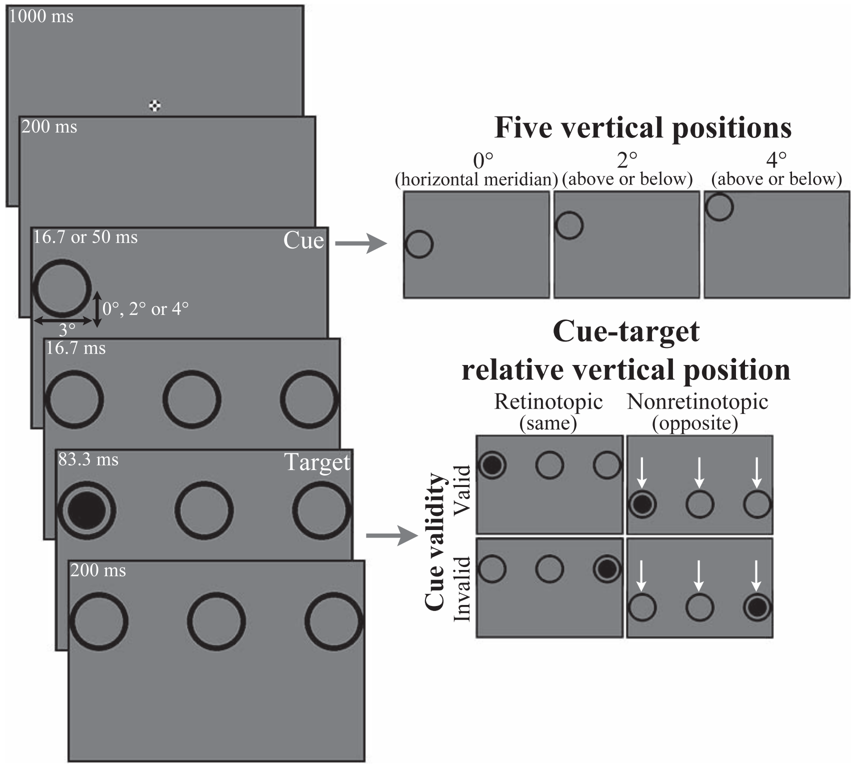

Figure 1. Procedure and design of Experiment 1. Both the cue display and the target display consisted of three circles. In the cue display, either the left or right circle appeared slightly earlier than the other two, serving as an abrupt onset cue. The vertical distance from the cue display to the fixation was 0°, 2°-above, 4°-above, 2°-below, or 4°-below. In the target display, on 80% of the trials, a dot was presented randomly at the cued location ("valid") or at the uncued location ("invalid"). Subjects were asked to press a button as quickly as possible when the dot appeared, but refrain from response when there was no dot. The target display could spatially overlap the cue display ("retinotopic") or they could be opposite to each other ("nonretinotopic"). Thus, there were five possible cue–target relative vertical positions. Specifically, when the cue-to-fixation vertical distance was 0°, the target display always overlapped the cue display; this position was referred to as "0°-R" (R meaning retinotopic). When the distance was 2° or 4°, the cue display and the target display could appear equally likely (a) at the same vertical position (e.g., both 2° above the fixation)—these two positions were referred to as "2°-R" and "4°-R," respectively; (b) at opposite vertical positions (e.g., one 2° above and the other 2° below the fixation)—these two positions were referred to as "2°-N" and "4°-N," respectively (N meaning nonretinotopic). Thus, there were two factors: cue validity (valid vs. invalid) and cue–target relative vertical position (0°-R, 2°-R, 2°-N, 4°-R, vs. 4°-N). The white arrows in the figure, not shown in the actual experiment, depicted the apparent motion direction in the nonretinotopic condition in this example.

display: This target vertical position was referred to as "0°-R" (R meaning retinotopic). The target randomly appeared at either the cued location ("valid") or the uncued location ("invalid"). When the distance was 2° or 4°, the cue display and the target display could appear at the same vertical position (e.g., both 2° above): These two vertical positions were referred to as "2°-R" and "4°-R," respectively. Equally likely, however, they could appear at opposite vertical positions (e.g., 2° above and below): These two vertical positions were referred to as "2°-N" and "4°-N," respectively (N meaning nonretinotopic). Thus, whereas cue validity had two levels (valid vs. invalid), cue–target relative vertical position had five levels (0°-R, 2°-R, 2°-N, 4°-R, vs. 4°-N).

The three cue-to-fixation vertical distances (0°, 2°, or 4°) were blocked, but cue validity was randomized within blocks.

The cue awareness test

Immediately after the cueing task, subjects participated in a test that assessed visual awareness of the cue. The test included 160 experimental trials (in one block) and five practice trials. The procedure of each trial was the same as in the cueing test except as noted below. The task was to discriminate whether the cue appeared on the left or right side of the fixation mark by left or right clicking the mouse, respectively. Subjects were told that "at the very beginning either the left or right circle will appear an instance earlier" and they were asked to "attend to the circles, not the dot, while fixating at the center." They were also informed that "response time is not important" and to "respond as accurately as possible." Each trial ended as soon as a response was made or 30 s after the offset of the three circles, whichever was earlier. Thus, the awareness test was conservative: Performance benefited from both perceptual learning in the previous cueing experiment and attention to the circle during the test.

Data analysis

No trimming of reaction times (RTs) were applied (the same patterns of results were obtained when excluding data outside of three standard deviations in each condition). Effects that were not significant are not reported unless stated otherwise. All data are available upon request.

Results and discussion

The main purposes were to (a) examine whether unconscious exogenous cueing traveled and (b) compare unconscious exogenous cueing from 16.7 ms cues with conscious exogenous cueing from 50 ms cues.

To do so, we first assessed cue awareness. For cue duration of 16.7 ms, 17 of the 31 subjects performed at chance in the conservative measure of cue awareness (binomial test, one tailed, $p > 0.05$), suggesting that these subjects were unable to perceive the briefly presented and masked cue. This was further confirmed at the group level: theses 17 subjects performed at chance level, $d' = 0.082$, $SD = 0.31$; accuracy = 51.6%, $SD = 6.22$; two tailed, $t(16) = 1.09$, $P = 0.293$. For cue duration of 50 ms, 26 of the 31 subjects performed better than chance in cue awareness (binomial test, $p < 0.05$), with a significant higher than chance performance in both d′ and accuracy for these subjects, $d' = 1.941$, $SD = 1.00$; accuracy = 80.8%, $SD = 10.15$; two tailed, $t(25) = 15.47$, $P < 0.001$.

Next, we focused on these two groups to (a) probe unconscious exogenous cueing from 16.7 ms cues and (b) compare it with conscious exogenous cueing from 50 ms cues.

Unconscious exogenous cueing from 16.7 ms cues: Retinotopic and nonretinotopic effects

Subjects in the unconscious 16.7 ms group had a very low miss rate (1.19%; see Table 1 for details). Our focus therefore was on the RTs. A significant cueing effect was found at 0°-R, 13.3 ms; $t(16) = -4.31$, $P < 0.001$, $d = -1.04$, replicating a traditional unconscious retinotopic cueing effect (Figure 2A left).

To examine unconscious cueing at further distances and its interaction with retinotopicity, we conducted a $2 \times 2 \times 2$ repeated measures analysis of variance (ANOVA) with three factors (illustrated in Figure 1): (a) cue validity (valid vs. invalid), (b) distance to fixation (2° vs. 4°), and (c) retinotopicity (R vs. N). This revealed only a main effect of validity, $F(1, 16) = 12.79$, $P = 0.003$, $\eta_p^2 = 0.44$, which interacted with distance, $F(1, 16) = 4.81$, $P = 0.044$, $\eta_p^2 = 0.23$. The simple main effect of validity was significant at the distance of 2° (10.1 ms; $P < 0.001$) but not at the distance of 4° (4.3 ms; $P = 0.103$).

To separately examine how spatial distance affected the retinotopic and nonretinotopic effects, we conducted two repeated measures ANOVAs: (a) one with cue validity (valid vs. invalid) and distance in retinotopic cueing (0°-R, 2°-R, vs. 4°-R); (b) the other with cue validity (valid vs. invalid) and distance in nonretinotopic cueing (2°-N vs. 4°-N). For retinotopic cueing, we observed only a main effect of cue validity, $F(1, 16) = 22.22$, $P < 0.001$, $\eta_p^2 = 0.58$, without a main effect of distance, $F(2, 32) = 0.75$, $P = 0.482$, $\eta_p^2 = 0.04$, or an interaction, $F(2, 32) = 0.92$, $P = 0.408$, $\eta_p^2 = 0.05$. Figure 2A left shows the cueing effect for each distance, suggesting that retinotopic cueing does not depend on the distance from the fixation.

Yet for nonretinotopic cueing, we observed not only a main effect of cue validity, $F(1, 16) = 6.48$, $P = 0\ .022$, $\eta_p^2 = 0.29$, but also an interaction between cue validity and distance, $F(1, 16) = 4.78$, $P = 0.044$, $\eta_p^2 = 0.23$, without a main effect of distance, $F(1, 16) = 1.75$, $P = 0.205$, $\eta_p^2 = 0.10$. As indicated in Figure 2A left, follow-up t tests revealed that this interaction was due to a significant cueing effect at the 2°-N position, $t(16) = -3.73$, $P = 0.002$, $d = -0.90$, but not at the 4°-N position, $t(16) = -0.39$, $P = 0.700$, $d = -0.10$, suggesting that unconscious nonretinotopic cueing travels, but only within a limited range (e.g., with an upper limit of cue-to-target distance between 4° and 8°). We refer to the unconscious nonretinotopic cueing effect as *unconscious mobile cueing*, in which the allocation of unconscious exogenous cueing travels as determined by motion perception.[1]

This distance-dependent effect—a cueing effect at 2°-N but not at 4°-N—could not be accounted for by different levels of cue awareness at 2° and 4°, as performance was similar across all three cue-to-fixation vertical distances, $F(2, 32) = 0.23$, $P = 0.797$, $\eta_p^2 = 0.01$; all pairwise t tests: $Ps > 0.486$.[2] The difference was also unlikely to be attributed to a distinction of short-range and long-range apparent motion, since in both cases the distances—4° and 8°—were far longer than the typical small displacement of less than 0.25° in short range apparent motion (Braddick, 1974). Degradation of cueing at the longer distance then might reflect weaker perceptual continuity across 8° than 4°.

We performed two additional tests to examine whether the key finding here—the unconscious nonretinotopic cueing effect at the 2°-N position (i.e., traveling 4°)—was due to the exogenous cue being perceived in a few trials or by a subset of subjects. We first plotted the entire RT distribution in bins of 100 ms from 150 ms to 650 ms and found that the RT distribution of the invalid trials was shifted rightward compared with that of the valid trials (Figure 2B), an effect that could not be accounted for by just a few trials. In addition, a correlation analysis between cue visibility (d′) and cueing effect revealed no significant effect, $r(16) = 0.06$, $p = 0.82$; if anything, a regression analysis showed that the cueing effect appeared to be negatively related to cue awareness (see Figure 2C). Thus, these results could not be attributed to underestimation of cue awareness.

Finally, note that these effects could not be accounted for by eye movements: Since the duration between the onset of the cue and the offset of the target (i.e., cue to target SOA + target duration) was 116.7 ms, and that saccades require about 250 ms to occur (Mayfrank, Kimmig, & Fischer, 1987), goal or target directed eye movements could not take place between the cue onset and the target offset.

Conscious exogenous cueing from 50 ms cues: Retinotopic and nonretinotopic effects

We next focused on the cueing effect evoked by 50 ms cues that were consciously perceived. As expected, a significant cueing effect was found at 0°-R, 18.3 ms; $t(25) = -5.69$, $P < 0.001$, $d = -1.12$. A 2 × 2 × 2 repeated measures ANOVA on cue validity (valid vs. invalid), distance to fixation (2° vs. 4°), and retinotopicity (R vs. N) revealed only a significant main effect of validity, $F(1, 25) = 45.59$, $P < 0.001$, $\eta_p^2 = 0.44$. Indeed, as Figure 2A indicates, significant cueing effects were observed at all levels, demonstrating that visible exogenous cues robustly attract attention to both retinotopic and nonretinotopic locations, consistent with a recent finding using discrimination tasks (Lin, 2013).

Relating nonretinotopic exogenous cueing to cue visibility

So far, we have demonstrated unconscious mobile cueing based on subjects that could not discriminate the location of the exogenous cue. An alternative approach is to relate the cueing effect (y) to cue visibility (x) by applying regression functions to all the 31 subjects, regardless of their awareness of the cue. Zero values of y and x indicate absence of exogenous cueing and cue visibility, respectively. Thus, the regression intercept (the y value when x is zero) provides a critical test whether

Condition	16.7 ms: unaware ($n = 17$)			50 ms: aware ($n = 26$)			16.7 ms: aware ($n = 14$)			50 ms: unaware ($n = 5$)		
	Valid	Invalid	Absent	Valid	Invalid	Absent	Valid	Invalid	Absent	Valid	Invalid	Absent
0°-R												
RT	349.9 (6.9)	363.2 (7.0)	8.8 (1.6)	309.4 (5.9)	327.7 (6.8)	15.2 (2.3)	307.2 (6.1)	320.6 (7.1)	9.5 (2.2)	334.2 (14.5)	347.8 (15.3)	8.3 (1.7)
Error	0.6 (0.3)	0.2 (0.2)		0.5 (0.2)	0.7 (0.3)		0.7 (0.6)	0.7 (0.5)		0.0 (0.0)	0.4 (0.4)	
2°-R												
RT	352.7 (9.0)	360.5 (9.6)	7.3 (1.9)	323.5 (8.4)	335.4 (8.4)	12.2 (2.2)	315.4 (6.7)	323.7 (10.4)	11.9 (4.1)	327.3 (9.2)	328.8 (11.4)	10.0 (4.3)
Error	0.5 (0.3)	0.5 (0.3)		1.3 (0.6)	0.3 (0.2)		1.2 (0.8)	0.6 (0.4)		0.0 (0.0)	0.0 (0.0)	
2°-N												
RT	344.9 (8.6)	357.2 (10.1)	17.1 (2.9)	326.9 (9.0)	336.9 (9.0)	18.3 (2.4)	320.6 (8.6)	321.6 (7.6)	20.8 (5.4)	332.6 (9.1)	353.0 (9.2)	3.3 (3.0)
Error	0.0 (0.0)	0.5 (0.3)		1.3 (0.5)	1.0 (0.4)		0.0 (0.0)	1.2 (0.7)		0.0 (0.0)	0.0 (0.0)	
4°-R												
RT	357.7 (7.5)	365.3 (8.8)	7.4 (1.9)	330.9 (7.7)	343.1 (8.8)	12.8 (2.3)	318.4 (9.1)	324.0 (7.5)	10.7 (4.3)	332.3 (11.6)	344.9 (9.8)	3.3 (3.0)
Error	0.0 (0.0)	0.5 (0.3)		0.5 (0.3)	0.5 (0.3)		0.6 (0.4)	0.3 (0.3)		0.0 (0.0)	1.7 (0.9)	
4°-N												
RT	357.5 (7.5)	358.7 (8.0)	11.8 (2.2)	332.7 (6.7)	340.3 (7.7)	22.8 (2.9)	320.2 (7.4)	327.2 (8.0)	20.8 (3.9)	347.4 (12.9)	357.7 (15.3)	15.0 (5.5)
Error	0.2 (0.2)	0.2 (0.2)		0.6 (0.3)	0.8 (0.3)		0.3 (0.3)	0.9 (0.5)		0.8 (0.8)	0.0 (0.0)	

Table 1. Mean reaction times (*SEM*) and error rates (*SEM*) as a function of cue duration (16.7 ms: aware vs. unaware; 50 ms: aware vs. unaware), cue validity (valid, invalid, vs. target absent), and cue–target relative vertical position (0°-R, 2°-R, 2°-N, 4°-R, vs. 4°-N) in Experiment 1. *Notes*: R: retinotopic; N: nonretinotopic.

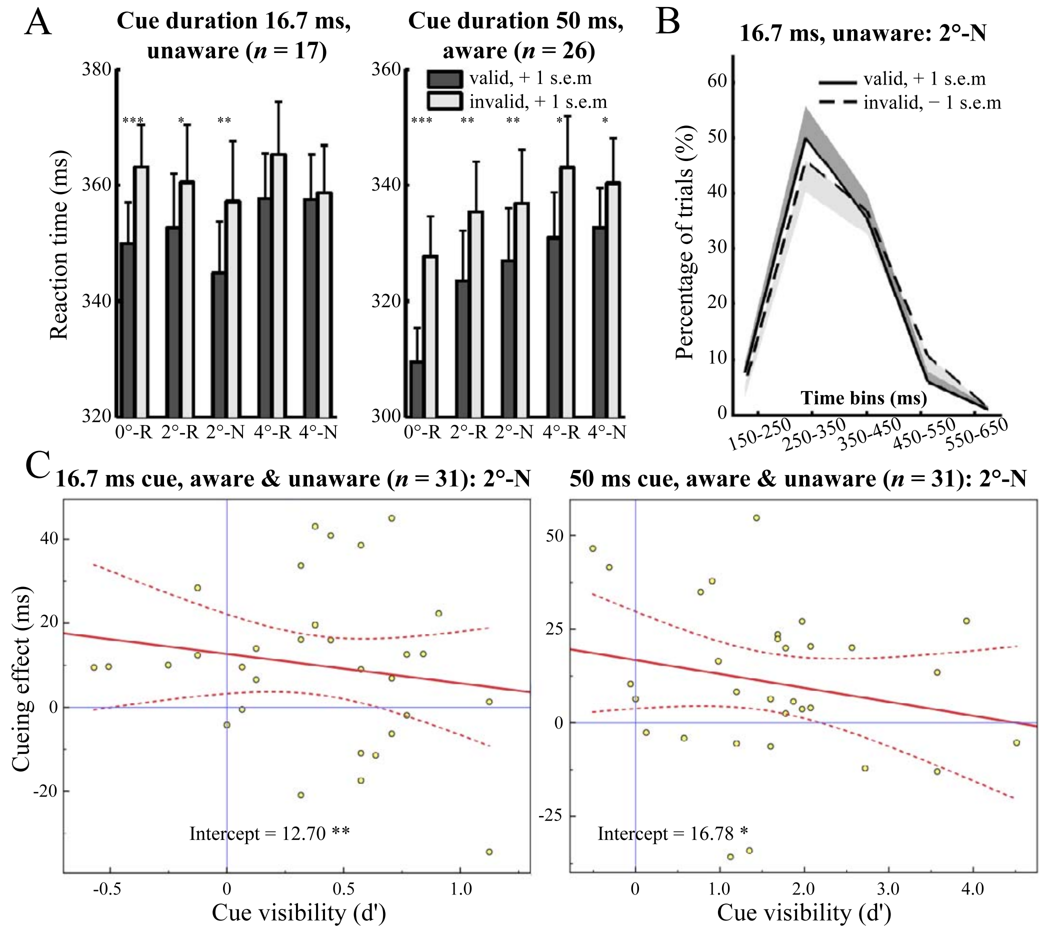

Figure 2. Demonstration of unconscious mobile cueing (Experiment 1). (A) Attentional cueing driven by invisible exogenous cues (cue duration 16.7 ms, shown on the left) and visible exogenous cues (cue duration 50 ms, shown on the right). The cueing effect—faster response in the valid condition than the invalid condition—is plotted as a function of cue–target relative vertical position (0°-R, 2°-R, 2°-N, 4°-R, vs. 4°-N). Invisible cues attracted attention not only to the retinotopic locations but also to the nonretinotopic locations with a cue-to-target distance within 4° to 8°; visible cues attracted attention to both the retinotopic and nonretinotopic locations for all the distances tested. (B) For the unconscious cueing effect in 2°-N (i.e., traveling of 4°), the reaction time distribution of the invalid trials was shifted rightward compared with that of the valid trials (plotted in five bins of 100 ms from 150 ms to 650 ms). (C) To relate the cueing effect in the 2°-N condition to cue visibility, a regression function was applied to all the data (aware of the cue or not) for the two cue durations: 16.7 ms (left) and 50 ms (right). Each data point represented an individual subject. A linear regression function with its 95% confidence interval was superimposed; the regression intercept estimated the magnitude of cueing associated with zero visibility of the cue. Stars represent levels of significance from two-tailed *t* tests: *, **, and *** are statistically significant differences at the level of $p < 0.05$, 0.01, and 0.001, respectively.

nonretinotopic exogenous cueing has occurred unconsciously: The regression intercept estimates the magnitude of nonretinotopic exogenous cueing associated with zero visibility of the cue, and thus, if the intercept is significantly greater than zero, this would reveal nonretinotopic exogenous cueing (Greenwald, Draine, & Abrams, 1996). Here, to ascertain that the cueing effect was not biased by speed–accuracy tradeoff, we adopted a commonly used combined measure of RT and accuracy called inverse efficiency scores by dividing mean RTs with accuracy (Townsend & Ashby, 1978). As Figure 2C shows, nonretinotopic exogenous cueing associated with zero visibility of the cue was 12.70 ms and 16.78 ms for the 16.7 ms cue and the 50 ms cue, respectively, both significantly greater than zero, $t(29) = 2.75$, $P = 0.010$; $t(29) = 2.65$, $P = 0.013$, respectively.

Experiments 2–4

We next conducted three follow-up experiments to (a) replicate the critical finding—the unconscious nonretinotopic cueing effect at the 2°-N position—with a

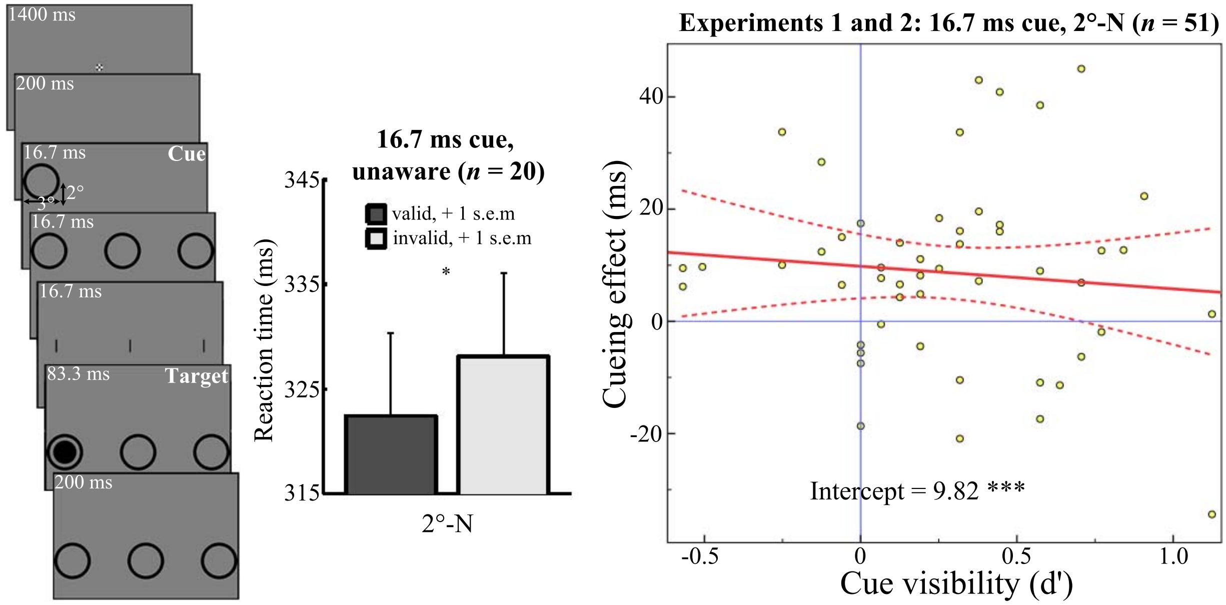

Figure 3. Replicating unconscious mobile cueing (Experiment 2). (A) Travelling of unconscious cueing in 2°-N. In between the cue display and the target display, three vertical lines were inserted to further interrupt cue visibility but also to link the two displays (path-guided apparent motion). As in Experiment 1, a significant unconscious nonretinotopic cueing effect was observed. (B) Results of a regression analysis on the data from all the subjects, aware of the cue or not, in the 16.7 ms 2°-N condition across Experiments 1 and 2. * $P < 0.05$. *** $P < 0.001$.

more focused and stringent design (Experiment 2), (b) test whether unconscious nonretinotopic cueing was due to an attentional gradient—spontaneous spatial spreading from the cued location—rather than apparent motion (Experiment 3), and (c) uncover whether the motion mechanism at play was top-down, tracking-based or low-level, energy-based (Experiment 4).

Experiment 2: Replication

Method

The procedure in Experiment 2 was the same as Experiment 1 except as noted here. The sample size of 20 for Experiments 2 to 4 was predetermined. A new group of 20 subjects participated (seven males, age 19.5). The fixation duration was increased from 1000 ms to 1400 ms. The cue duration was fixed at 16.7 ms. In between the cue display and the target display, to further interrupt cue visibility but also to link the two displays (path-guided apparent motion), three vertical lines (size = 1.04° × 0.11°; luminance = 0.1 cd/m^2) were inserted for 16.7 ms (Figure 3A). Only the 2°-N condition was tested. The cueing session included 240 trials (in three blocks); the awareness test included 80 trials (in one block) and five practice trials.

Results and discussion

All subjects performed at chance in locating the cue (binomial test, $p > 0.05$; group average accuracy = 52.0%, $SD = 4.62$). In the cueing task, miss rate was 0.45% and false alarm rate was 21.6%. As Figure 3A indicates, there was a significant unconscious nonretinotopic cueing effect, $t(19) = -2.45$, $P = 0.024$, $d = -0.55$. A regression analysis using inverse efficiency scores showed that the nonretinotopic effect associated with zero visibility of the cue was 7.04 ms, significantly greater than zero, $t(19) = 2.38$, $P = 0.029$. These results replicated the key finding in Experiment 1. Indeed, a meta-analysis, by combining data in the 2°-N condition from both Experiments 1 and 2, revealed that the cueing effect associated with zero visibility of the cue was 9.82 ms, significantly greater than zero, $t(49) = 3.46$, $P = 0.001$ (Figure 3B).

Experiment 3: Attentional gradient

The unconscious nonretinotopic cueing effect in Experiments 1 and 2 was dubbed unconscious mobile cueing because the novel effect appeared to be enabled by motion perception, as if the stimulus-driven attentional priority signal travelled through motion. But might unconscious cueing automatically spread to

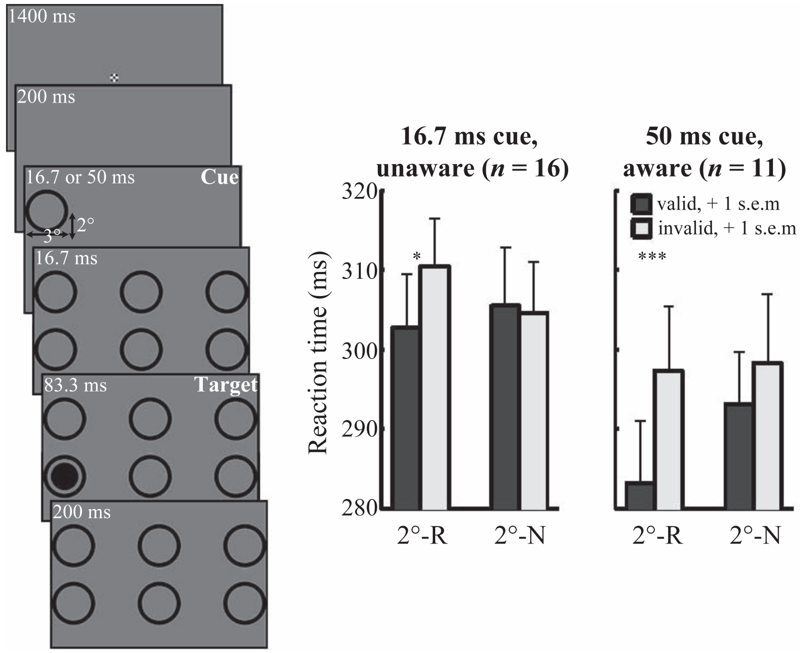

Figure 4. Apparent motion, rather than an attentional gradient, underlies nonretinotopic cueing (Experiment 3). The cue display and the target display were presented simultaneously to remove apparent motion. Significant cueing effects were observed at the retinotopic locations but not at the nonretinotopic locations, indicating a lack of transfer from exogenous cueing 4° apart. * $P < 0.05$; *** $P < 0.001$.

nearby regions, without relying on motion at all? While such an attentional gradient has been observed following voluntary attention (Brefczynski-Lewis, Datta, Lewis, & DeYoe, 2009; Downing & Pinker, 1985), reflecting the minimal window of attentional focus, in conscious exogenous cueing, it is well documented that attention is attracted to the retinotopic location of the cue (Posner & Cohen, 1984). In other words, facilitation effects are normally limited to the retinotopically cued location, without spreading to other locations. Notable exception are cases when apparent motion is introduced, in which exogenous attention is attracted to object-centered, relative locations across motion correspondence (Lin, 2013). Thus, conscious exogenous cueing is retinotopic without apparent motion.

Accordingly, just like conscious nonretinotopic cueing, the unconscious nonretinotopic cueing effect observed in Experiments 1 and 2 likely is attributed to motion perception as well. Nevertheless, to directly test whether unconscious exogenous cueing might spread to nonretinotopic locations without apparent motion, the cue display and the target display in Experiment 3 now consisted of two simultaneously presented arrays 2° above and below the fixation, each with three circles (Figure 4). The 2°-R and 2°-N conditions were tested.

Method

The procedure in Experiment 3 was the same as Experiment 1 except as noted here. A new group of 20 subjects participated (seven males, age 19.7). The fixation duration was 1400 ms as in Experiment 2. To remove apparent motion, the cue display and the target display now consisted of two simultaneously presented arrays 2° above and below the fixation, each with three circles (Figure 4). Thus, the 2°-R and 2°-N conditions were tested. The cueing session included 400 trials (in five blocks); the awareness test included 160 trials (in one block) and five practice trials.

Results and discussion

As Figure 4 shows (see also Table 2), data from those subjects who performed at chance in locating the 16.7 ms cue (binomial test, $p > 0.05$; group average accuracy = 51.5%, $SD = 4.45$) showed an unconscious cueing effect only at the retinotopic location, $t(15) = -2.67$, $P = 0.017$, $d = -0.67$, but not at the nonretinotopic location, $t(15) = 0.30$, $P = 0.771$, $d = 0.07$; interaction: $F(1, 15) = 4.49$, $P = 0.051$, $\eta_p^2 = 0.23$. This pattern paralleled the results of conscious exogenous cueing from the 50 ms cue (binomial test, $p < 0.05$; group average accuracy = 75.3%, $SD = 9.71$), showing a

Condition	16.7 ms: unaware ($n = 16$) Valid	Invalid	Absent	50 ms: aware ($n = 11$) Valid	Invalid	Absent	16.7 ms: aware ($n = 4$) Valid	Invalid	Absent	50 ms: unaware ($n = 9$) Valid	Invalid	Absent
2°-R												
RT	302.8 (6.5)	310.5 (5.8)	9.1 (2.1)	283.2 (7.5)	297.3 (7.7)	8.6 (3.8)	303.3 (7.8)	308.2 (5.7)	7.5 (2.8)	272.6 (10.2)	288.3 (11.1)	11.1 (2.8)
Error	0.9 (0.4)	0.5 (0.2)		0.2 (0.2)	0.2 (0.2)		0.0 (0.0)	0.0 (0.0)		0.3 (0.3)	0.3 (0.3)	
2°-N												
RT	305.5 (7.1)	304.6 (6.2)	13.1 (2.4)	293.1 (6.3)	298.3 (8.1)	11.8 (3.6)	311.8 (5.1)	309.0 (8.8)	5.0 (1.8)	278.7 (13.5)	287.3 (10.8)	12.8 (2.4)
Error	0.3 (0.3)	0.6 (0.3)		0.2 (0.2)	0.2 (0.2)		0.0 (0.0)	0.0 (0.0)		0.6 (0.5)	0.6 (0.3)	

Table 2. Mean reaction times (*SEM*) and error rates (*SEM*) as a function of cue duration (16.7 ms: aware vs. unaware; 50 ms: aware vs. unaware), cue validity (valid, invalid, vs. target absent), and spatial distance (2°-R vs. 2°-N) in Experiment 3. *Notes*: R: retinotopic; N: nonretinotopic.

conscious cueing effect only at the retinotopic location, $t(10) = -6.63$, $P < 0.001$, $d = -2.00$, but not at the nonretinotopic location, $t(10) = -1.29$, $P = 0.227$, $d = -0.39$; interaction: $F(1, 8) = 3.19$, $P = 0.105$, $\eta_p^2 = 0.24$. These results from both unconscious and conscious cueing confirm that without apparent motion exogenous cueing is confined to the cued location, without spreading to other regions. Thus, apparent motion, rather than an attentional gradient, underlies nonretinotopic cueing.

Experiment 4: Perceptual mechanisms

Experiment 3 suggests that unconscious exogenous cueing does not automatically spread to noncued locations without apparent motion. One might still argue that the lack of cueing effects at noncued locations might be due to dilution of cueing effects by the simultaneous presentation of six circles in Experiment 3 (as opposed to three circles in Experiments 1 and 2, referred to as the "dilution account") or due to the continuous presentation of the circle at the cued location that might confine the spreading effect (referred to as the "confinement account"). The goal of Experiment 4 was two-fold: first, to put these two accounts into test, and second, to investigate whether unconscious mobile cueing was enabled by a top-down tracking-based mechanism (Cavanagh, 1992; Lu & Sperling, 1995a) or a bottom-up energy-based mechanism (Lu & Sperling, 1995b).

To do so, in Experiment 4 we used the same display as in Experiment 1, but critically we also added a top-down, central cue at the fixation at the beginning of each trial, which predicted the forthcoming target region (up or down, with 100% validity in the first 160 trials and 75% validity in the remaining 640 trials; Figure 5A)—in valid trials, the target, when present, would appear either at the left of right location of the cued region. It is important to note that our goal was not to investigate attentional modulation of visual detection, which has been well documented (Posner, Snyder, & Davidson, 1980). Instead, the top-down central cueing method was used to disrupt attentive tracking by focusing top-down attention to either the top or bottom region of the display.

Thus, based on the dilution or confinement account, there should be a similar unconscious mobile cueing effect as in Experiments 1 and 2: The display was the same as Experiment 1 so there should be no holding back by dilution or confinement. Similarly, based on the energy-based motion account, there should also be a similar unconscious mobile cueing effect: With the same display as Experiment 1, bottom-up motion mechanisms—such as motion filters oriented in space–time in early visual cortex—should be capable of registering the spatiotemporal motion signals. However, based on the tracking-based account, little unconscious mobile cueing would be expected: A highly valid central cue would engage focal attention to the cued region, disrupting attentive tracking across regions that was essential for establishing perceptual continuity from the cue to the target.

Method

The procedure in Experiment 4 was the same as Experiment 1 except as noted here. A new group of 20 subjects participated (eight males, age 20.4). The fixation duration was 1400 ms as in Experiment 2, and during 800–1000 ms, either the upper part or the lower part was colored red, serving as a top-down central cue that predicted the target region (Figure 5A). Subjects were asked to attend to the cued region; to encourage this, the central cue was 100% valid in the first 160 trials and 75% valid in the remaining 640 trials. The 2°-R and 2°-N conditions were tested. The cueing session included 800 trials (in 10 blocks); the awareness test included 160 trials (in one block) and five practice trials.

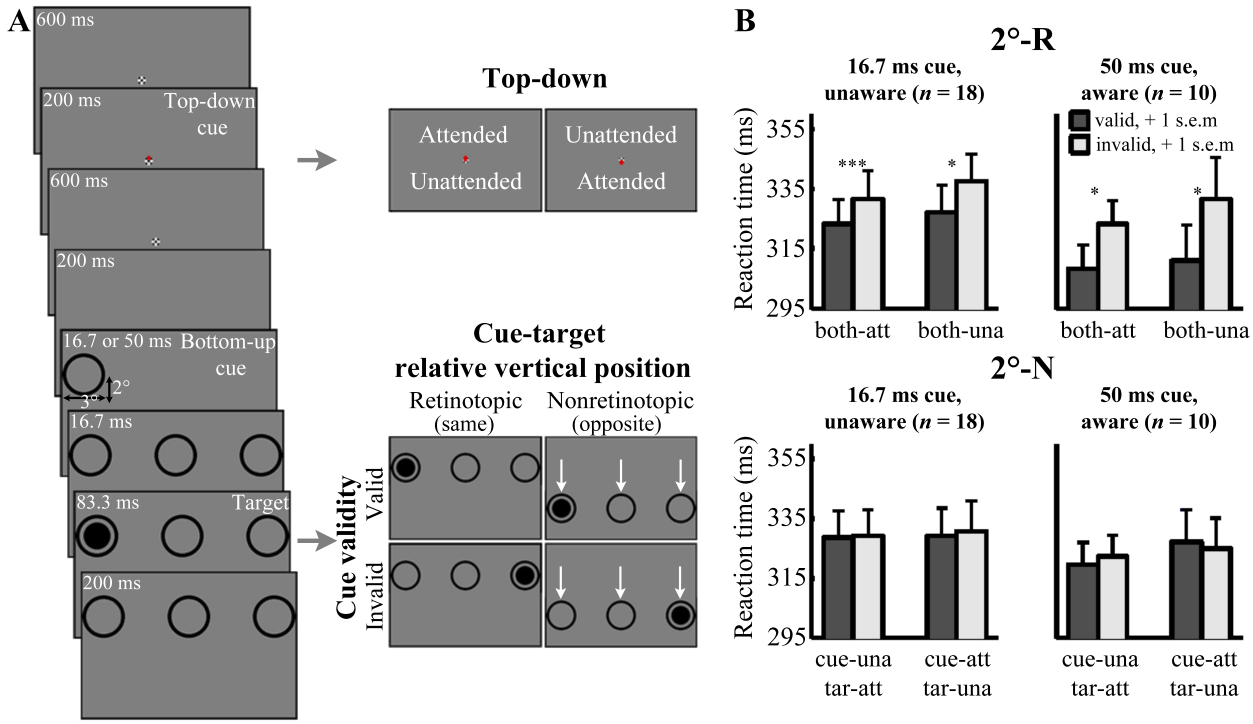

Figure 5. Tracking-based, rather than energy-based, apparent motion is responsible for nonretinotopic cueing (Experiment 4). (A) Procedure and design: A central cue, presented at the beginning of the trial, predicted the target position (up or down) 100% and 75% for the first 160 trials and the subsequent 640 trials, respectively. (B) Results: Significant exogenous cueing effects were observed at the retinotopic locations, regardless of whether the cue and the target appeared both at the attended position or both at the unattended position. In contrast, exogenous cueing disappeared at the nonretinotopic locations when the cue but not the target appeared at the attended position or the reverse, implicating a tracking-based, rather than energy-based, apparent motion mechanism in nonretinotopic cueing. * $P < 0.05$; *** $P < 0.001$.

Results and discussion

As Figure 5B indicates (see also Table 3), data from those subjects who performed at chance in locating the 16.7 ms cue (binomial test, $p > 0.05$; group average accuracy = 52.7%, $SD = 2.76$) showed no unconscious nonretinotopic cueing when top-down tracking was disrupted, both when the cue appeared at the unattended region and the target at the attended region, $t(17) = -0.28$, $P = 0.780$, $d = -0.07$, and the reverse, $t(17) = -0.45$, $P = 0.658$, $d = -0.11$; interaction: $P = 0.829$. The same pattern even held for conscious nonretinotopic cueing from the 50 ms cue (binomial test, $p < 0.05$; group average accuracy = 71.4%, $SD = 8.84$)—no cueing effect when the cue appeared at the unattended region and the target at the attended region, $t(9) = -0.84$, $P = 0.422$, $d = -0.27$, or the reverse, $t(9) = 0.51$, $P = 0.624$, $d = 0.16$; interaction: $P = 0.201$.

In contrast, for retinotopic cueing, unconscious cueing was apparent whether the cue and target appeared at the attended region, $t(17) = -3.97$, $P < 0.001$, $d = -0.94$, or at the unattended region, $t(17) = -2.14$, $P = 0.048$, $d = -0.50$; interaction: $P = 0.670$, as was conscious cueing (attended: $t(9) = -2.90$, $P = 0.018$, $d = -0.92$; unattended: $t(9) = -3.00$, $P = 0.015$, $d = -0.95$; interaction: $P = 0.515$).

Therefore, these results indicate that a tracking-based, rather than energy-based, motion mechanism is responsible for nonretinotopic cueing. They also imply that the lack of unconscious nonretinotopic cueing without apparent motion in Experiment 3 was unlikely to be explained by either the dilution account or the confinement account, for otherwise there should have been a similar unconscious nonretinotopic cueing effect here.

Undoubtedly, when the target appeared in the unattended region (invalid trials), attention could be shifted back to the unattended region, a process known as reorienting (Corbetta & Shulman, 2002). But by committing focal attention to the cued region and only reorienting to the noncued region when the target did not appear there, it effectively disrupted attentive tracking, which would require continuous, fluid tracking of a visual sequence rather than discrete monitoring of unrelated spatial locations.

Discussion

In this study, we investigate the coordination of unconscious and conscious processing by examining whether unconscious exogenous attention travels to affect performance at uncued locations based on the conscious perception of apparent motion direction. In a paradigm combining masked unconscious cueing (Mulckhuyse et al., 2007) and apparent motion (Lin, 2013), we showed that (a) when the cue was brief (16.7 ms) and rendered objectively invisible, exogenous cueing traveled to affect performance at nonretinotopic, uncued locations—a unconscious mobile cueing effect; (b) unconscious mobile cueing diminished when the cue-to-target distance was 8°, a distance where conscious mobile cueing from 50 ms cues was readily revealed; and (c) unconscious mobile cueing relied on top-down, tracking-based motion mechanisms, rather than on an attentional gradient, or energy-based motion mechanisms. Below, we consider the implications of these findings for mechanisms of exogenous attention and unconscious processing.

Theoretical interpretation

Traditionally, exogenous cueing is thought to be driven by image salience (Itti & Koch, 2001). Different accounts have been proposed regarding the neural mechanisms for exogenous attention, ranging from those that favor early mechanisms such as saliency maps in primary visual cortex (V1; Li, 2002) to accounts that emphasize late mechanisms such as priority evaluation in the ventral frontoparietal network (Corbetta & Shulman, 2002; Thompson & Bichot, 2005). Using invisible orientation singletons, a recent masking study observed that activity in V1 but not higher areas correlated with the magnitude of attentional capture (Zhang, Zhaoping, Zhou, & Fang, 2012), supporting an early mechanism in unconscious exogenous cueing. However, the V1 saliency model (Li, 2002), as is, cannot explain the unconscious nonretinotopic cueing effect reported here. Our results suggest that saliency signals in V1 must be fed to higher areas that contain neurons with larger receptive fields that can tag and spatially transfer the saliency signals based on perceived motion (Lin & He, 2012a).

Such an account of nonretinotopic effects based on perceptual continuity is consistent with object file theory (Kahneman, Treisman, & Gibbs, 1992; Treisman, 1992), in which perceiving a visual item leaves an episodic representation that can be retrieved after subsequent reperceiving of that item. This account is supported by studies showing that detection or discrimination performance on the subsequent target

Condition	16.7 ms: unaware ($n = 18$)			50 ms: aware ($n = 10$)			16.7 ms: aware ($n = 2$)			50 ms: unaware ($n = 10$)		
	Valid	Invalid	Absent	Valid	Invalid	Absent	Valid	Invalid	Absent	Valid	Invalid	Absent
2°-R: *both-att*												
RT	323.3 (8.0)	331.5 (9.1)	7.6 (1.4)	308.4 (7.6)	323.1 (7.5)	10.3 (2.9)	323.0 (12.5)	322.8 (16.1)	4.6 (1.1)	316.2 (15.0)	334.8 (17.3)	11.9 (3.6)
Error	0.4 (0.2)	0.8 (0.2)		0.5 (0.2)	0.3 (0.3)		1.5 (1.1)	0.0 (0.0)		1.2 (0.4)	0.0 (0.0)	
2°-R: *both-una*												
RT	327.0 (9.1)	337.6 (8.8)	12.5 (3.5)	310.9 (11.4)	331.6 (13.1)	10.0 (3.9)	325.7 (12.7)	334.1 (17.1)	6.2 (4.4)	317.0 (15.3)	339.3 (13.5)	18.7 (6.7)
Error	0.0 (0.0)	1.4 (0.6)		0.6 (0.6)	1.2 (0.8)		0.0 (0.0)	0.0 (0.0)		2.1 (1.1)	0.5 (0.5)	
2°-N: *cue-una, tar-att*												
RT	328.6 (8.6)	329.2 (8.5)	11.4 (2.3)	319.5 (7.2)	322.3 (6.8)	10.6 (2.9)	316.1 (6.6)	315.0 (7.0)	7.8 (5.5)	328.4 (14.3)	332.1 (15.0)	15.3 (3.0)
Error	0.3 (0.1)	0.3 (0.2)		0.5 (0.3)	0.0 (0.0)		0.8 (0.6)	0.0 (0.0)		0.0 (0.0)	0.5 (0.5)	
2°-N: *cue-att, tar-una*												
RT	329.3 (8.9)	330.7 (10.0)	7.6 (2.0)	327.2 (10.2)	325.0 (9.7)	1.2 (1.2)	323.5 (11.5)	328.8 (0.8)	0.0 (0.0)	332.3 (12.2)	330.7 (15.4)	8.7 (1.8)
Error	0.3 (0.3)	0.7 (0.5)		0.0 (0.0)	0.6 (0.6)		0.0 (0.0)	3.1 (2.2)		2.1 (1.1)	0.5 (0.5)	

Table 3. Mean reaction times (*SEM*) and error rates (*SEM*) as a function of cue duration (16.7 ms: aware vs. unaware; 50 ms: aware vs. unaware), cue validity (valid, invalid, vs. target absent), spatial distance (2°-R vs. 2°-N), and central cue in Experiment 4. *Notes*: R: retinotopic; N: nonretinotopic.

is enhanced when all of the attributes match those in the preceding item, but is impaired if some attributes are changed. We have recently introduced the idea of an "object cabinet" into this framework, by showing that object representations ("files") are automatically centered on their contextual reference frame ("cabinet"): Processing of an object is much more strongly affected by a distant item of the same object-centered space (e.g., both on the left end of its respective contextual frame) than by the same equidistant stimulus with a different object-centered space (Lin & He, 2012a; Lin & Murray, 2013a). In principle, the unconscious mobile cueing effect could be supported by either an object-based mechanism, in which case the cued circle serves as the object of attention ("the object file theory"), or an object-centered mechanism, in which case the cued circle is centered on the display of three circles, with this global display serving as the object of attention ("the object cabinet account"). Up to now, both accounts are supported by studies showing how the footprint of consciously perceived features is carried across perceptual continuity. By demonstrating a carryover effect of unconscious attentional signals, the current study extends attentional effects from the conscious domain (Boi, Vergeer, Ogmen, & Herzog, 2011; Lin, 2013) to the unconscious domain.

Implications for conscious attention and unconscious attention

The demonstration of mobile unconscious attention is consistent with recent studies showing mobile conscious attention from exogenous cueing, in which attention is shown to be dynamically attracted to a relative, object-centered location of the visible cue, resulting in a nonretinotopic cueing effect across translational apparent motion (Lin, 2013; Theeuwes, Mathot, & Grainger, 2013) and mirror reflection (Lin, 2013). One persistent issue in previous demonstrations of nonretinotopic exogenous attention is the potential confound from top-down strategies: Subjects may have adopted a strategy of using the cued location, particularly when the design is not meticulous enough to ensure that the cue is of no value for the task (for a detailed treatment on this issue, see Lin, 2013). When the cue is visible, it is difficult to rule out strategic factors. Here, with invisible cues, the current findings bring unique evidence to this debate, by showing that nonretinotopic exogenous attention can occur without cue awareness. In other words, our findings not only strengthen the demonstration of nonretinotopic exogenous attention but also constrain its potential mechanisms: Any account based on top-down strategic utilization of cues can now be refuted.

The retinotopic results of Experiment 4 also provide new insights into our understanding of unconscious retinotopic cueing, particularly regarding its relationship with top-down attention. Specifically, they show that top-down attention is necessary for unconscious nonretinotopic cueing, but may be unnecessary for unconscious retinotopic cueing. The latter notion is consistent with a bottom-up origin of cueing from abrupt luminance onsets (see also Fuchs et al., 2012), but contradicts a recent study showing that removing top-down attention seems to abolish unconscious retinotopic pop-out effects (Hsieh, Colas, & Kanwisher, 2011). In this study, top-down attention to the cue was removed by adding a demanding rapid sequential visual presentation (RSVP) display. However, given that the RSVP stimuli were highly dynamic and salient, strongly drawing bottom-up attention, it is unclear whether the lack of the unconscious popout effect was due to top-down or bottom-up factors in their study. Alternatively, it is also possible that the top-down attention manipulation in our study was not strong enough; indeed, the goal of Experiment 4 was not to probe the modulation effect of attention but rather to examine the role of attentive tracking in unconscious mobile cueing (for recent examples using attentional load to examine attentional modulation, see Lavie, Lin, Zokaei, & Thoma, 2009; Lin & He, 2012b). This issue remains an important challenge for future research.

Importantly, our data from Experiments 3 and 4 provide the first empirical validation of the unconscious cueing task based on visual masking (Mulckhuyse et al., 2007). In general, although faster responses at the cued location than at the uncued location are considered a signature of unconscious allocation of spatial attention, the cueing effect is also consistent with response priming. For instance, a left cue would prime a left response, facilitating the target response if the target also appears on the left (a left response) but interfering with the target response if the target appears on the right (a right response). Indeed, it has long been documented that a masked, and thus invisible, stimulus triggers a motor response as early as an unmasked stimulus does; this finding, known as the Fehrer–Raab effect (Fehrer & Raab, 1962), is robust for both detection and spatial localization tasks (Neumann & Klotz, 1994). Previous studies have been unable to rule out this response priming account. Here the results of Experiments 3 and 4 provide novel evidence against the response priming account. Specifically, if the cueing effect were solely due to response priming, the effect should not be modulated by the distance between the cue display and the target display, nor should it depend on attentive tracking, as both manipulations are irrelevant to response priming. If anything, based on response priming, in Experiment 4 one would have expected to see a larger cueing effect in the 2°-N cue-attended but target-unattended condition than other conditions, because in this condition the cue was strongly primed whereas the target was weakly activated. These predictions, however, are inconsistent with the findings in Experiments 3 and 4, which support a genuine spatial attention cueing effect.

Implications for conscious and unconscious processing

We consider unconscious mobile cueing as a compelling demonstration of the coordination of unconscious and conscious processing. In other words, although the initial bottom-up attraction of spatial attention is unconscious, its propagation appears to require conscious tracking. This is because unconscious mobile cueing requires apparent motion (comparing Experiments 1 and 2 with Experiment 3) and top-down tracking (Experiment 4). These findings are consistent with a recent study showing that the extrapolation of a motion trajectory appears to depend on an awareness of the motion trajectory itself (Hsieh & Colas, 2012). However, they appear to contradict a blindsight study showing that nonretinotopic cueing effects could be induced without conscious connection of the cue location and the target location, in which top-down, goal-directed endogenous attention could be engaged with informative symbolic cues presented in patient GY's blind field (Kentridge, Heywood, & Weiskrantz, 1999). Such a difference could reflect (a) a distinction between exogenous attention and endogenous attention, (b) potential differences between normal subjects and blindsight subjects, or (c) differences in awareness measurements (objective forced-choice here vs. subjective reports from GY).

Explicit coordination of unconscious and conscious processing as revealed in unconscious mobile cueing argues against theories in consciousness that assume independent and noninteractive unconscious processing and conscious processing (Dahaene, 2008; Lau & Rosenthal, 2011; Pasquali, Timmermans, & Cleeremans, 2010). Instead, given that both unconscious processing and conscious processing affect perception and performance (Kouider & Dehaene, 2007; Lin & He, 2009; Lin & Murray, in press), for coherent behaviors to emerge, they somehow must be coordinated. At the neural level, the interaction of unconscious neural processing and conscious neural processing is consistent with recent integrated models that emphasize the role of recurrent connections in enabling conscious vision (Lamme & Roelfsema, 2000). Assuming a V1 mechanism for the initial, retinotopic exogenous attention, our findings suggest that the coordination of unconscious and conscious processing may be an early process. This is consistent with models suggesting that recurrent processing in early visual areas is necessary for visual awareness, perhaps with early visual areas acting as active "black-boards," integrating computation outputs from higher-order areas (Bullier, 2001).

More generally, that mobile cueing depends on conscious, attentive tracking provides evidence against a widespread assumption that unconscious processes are automatic whereas conscious processes are controlled (e.g., Jacoby, Yonelinas, & Jennings, 1997). Instead, the unconscious is not as automatic as previously thought and may well be controlled just like the conscious.

Keywords: unconscious attention; exogenous attention; attention capture; object-centered representation

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Footnotes

[1]Table 1 also presented the data from the remaining 14 subjects who perceived the 16.7 ms cues, $d' = 0.757$, $SD = 0.19$; accuracy = 64.7%, $SD = 3.41$; two tailed, $t(13) = 16.10$, $P < 0.001$. The major difference of note is that the validity effect at 2°-N was minimal in RTs, $t(13) = -0.19$, $P = 0.849$, $d = -0.05$, with a trend in accuracy, $t(13) = 1.75$, $P = 0.103$, $d = 0.47$. This might reflect an attempt by subjects who could somewhat perceive the cue to inhibit the cue; such an attempt could be more successful when the cue was weak (16.7 ms) than when it was strong (50 ms). This suppression account appears to be consistent with the observation that the cueing effect was negatively correlated with cue awareness (Figure 2C) and the recent finding that the same cue duration (16.7 ms) could produce a larger cueing effect when invisible than when visible (their experiment 4, Fuchs et al., 2012).

[2]The number of trials used in the awareness test was in keeping with previous studies in unconscious attention. However, it is worth noting that in future studies such a procedure can be improved in two aspects: (a) by increasing the number of trials so as to reduce statistical uncertainty and allow for separate assessments of awareness for different locations; (b) by appending clearly visible trials at the end so as to assess experiment participation (Lin & Murray, 2013b).

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