Is there stimulus-driven attention without awareness?

By

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Introduction

Attention and awareness are doubtless tightly interwoven constructs. Attention is the end result of numerous interacting cognitive processes (Asplund, Todd, Snyder, & Marois, 2010; Han & Marois, 2014; James, 1890; Posner & Boies, 1971) that work in concert to permit an organism to select a small subset of the countless physical and cognitive events that continuously bombard it for further processing. Perceptual awareness, or consciousness, refers to the reportable contents of mental life (Kouider & Dehaene, 2007). Conversely, perceptual unawareness refers to a state in which the organism is unable report stimulus presence; such failure may be due to inattention, as in the case of inattentional blindness (Simons, 2000) or the attentional blink (Asplund, Fougnie, Zughni, Martin, & Marois, 2014), or because the stimulus is presented below the limen for conscious awareness, as in the case of masked stimuli (Merikle & Joordens, 1997).

Although the scientific community has, by and large, come to recognize the existence of subliminal perception (see Kouider & Dehaene, 2007 for review), the extent to which subliminally presented stimuli are able to influence higher order cognitive representations remains unknown. Specifically, are unexpected or novel stimuli that are subliminally presented able to automatically capture and orient visual attention? In other words, can a stimulus that an organism is not aware of elicit the deployment of stimulus-driven attention?

This question is theoretically crucial as it directly addresses the mechanisms that regulate attentional deployment. Broadly speaking, there are considered to be two modes of attentional deployment, and the successful coordination of both is pivotal to nearly every cognitive process (Chun, Golomb, & Turk-Browne, 2011). Endogenous deployment, also known as *goal-directed* or *top-down* deployment, is effortful and voluntary. In contrast, exogenous deployment, also known as *stimulus-driven* or *bottom-up* deployment, is effortless and considered to be automatic (Eriksen, Eriksen, & Hoffman, 1986; Jonides, 1981; Theeuwes, Kramer, Hahn, & Irwin, 1998; Yantis, 2000). Recently, several groups of researchers (Ivanoff & Klein, 2003; Lin, Murray, & Boynton, 2009; Lin & Murray, 2013; McCormick, 1997; Mulckhuyse, Talsma, & Theeuwes, 2007; Sato, Okada, & Toichi, 2007) have proposed that because the deployment of stimulus-driven attention is automatically mediated, such deployment can occur even when observers are unaware of the presence of the stimulus to which attention is deployed. However, evidence presented to support this claim is mitigated.

In the remainder of this document, I will discuss the hallmark characteristics of automatic cognition and review the extent to which deployment of stimulus-driven attention demonstrates these characteristics. I will then review the current literature claiming to have demonstrated evidence of stimulus-driven attention without awareness, and I will present an experiment that re-instantiates the most compelling paradigm thus far for demonstrating such attentional deployment (Mulkhuyse, Talsma, & Theeuwes, 2007; Lin & Murray 2013). Finally, I will offer an alternative explanation for the results that this paradigm yields. Specifically, I will claim that the putative demonstrations of stimulus-driven awareness in response to suppressed cues actually rely on differential cue awareness that is modulated by the contingent relationship of the cue to the target.

Stimulus-driven attention as automatic cognition

Evidence of automatic cognitive processes is found in a diverse range of behaviors including reflexes (e.g., blinking, tensing in advance of an oncoming collision), highly skilled behaviors (e.g., driving, nonverbal communication, and typing – Charlton & Starkey, 2011; Lakin, 2006; Snyder & Logan, 2013), and the formation of attitudes (stereotyping and prejudice (Galdi, Cadinu, & Tomasetto, 2014) and action schema (Tiffany, 1990). Although theories of automaticity are divided as to the cognitive architecture supporting automatic processes (Bargh, 1992; Logan, 1988; Moors, 2016), the features of automatic processes are largely agreed upon. Specifically, automatic processes are characterized by fast, effortless, and obligatory execution. Such processes can also be executed without attending to the details of the actions being performed (Logan & Crump, 2009; Snyder, Ashitaka, Shimada, Ulrich, & Logan, 2014) and without detailed knowledge about the objects upon which the actions are being performed (Liu, Crump, & Logan, 2010; Snyder & Logan, 2013). In lay terms, automatic processes can be thought of as those processes that appear to run themselves regardless of the actor's intention.

In one of the first studies explicitly investigating distinctions between goal-directed and stimulus-driven attentional deployment, Jonides (1981) demonstrated that whereas observers could easily suppress goal-directed attentional deployment and that the efficacy of such attentional processing was capacity-limited and affected by task demands, observers could not easily suppress stimulus-driven orientation regardless of task-set and current working memory load. These findings and the results of following investigations (e.g., Folk, Remington, & Johnston, 1992; Theeuwes, 1991; Yantis & Jonides, 1984) have lead researchers to conclude that exogenous deployment of spatial attention occurs is an automatic process provided that observers are attending over a diffuse region of space and that the stimulus capturing attention has the potential to be behaviorally relevant.

The spatial-cueing paradigm

Verifying the claim that stimulus-driven attention can operate outside the bounds of cue-awareness requires two conditions to be met. First, the stimuli used to capture attention must be completely masked from perceptual awareness. Second, any benefits conferred by attention must be attributable only to stimulus-driven processes. In other words, contamination of the results by possible goal-oriented attentional mechanisms would invalidate a direct appeal to stimulus-driven attention without awareness. As detailed below, studies claiming to find stimulus-driven attention in the absence of awareness suggests that previous works have failed to meet one or both of these conditions.

Typically, researchers seeking to demonstrate stimulus-driven attention in the absence of awareness have used some variation of the spatial-cueing paradigm to provide evidence of attentional deployment (Ivanoff & Klein, 2003; Lin & Murray, 2013, 2015; McCormick, 1997; Sato et al., 2007) although see Lin et al., 2009). To simplify discussion of the above studies, I will briefly review the spatial-cueing paradigm and how the basic paradigm can be used to study both goal-directed and stimulus-driven attention.

The spatial-cuing paradigm refers to any of a class of experimental paradigms in which a spatially circumscribed target is preceded by some stimulus that may or may not validly predict the location of the upcoming target (see Chica, Martin-Arevalo, Botta, & Lupianez, 2014 for a detailed review). In the goal-directed version of the paradigm, the initial stimulus is a centrally presented cue with arbitrarily chosen features that are highly predictive of upcoming target location. For example, a red circle may predict with 75% accuracy that the upcoming target will be presented to the left of center while a blue circle may predict with the same accuracy that the target will be presented to the right of center. In this version of the paradigm, cue-target mapping can be counterbalanced across subjects such that there is no unintentional bias introduced (e.g., participants as a whole tend to associate the color blue with the right side of space for reasons having nothing to do with the experiment) such that any reaction-time or accuracy benefits imparted to validly cued targets over invalidly cued targets can be attributed to the effects of purely voluntary shifts in attention. Crucially, truly symbolic cues must predict upcoming target location with above chance in order to produce no attentional effects. Results of such experiments demonstrate that endogenously deployed attention typically improves target detection reaction times/accuracy for cues compared to non-cued and invalidly cued trials. Typically, such improvements are observed beginning at cue-target stimulus-onset asynchronies of approximately 300 ms (Remington & Pierce, 1984) and persist for several seconds (Posner, 1980).

In contrast, the stimulus-driven version of the spatial cueing paradigm uses non-predictive, peripherally presented stimuli to shift attention to different spatial locations. Such cues can include brief luminance changes (usually giving participants the impression of a flash at the stimulus location) or the sudden onset of new objects at or near possible target locations. These sorts of peripheral cues attract attention to their locations even when observers are explicitly informed that cues do not validly predict upcoming target location. The attentional benefits of peripherally presented cues can be observed at cue-target stimulus-onset asynchronies as short as ~50 ms. However, these effects are short lived, and typically subside within ~300 ms. In some cases, exogenous cueing even leads to performance decrements at the cued location at cue-target onset asynchronies exceeding 300 ms (Klein & MacInnes, 1999; Posner, Rafal, Choate, & Vaughan, 1985; Wolfe, 1994). This performance decrement is known as inhibition-of-return (IOR), and is theorized to reflect a bias against revisiting previously explored locations (Wolfe, 1994).

Previous research

McCormick (1997) published the first paper claiming to address the question of stimulus-driven attention in the absence of cue awareness. Here, the author presented a number of experiments, all of which included a putatively perceptually suppressed cue as well as a target-detection component in which participants were told to make speeded responses to targets. McCormick found a significant validity effect when targets appeared at the location predicted by the cue.

While some have taken McCormick's work as compelling evidence (Wright & Ward, 2008), the logic underlying McCormick's work fundamentally rules out a direct appeal to stimulus-driven attention without awareness because McCormick confounded stimulus-driven and goal-oriented attentional effects. In all the experiments presented, McCormick created cue-target contingencies wherein the cue was predictive of the target location 85% of the time, thus incentivizing participants to adopt a strategy where they intentionally looked for a cue. McCormick's work is also problematic because he did not objectively measure cue awareness. Instead, McCormick relied on participants' subjective judgments of cue visibility and adjusted the contrast between the cue and the monitor accordingly.

Relying on subjective judgments introduces a criterion effect in which, for any given cue presentation, participants who have adopted a conservative threshold are less likely to report having detected a cue cues than participants who have adopted a more liberal threshold (Swets, 1961). Consequently, it is impossible to rule out cue awareness as a factor contributing to the reaction time benefits conferred to target detection in McCormick's investigation.

Ivanoff and Klein (2003) address many of the concerns regarding McCormick's (1997) work. Here, the authors instructed subjects to complete a go/no-go target detection task wherein the participants were told to make a speeded response to a target when the cue preceding the target was in the 'go' configuration, and to inhibit target response when the preceding cue was in the 'no-go' configuration. Critically, the cue was perceptually suppressed on half of the trials. Subjects participated in two experimental blocks. In the first block, subjects completed only the go/no-go task. In the second block, subjects additionally indicated cue awareness at the end of each trial. Thus, the first block constituted a single task, whereas the second block imposed dual-task conditions on the subjects. The authors found evidence of IOR in the experimental block in which observers did not additionally indicate cue awareness at the end of each trial. The authors argue that IOR is a purely stimulus-driven effect, and that therefore the presence of IOR indicates the deployment of stimulus-driven attention.

The imposition of the dual-task condition makes it difficult to interpret Ivanoff and Klein's (2003) results. Participants in the dual-task condition had to deploy both goal-oriented and stimulus-driven attentional processes in order to actively look for the cue as well as make a speeded response to the presence of the target. In contrast, participants in the single-task condition only had to deploy stimulus-driven attentional processes to make speeded target responses. The researchers found that the imposition of a second task led to qualitatively different results in the target-detection task. Specifically, the researchers found that evidence of inhibition of return when participants were required to only complete the go/no-go task. In other words, reaction time to target detection was significantly slower at validly cued locations than at invalidly cued locations in the single-task condition. However, this effect disappeared and was replaced with a significant validity effect in the dual-task condition.

Ivanoff and Klein (2003) based their argument for the existence of stimulus-driven attention in the absence of cue-awareness on the significant IOR effect observed in the single-task condition. However, IOR is not necessarily a hallmark of stimulus-driven attention. Not only have researchers demonstrated that IOR need not occur in tandem with the performance enhancing effects of stimulus-driven attention (Fuchs & Ansorge, 2012; Posner, Walker, Friedrich, & Rafal, 1984), recent evidence has further suggested that inhibition of return can be observed at endogenously attended locations provided that no attentional disengagement as occurred (Berlucchi, 2006; Chica, Lupiáñez, & Bartolomeo, 2006; Martin-Arevalo, Kingstone, & Lupianez, 2013). Consequently, the mere presence of IOR does not constitute strong evidence for the deployment of stimulus-driven attention in the absence of stimulus-awareness.

Sato et al. (2007) attempted to demonstrate stimulus-driven attentional effects in the absence of awareness a variant of the spatial-cuing paradigm that included two major deviations from traditional stimulus-driven attention spatial cuing paradigms. Specifically, the authors elicited the deployment of stimulus-driven attention via eye-gaze cues that were rendered perceptually invisible. Using this paradigm, the authors found that subliminal gaze shifts can lead to a significant reaction time advantage for gaze shifts that validly indicated upcoming target location compared to shifts that did not validly indicate upcoming target location. Although these results may seem like compelling evidence demonstrating the deployment of stimulus-driven attention absent awareness of the stimulus eliciting this deployment, using eye-gaze cues introduces the possibility that the results reported were due, at least partially, to non stimulus-driven attentional deployment.

In addition to the two classic variants of the spatial-cueing paradigm discussed earlier, and additional variation of the paradigm uses centrally presented, overlearned, ecologically meaningful symbols such as eye-gaze or directional arrows as cues (Friesen & Kingstone, 2003a, 2003b; Friesen, Moore, & Kingstone, 2005; Friesen, Ristic, & Kingstone, 2004). Unlike truly symbolic cues, centrally presented overlearned symbols can direct spatial attention even when they are not predictive of upcoming cue location (Bayliss & Tipper, 2005; Hommel, Pratt, Colzato, & Godijn, 2001; Marotta, Lupianez, Martella, & Casagrande, 2012), a finding that suggests that, to some extent, attention is deployed involuntarily to the cued location.

Attention deployed in response to gaze cues displays behavior more similar to exogenous or endogenous orienting depending on the onset asynchrony between the cue and target, and, at intermediate onset asynchronies, gaze cues appear to elicit attentional deployment that displays characteristics of both reflexive and volitional attention (Friesen, Ristic, & Kingstone, 2004). These results demonstrated that attention directed by overlearned symbols cannot be considered to be purely a result of either endogenous or exogenous processes and, therefore, that Sato et al.'s (2007) results do not constitute strong evidence for exogenous deployment of attention absent stimulus awareness.

Although the bulk of research investigating the stimulus-driven attention absent awareness has used spatial-cuing paradigms in which the cues are putatively rendered invisible via masking, this is by no means the only paradigm that has been employed. Specifically, a 2009 investigation by Lin, Murray, and Boynton used looming stimuli to direct attention to specific spatial locations. In this study, the authors claimed that threatening stimuli could elicit stimulus-driven attention to specific spatial locations even when observers were not aware that the stimuli present a threat. Specifically, the researchers asked subjects to detect targets whose presentation was preceded by looming stimuli whose paths appeared to either collide with the observers' heads (threat) or to just miss the observers' heads (non-threat). Even though observers were unable to reliably differentiate between threatening and non-threatening looming objects, targets that appeared at the threatening stimuli's points-of-origin were detected more quickly than targets that appeared at the non-threatening stimuli's points-of-origin.

Unlike the other studies discussed, this study does not suffer from possible contamination by goal-directed attentional processes. However, this study does not actually address the crucial question of whether stimulus-driven attention can be deployed in the absence of stimulus awareness. Rather, observers in this study were perfectly aware of the looming stimulus, although they were unable to reliably indicate whether or not the stimulus was threatening. In other words, the authors demonstrate that stimulus-driven attention can be deployed in response to objects whose characteristics are not completely known to the observers. They do not demonstrate that such stimulus-driven attention can be deployed in response to objects whose existence is completely hidden from observers.

Mulckhuyse et al. (2007) pioneered a paradigm that appears to demonstrate compelling evidence for stimulus-driven attention in the absence of cue awareness. This paradigm has been adopted by subsequent studies (Lin & Murray, 2013; Lin & Murray, 2015) and used to explore the consequences of stimulus-driven attention without awareness, rather than exploring whether the phenomenon itself is sound. Because the paradigms in the follow-up studies are similar in principle to Mulckhuyse's original study, I will focus the methodological critique on the original study, the results that it demonstrated, and their implications.

Mulckhuyse et al. (2007) presented a modified cueing paradigm (Posner, 1980) in which participants were told either to detect a target as quickly as possible, or, on different blocks, to localize the position of the cue. Dividing the task into avoided creating a dual-task condition, allowing the experimenters to dissociate the effects top-down attentional sets from those of the unaware bottom-up cue. Mulckhuyse et al., and subsequent researchers using a similar design (Lin & Murray, 2013; Lin & Murray, 2015) found a reaction time advantage for targets that had been validly predicted by putatively unaware cues after a 16.7 ms cue-target onset asynchrony. Mulckhuyse et al. also found a significant effect of inhibition of return after a 1016.7 ms cue-target onset asynchrony.

If the reaction time results presented in Mulckhuyse et al. (2007) were elicited under conditions of complete perceptual unawareness, this would present compelling evidence of stimulus-driven attention that is not predicated on cue awareness. Mulckhuyse et al. attempt to objectively measure cue awareness by requiring participants to complete a two-alternative forced choice task directed at localizing the position of the cue following the completion of the speeded target detection task. Typically, forced-choice methods are thought to be conservative, and have been hailed at the gold standard for establishing unconscious processing. However, recent evidence published by Lin & Murray (2014) suggests that typical alternative force-choice methods of assessing stimulus awareness may, in fact, underestimate the extent to which participants are aware of stimuli. Lin & Murray (2014) demonstrate that chance performance in two-alternative forced choice tasks is due to a combination of (1) participants failing to understand task instructions when all trials are at the threshold of awareness (i.e., when the target stimulus is strongly masked), and (2) priming of the target object increasing the perceptual trace of the target and boosting it above the threshold of awareness.

Irrespective of the concern raised above, Mulckhuyse et al. (2007) and Lin & Murray (2014) both argue that reaction time facilitation at validly cued locations in conjunction with chance performance in the two-alternative forced choice cue-localization task indicates the presence of stimulus-driven attention without awareness. However, this may not be the case if participants are differentially aware of cues across experimental conditions. In other words, if participants were aware of valid cues but not aware of invalid cues, we would expect reaction time facilitation for valid locations over invalid locations in the target-detection task. Further, in the cue localization-task, we might expect the variance created in the data by collapsing across valid and invalid conditions to mask the effects of cue awareness in the valid condition.

One alternative account of Mulckhuyse's results is that differential cue awareness across trial types (i.e., valid compared to invalid) underlies the reaction time benefit to valid trials. Specifically, I hypothesized that Mulckhuyse et al. found a validity effect because participants were aware of valid cues but not of invalid cues. Below, I present an experiment that tests this hypothesis. I first replicated Mulckhuyse et al.'s (2007) findings in both the target-detection and cue-localization tasks. However, when I examined the cue-localization data at a more granular level, I found that the apparent non-awareness of cues in Mulckhuyse et al.'s original presentation of the data could have resulted from collapsing awareness-assessment across all trial types (i.e., valid and invalid cues, long and short stimulus-onset asynchronies). My results reveal the predicted asymmetry in cue-awareness across validity conditions, thus casting doubt on the conclusion that exogenous attention can operate in the absence of awareness of the stimulus capturing this form of attention.

Method

Participants

Thirty-two subjects (22 female; mean age, 24 years) participated in the experiment. All subjects participated in the reaction time task and the cue-awareness task. The first sixteen subjects participated first in the reaction time task and then the cue-awareness task. Task order was reversed for the second 16 subjects. All subjects were recruited using the Vanderbilt SONA recruitment system and participated in return for either $12/hour or for course credit. All subjects reported normal or corrected-to-normal vision. All experiments were performed in accordance with the Vanderbilt University Institutional Review Board.

Display

A MacMini computer running MATLAB 2007 (www.mathworks.com) and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) controlled stimulus presentation and data collection. Subjects were seated at a distance of approximately 60 cm the monitor in a silent, non-illuminated room. All measures of stimulus size in degrees of visual angle are reported from a 60 cm viewing distance. Subjects responded with their dominant hand using a Macintosh keyboard.

Procedure and design

Participants completed five blocks of a target-detection task and four blocks of a cue-localization task (see Figure 1A). The cue localization task was visually identical to the detection task; however during cue-localization participants were instructed to ignore the target. This experiment was modeled after Mulckhuyse et al.'s (2007) work and the orientation task was identical to the procedure published in Mulckhuyse et al. (2007). However, we included one slight change in the cue-localization task. Whereas Mulckhuyse et al. allowed participants to respond with the location of the cue as soon as the cue was presented and then began a new trial as soon as participants keyed-in their responses, we forced participants to wait until the end of each trial to localize the cue. This changed forced all cue-localization trials to look identical to the orientation trials. All stimuli were presented on a light gray background.

Subjects sat approximately 60 cm away from the computer screen. Subjects were explicitly instructed to maintain fixation on the center of the screen throughout the duration of both tasks. The orientation task consisted of five blocks of 40 trials per block. Each cell of the design was repeated four times per block, for a total of 20 trials per cell in the orientation task. Seven trials per block had no target. These no-target "catch" trials

Figure 1

A. Trial structure for target detection and cue localization tasks. Time reported in milliseconds.

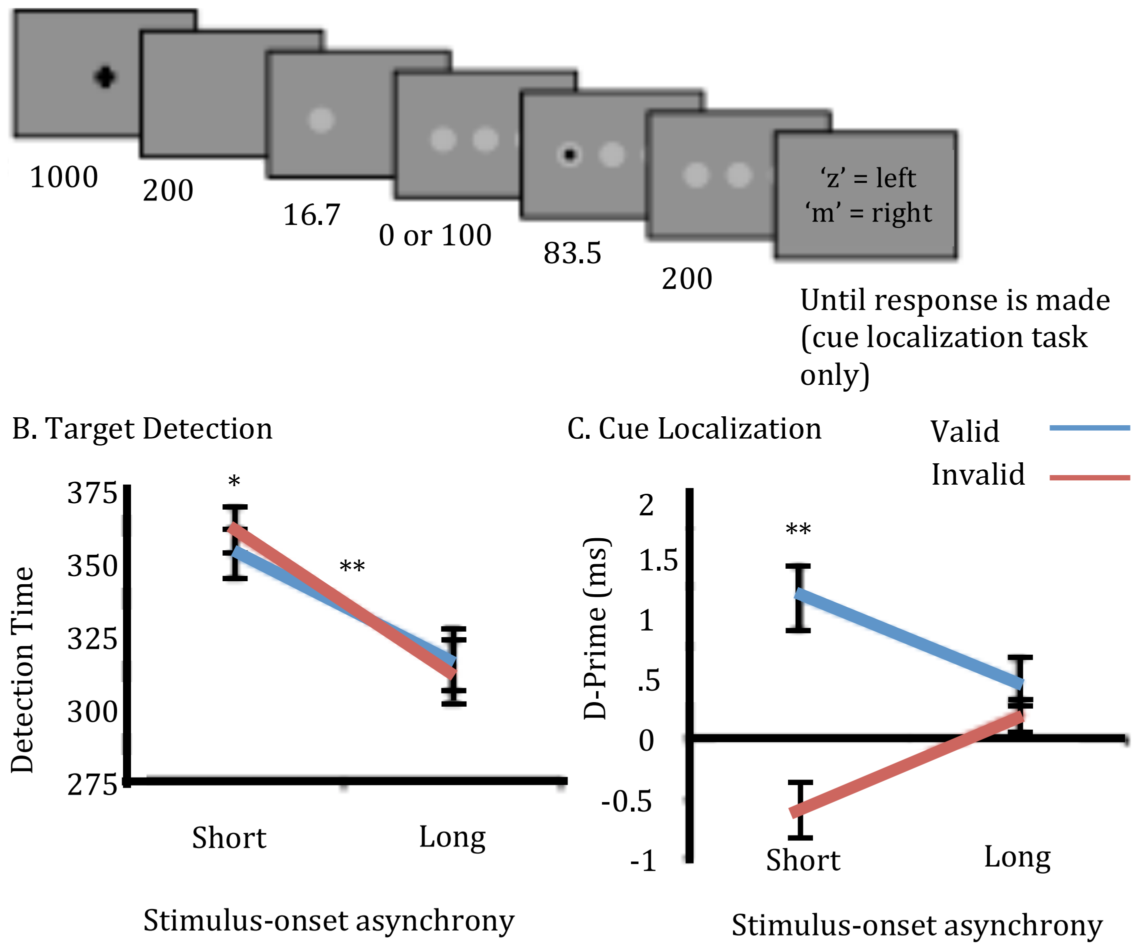


Figure 1. Trial structure and results for the cue sensitivity and target detection tasks in Experiment 1. A. Trial structure for cue sensitivity and target detection tasks. Both tasks are identical until the probe frame. The target detection task omits the probe frame. B. Average reaction time for aware and non-aware cues in the target detection task. Error bars are average within-subject standard error. C. Average d' scores on the cue sensitivity task separated by validity. Error bars are average within-subject standard error.

were included to encourage subjects not to respond prior to target presentation. Subjects who responded prior to target presentation or during "catch" trials heard a tone indicating an incorrect response. Of the remaining trials, there were equal numbers of trials in each experimental condition: short-cue-target onset asynchrony (CTOA) valid (SV), short-CTOA invalid (SI), long-CTOA valid (LV), long-CTOA invalid (LI).

Each trial began with 1000 msec fixation on a black cross (0.6º visual angle) at the center of the screen, followed by a 217 msec blank gray screen (the screen was light gray for the duration of both the orientation and cue sensitivity tasks). Following the blank screen, a gray cue disk (2.6º visual angle, center 9.2º away from the center of the screen either to the right or to the left) appeared. After a 16.7 msec cue period, two placeholder disks that were identical to the cue disk appeared. The three disks were arranged in a straight line along the horizontal meridian of the monitor with 9.2º visual angle separating the center of each element. As did Mulckhuyse et al. (2007), I included two CTOAs. The target appeared concurrently with the two placeholder-disks in the short CTOA condition and 1000 msec after the onset of the two placeholder-disks in the long CTOA condition (see Figure 1A). The target was a black dot that appeared in the center of one of the peripheral gray disks. It stayed on the screen for 83msec, and participants were instructed to hit the spacebar as soon as they detected the target. The trial was considered valid if the cue and the target were presented at the same location. There were no targets presented in catch trials. The disks remained on the screen for 200 msec following target offset. There was a 1000 msec inter-trial interval between each trial.

As with Mulckhuyse et al., the cue-localization task consisted of four runs of twenty trials per run. The proportion of valid, invalid, and no-target trials was the same in the cue sensitivity task as in the orientation task. The cue sensitivity task was visually similar to the orientation task, with the following notable differences. Subjects were instructed to ignore the target and attend to the onsets of the cue and placeholder disks. Subjects were also told that the location of the black target dot was random and did not provide any information pertinent to completing the localization task. Following the 200 msec inter-trial-interval, subjects were asked to indicate which of the two peripheral gray disks appeared first on the screen. Subjects pressed the 'z' key if they thought that the leftmost disk was first, and the 'm' key if they thought the rightmost disk was first. Subjects were required to respond on every trial, and there was no option to say that all disks appeared simultaneously. Each trial ended when a response was given. The cue sensitivity task was visually identical to the target-detection in all other respects.

Results

T-tests on the effect of task order reveal no differences in the d-prime task, $t(126) = 0.95$, $p = 0.3$, or in the RT task, $t(126) = 1.35$, $p = 0.8$. As such, data from both task-orders are analyzed together within the tasks. Results of the target-detection task are presented first for conceptual clarity.

Target-detection task

Figure 1B shows mean reaction time (RT) scores for each condition (short valid, short invalid, long valid, long invalid; SV, SI, LV, LI). Reaction time latencies less that 100 msec and greater than 630 msec (1.62%) were dropped from the reaction time analysis. I analyzed the data by running a mixed-factors repeated-measures analysis of variance

(ANOVA) with Cue-Target Onset Asynchrony (2 levels; 16 or 1016 msec), and Cue Validity (2 levels; valid or invalid) as fixed effects. I found main effects of both CTOA, $F(1,31) = 125.46$, $p < 0.001$, and Validity, $F(1,31) = 8.51$, $p < .01$, as well as a significant interaction CTOA x Validity interaction, $F(1,31) = 9.91$, $p < 0.005$. The data replicate the validity effect found by Mulckhuyse et al., such that participants have shorter RTs for validly cued trials than for invalidly cued trials, $t(31) = -3.51$, $p < 0.005$. In contrast to Mulckhuyse et al., however, I find no evidence of inhibition of return (IOR) in the long CTOA condition, $t(31) = 0.28$, $p = 0.78$.

These results indicate that there is a significant validity effect in the CTOA range consistent with exogenous attentional cueing. If this effect is driven by unaware exogenous cueing, I would expect to find that participants are unable to localize cue location above a chance level in the cue localization task.

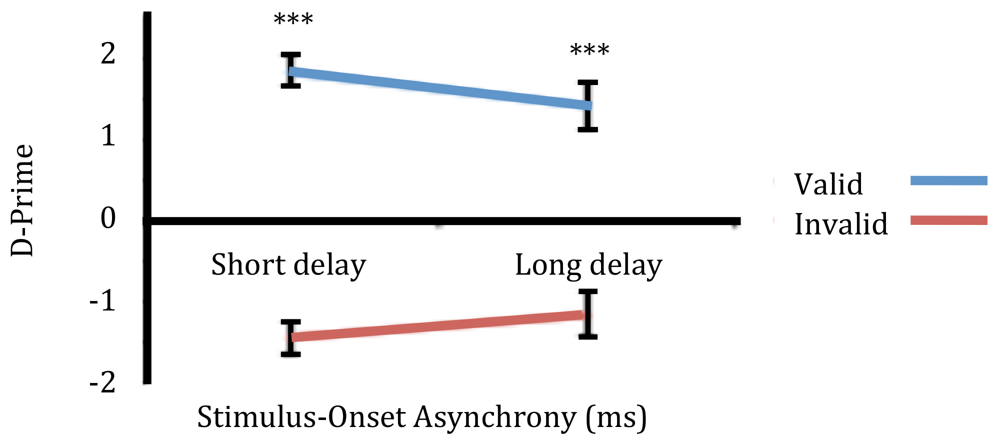
Cue-localization task

Figure 1C shows mean *d'* scores across subjects. *D'* is a measure of sensitivity to a given signal (Tanner & Swets, 1954). A *d'* score of 0 reflects chance performance, or complete perceptual unawareness. Generally, *d'* is calculated by subtracting a normalized measure of false alarmsec—erroneous detections of a signal when no signal is present—from a normalized measure of hits—correct detections of a signal that is actually present. Because this experiment presents a signal at every trial going into the analysis, I arbitrarily chose to consider trials in which participants correctly localized leftmost cues as "hits," and trials in which participants incorrectly said that rightmost cues appeared on the left as "false alarms".

I analyzed the results of the cue-localization task using a mixed-factors repeated measures ANOVA with Cue-Target Onset Asynchrony (2 levels; 16 or 1016 msec), and Cue Validity (2 levels; valid or invalid) as fixed effects. I modeled subject as a random effect. I found a main effect of validity showing that subjects were more likely to correctly localize

Figure 2

A. Reanalyzed cue-localization data, Mulckhuyse & Theeuwes, 2007



B. Reanalyzed cue-localization data, Lin & Murray (2014)

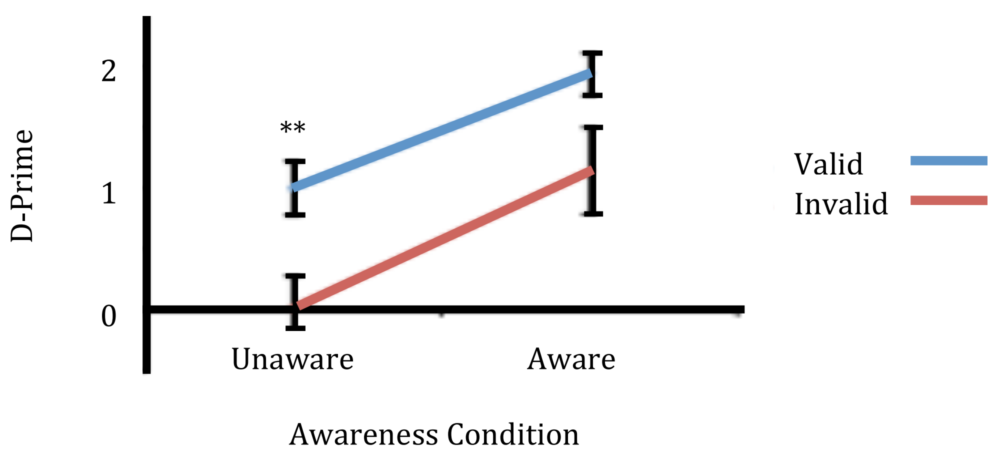


Figure 2. A. Average valid and invalid d’ scores reanalyzed from Mulckhuyse et al. (2007). Error bars are average within-subject standard error. B. Average valid and invalid d’ scores reanalyzed from Lin & Murray (2014), Experiment 1. Error bars are average within-subject standard error.

valid compared to invalid cues, $F(1,32) = 57.58$, $p < 0.001$. I also found a significant interaction between Validity and Cue-Target Onset Asynchrony such that the increased sensitivity to valid cues was restricted to short (16 msec) cue-target onset asynchronies. I ran two t-tests against the null hypothesis that cue-localization sensitivity should be at chance to determine whether the valid or the invalid short CTOAs were driving the effects found in the ANOVA. These tests showed that both the short valid cues (SV) and the short invalid cues (SI) differed significantly from chance, $t(31) = 8.07$, $p < 0.001$ and $t(31) = -4.04$, $p < 0.001$.

Negative *d'* values are theoretically troubling because, taken at face value, they indicate that the noise distribution is more salient than the signal distribution. In other words, negative *d'* values indicate that participants responded at below chance accuracy. One possibility that would yield these results would be if, in the absence of any consciously accessible knowledge of cue locations, participants discounted the instruction to ignore target position and reported that target position gave valid information about cue location. If this were the case, I would expect that, regardless of CTOA and cue validity, subjects would localize the cue to the same side as the target. However, this is not the case. Across CTOA and cue validity, subjects localized the cue to the same side as the target on 30.7% of trials. This indicates that, if anything, subjects were more likely to localize the cue to the side opposite the target. Therefore, it is unlikely that either the SV localization advantage or the SI localization disadvantage is due to an intentional strategy.

Re-analysis of data in existing literature

Given that I hypothesized that differential awareness of valid over invalid cues might be confounded in Mulckhuyse et al.'s experimental design, I reanalyzed the raw cue-localization data from both the original Mulckhuyse et al. (2007) experiment and from Lin & Murray's (2014) Experiment 1 (Figure 2A and 2B). Mulckhuyse et al.'s design differed from mine in Mulckhuyse et al. allowed participants to respond to cue location as soon as the cue was presented, regardless of the CTOA condition. Consequently, I would not expect a difference in their cue localization performance across CTOA conditions. I found that in Mulckhuyse et al., participants in both the short CTOA and long CTOA were able to correctly localize cues at levels significantly above chance, $t(15) = 9.73$, $p < 0.001$ and $t(15) = 4.79$, $p < 0.001$, respectively.

I also reanalyzed Lin & Murray's (2014) cue localization data from their first experiment. Critically, I collapsed their data across all vertical locations according to the validity of the cues. This gave me enough trials to compute *d'* measures, and is justified because their primary point in the experiment is the attentional orienting effect of their cue can travel with apparent motion. Here, I found that in the putatively unaware condition, valid cues were once again localized with above chance accuracy, $t(30) = 4.39$, $p < 0.001$. Taken together, these results indicate that the valid cue-localization sensitivity bias found in my experiment is most likely not a fluke, and, critically, that the validity effects found in these experiments may be caused by cue awareness in the valid condition.

Discussion

Here, I re-instantiated a previously published paradigm and demonstrated that claims of stimulus-driven attention without awareness (Mulckhuyse, Talsma, & Theeuwes 2007; Lin & Murray, 2014) have been based on a naïve analysis of awareness measurements. I demonstrated that participants are aware of putatively suppressed cues when such cues are valid and occur shortly before target onset, and that therefore, reaction time facilitation following short valid cues is not surprising.

This leaves open the question of why participants might be differentially aware of the cues across stimulus conditions. I believe that two factors contribute to such differential cue awareness. First, the cued retinal location receives more stimulus-energy than the two-placeholder locations. In other words, the 16.7 msec lead-time conferred on the cued location is well within the range of linear temporal luminance summation (Bloch, 1885). Because the cue period is immediately followed by the placeholders or placeholders-plus-target screen with no blanking period between the two, the amount of luminance at the cued location sums, leading to greater cortical activation at the cortical location corresponding to the cue's retinal position. When the target is presented at the same location as the cue, the corresponding cortical activation is already near threshold and participants are able to respond more quickly (LaBerge, 1995, 2001; Lamme, 2003). However, when the target is presented opposite the cue, the sudden onset of the target draws stimulus-driven attentional resources away from the primed location (Jonides & Irwin, 1981; Posner, 1980; Posner, Walker, Friedrich, & Rafal, 1984; Yantis & Jonides, 1984), allowing the perceptual trace left by the cue to fade before rising to the threshold of awareness.

Mulckhuyse et al.' assumption that a 16.7 msec delay between the cue and placeholder disk onsets would render the position of the cue inaccessible to awareness may be further flawed due to the temporal dynamics of the visual system. Multiple researchers (Anstis, 1970; Georgeson & Georgeson, 1985; Lappin & Disch, 1972; Smith, Howell, & Stanley, 1982) have demonstrated high temporal resolution within the visual system. Indeed, the temporal resolution of order detection for stimuli that are not defined by inter-stimulus luminance differences is estimated at approximately 20 msec (Hirsh & Sherrick, 1961) and is relatively robust when the visual angle separating the stimuli is between 5º to 20º degrees (c.f. (Westheimer & McKee, 1977); see (Blake & Lee, 2005) for review). My experiment and Mulckhuyse et al.'s (2007) experiment present the cue and placeholder stimuli at a 16.7 msec lag, placing the CTOA just short of the estimated threshold of temporal order resolution. This, in combination with the increased activation at the cued location, may raid the perceptual trace of the short CTOA valid cue above threshold for conscious perception.

Taken together with my critical review of the literature, my findings lead me to conclude that there is currently no compelling evidence that stimulus-driven attention can occur without awareness. One possible reason that I found no compelling evidence for stimulus-driven attention absent cue awareness is that stimulus-driven attentional processing comprises multiple complicated sub-processes; we must rapidly orient to, evaluate, and respond to unexpected environmental stimuli. The predication of any one of these stages on stimulus awareness would render a search for an overall effect of stimulus-driven attention without awareness futile. For instance, Rothkirch et al. (2012) demonstrate that some forms of orienting behavior are not dependent on stimulus awareness. Specifically, the researchers report that observers are biased to look at targets even when observers can only correctly locate target locations at chance level. These results demonstrate goal-directed oculomotor orienting in the objective absence of awareness (Rothkirch et al., 2012). However, the researchers do not then ask subjects to use the information contained in the perceptually suppressed targets to inform a later decision.

These results may extend to the realm of stimulus-driven attention. Perhaps the first stage of stimulus-driven attention (i.e., orienting) can operate independently of stimulus awareness. However, it may be possible the subsequent stages of stimulus-driven attention, specifically evaluation of the stimulus' the behavioral relevance, does depend on knowledge of the stimulus' nature. If that were the case, I would not expect to find an overall reaction time benefit elicited by cues of which observers are completely unaware.

In any event, compelling demonstrations of exogenous attention in the absence of awareness of the stimulus that has elicited the deployment of such attention will depend on researchers evaluating stimulus awareness independently for each cue-condition.

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