Title

Investigating how the modularity of visuospatial attention shapes conscious perception using type 1 and type 2 signal detection theory

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Abstract

Attention abilities rest on the coordinated interplay of multiple components. One consequence to this multifaceted account is that selection processes likely intersect with perception at various junctures. Drawing from this overarching view, the current research examines how different forms of visuospatial attention influence various aspects of conscious perception, including signal detection, signal discrimination, visual awareness, and metacognition. In this effort, we combined a double spatial cueing approach, where stimulus- and goal-driven orienting were concurrently engaged via separate cues, with type 1 and type 2 signal detection theoretic frameworks through five experiments. Consistent with the modular view of visuospatial attention, our comprehensive assessment reveals that stimulus- and goal-driven orienting operate independently of each other for increasing perceptual sensitivity and reducing the decision bound. Conversely, however, our study shows that both forms of orienting hardly influence visual awareness and metacognition once perceptual sensitivity is accounted for. Our results therefore undermine the idea that attention directly interfaces with subjective aspects of perception. Instead, our findings submit a general framework whereby these attention modules indirectly impact visual awareness and metacognition by increasing perceptual evidence and decreasing the decision bound.

Significance Statement

While most scientists agree that attention is not a unitary construct, few theories consider how different components of attention operate alongside each other to shape how we perceive the world. Addressing this shortcoming, the present work provides a comprehensive assessment of the combined influence of voluntary and involuntary orienting of attention on conscious perception. Our results show that both forms of attention operate independently of each other to improve perception and mitigate biases during perceptual decision making. In turn, however, we found that attention hardly influences subjective aspects of perception like visual awareness and metacognition. This outcome challenges the idea that attention shares an intimate relationship with consciousness.

Introduction

Attention reflects the ability to select relevant information from our cluttered environments (Nobre & Kastner, 2014). The need for this selection process arises from important resources limitations that make it impossible for the brain to fully process the barrage of sensory events it constantly encounters. Attention therefore promotes well-adapted behaviors by filtering out irrelevant inputs and boosting relevant ones (Carrasco, 2011). A key tenet that emerges from the extensive literature on this cognitive ability is that selection does not correspond to a unitary process, but instead emerges from the coordinated interplay of multiple functional systems (Awh et al., 2012; Chica et al., 2013; Chun et al., 2011; Corbetta et al., 2008; Corbetta & Shulman, 2002; Knudsen, 2007; Luo & Maunsell, 2018; Petersen & Posner, 2012; Posner & Petersen, 1990; Raz & Buhle, 2006; Wright & Ward, 2008). The capacity to select relevant information therefore comprises multiple components (Fan et al., 2002; Petersen & Posner, 2012; Posner & Petersen, 1990; Raz & Buhle, 2006). This multifaceted view of attention aligns with the emerging field of connectomics, wherein researchers advocate for the idea that the brain is fundamentally organized into anatomical and functional subcomponents (Bullmore & Sporns, 2009; Sporns, 2011, 2013a, 2013b). The ability to select sensory inputs and discard others rests on several such neural systems (Petersen & Posner, 2012). Mounting evidence emphasizes the importance of construing attention in light of this complexity to better understand how it shapes perception (Carrasco et al., 2004; Chica & Bartolomeo, 2012; Chica et al., 2016; Chica, Botta, et al., 2012; Chica et al., 2010; Chica, Paz-Alonso, et al., 2012; Colás et al., 2018; Kusnir et al., 2011). In sum, the notion that attention divides into functional units is paramount for elucidating the brain’s capacity to efficiently select relevant information.

Drawing from this general framework, the present collection of experiments evaluates this multifaceted account across different aspects of perception, including signal detection and discrimination, visual awareness, and metacognition. Our goal is to evaluate how distinct functional systems of visuospatial attention – namely stimulus- and goal-driven orienting – intersect with these components of perception. Our study builds from ongoing efforts to uncover the dynamics that characterizes these different forms of attention (Belopolsky et al., 2010; Berger et al., 2005; Blair & Ristic, 2018; Chica et al., 2013; Chica, Botta, et al., 2012; Chica et al., 2006; Egeth & Yantis, 1997; Folk & Remington, 1999; Folk et al., 1992; Godijn & Theeuwes, 2002; Leber & Egeth, 2006; Ogawa & Komatsu, 2004; Ristic & Kingstone, 2006, 2012; Ristic & Landry, 2015; Ristic et al., 2012; Schreij et al., 2008; Theeuwes, 2004, 2010; Yantis & Jonides, 1990). Our approach leverages type 1 and type 2 signal detection theory (SDT) across target detection and discrimination tasks to provide a comprehensive account of the influence of stimulus- and goal-driven orienting on conscious perception.

Stimulus- versus Goal-driven Attention

Researchers often characterize visuospatial attention as a dichotomy, where stimulus-driven attention corresponds to involuntary orienting responses following a salient event and goal-driven attention reflects voluntary shifts of attention resources (Jonides, 1981; Posner, 1980). In the lab, both forms of orienting are often operationalized through the spatial cueing paradigm - an experimental approach based on attentional cues that precede the onset of a target event and where the features of the cue determines the orienting response (Chica et al., 2014). Previous work establishes that presenting salient cues at the periphery of the visual field elicits stimulus-driven attention, even when the cues are made non-informative about the target’s potential location (Schreij et al., 2008). Salient events therefore trigger an orienting response despite being task-irrelevant, a fact which alludes to the automaticity of stimulus-driven attention. In contrast, informative symbolic cues presented centrally yield goal-driven responses as participants voluntarily guide their attention based on the information conveyed by the cue (Olk et al., 2014). This experimental procedure enables researchers to study each orienting system separately by varying cue features. Critically, this paradigm operationalizes attention processing by comparing cued and uncued trials, which highlights the perceptual gain of visuospatial orienting through facilitation effects and heightened sensory responses (Jonides, 1981; Luck et al., 2000; Müller & Rabbitt, 1989; Posner, 1980).

The characterization of stimulus- and goal-driven attention thrives primarily on distinct modes of control between involuntary versus voluntary orienting, respectively. This dichotomy brings about the possibility to frame stimulus- and goal-driven orienting as separate functional modules of visuospatial attention. The notion of modularity refers to the emergence of components that exhibit a high degree of differentiation along various dimensions within complex systems (Barrett & Kurzban, 2006; Newman, 2006). Consistent with this notion, the modular view of visuospatial attention draws upon a large body of findings that emphasize pivotal functional differences between stimulus- and goal-driven orienting (Chica et al., 2013). Modularity therefore supplies researchers with a useful framework to understand their dynamics, both from a psychological and a neuroscientific perspective, while keeping in mind that stimulus- and goal-driven attention perform the same function, namely the selection of relevant information. One important distinction between them concerns their respective temporal profiles, wherein stimulus-driven orienting deploys and disengages rapidly, while goal-driven orienting emerges gradually and exhibit the capacity to stay engaged for an extended period of time (Müller & Rabbitt, 1989). These contrasting temporal profiles match the quick reflexive responses of stimulus-driven attention on the one hand, and the slower more deliberate shifts of goal-driven attention on the other (Egeth & Yantis, 1997). Another important difference pertains to the interference of secondary information processing on goal-driven attention (Jonides, 1981) – a feature that reflects resource limitation during the voluntary control of attention (Buschman & Kastner, 2015; Katsuki & Constantinidis, 2014; Knudsen, 2007; Noudoost et al., 2010). Critically, a different kind of resource limitation has been found to impair stimulus-driven attention (Lavie et al., 2004). Likewise, some findings show a double dissociation between the effects of stimulus- and goal-driven cueing, which serves to further underline the divide between them (Funes et al., 2007). Altogether, a large body of research supports the idea that both forms of orienting correspond to distinct functional modules that operate through separate means (for a review, see Chica et al., 2013).

Questions that follow from this dichotomy concern the levels of independence, cooperation, and interference between these orienting modules. Despite compelling evidence about their functional differences, some findings highlight circumstances where the modularity of visuospatial attention breaks down (Egeth & Yantis, 1997; Hopfinger & West, 2006; Ruz & Lupiáñez, 2002). Along those lines, the contingent capture hypothesis posits that stimulus-driven attention rests on top-down processes and that task sets determine the emergence of the reflexive orienting response (Folk & Remington, 1999; Folk et al., 1992). Proponents of this viewpoint accordingly argue that salient events only elicit stimulus-driven responses when they harmonize with the overarching goals and intentions of individuals. In other words, mental processes typically linked to goal-driven orienting are made critical for the emergence of stimulus-driven orienting. In the same vein, some reports indicate that factors pertaining to goal-driven orienting modulate the capture of stimulus-driven attention via salient events (Müller & Rabbitt, 1989; Theeuwes, 1991; Yantis & Jonides, 1990). Note that other work submits opposing results and instead argues that stimulus-driven orienting rests solely on the automatic capture of attention resources (Theeuwes, 1992, 2004). Beyond these ongoing debates about the role of top-down factors in stimulus-driven orienting, the literature highlights instances where these different forms of attention orienting interact with one another, along their temporal dynamics (Grubb et al., 2015; Hopfinger & West, 2006) or in context of greater task difficulty (Berger et al., 2005). These findings demonstrate that certain experimental contexts can weaken the functional modularity of visuospatial orienting, which raises important questions about their dynamics.

The double cueing experimental approach tackles this line of inquiry by engaging both attention systems concurrently - each via a different cue (Berger et al., 2005). In this way, a peripheral abrupt onset engages stimulus-driven orienting, while a concomitant central symbolic cue prompts goal-driven orienting (see Figure 1). Relying on different cues allows for comparisons of isolated and joint effects of these orienting systems, and ultimately assess their interaction. The current study rests on this experimental strategy to investigate the dynamics of stimulus- and goal-driven attention across different facets of conscious perception. Our approach further rests on type 1 and type 2 SDT to ascertain these patterns. This analytical framework proceeds from two sorts of measure (Fleming & Lau, 2014; Macmillan & Creelman, 2005; Maniscalco & Lau, 2012, 2014): (1) An objective response, coined type 1 response, to assess task performance during detection, discrimination or identification of a target stimulus; and (2) subjective judgments of perception, labelled type 2 response, where participants report certain aspects of their phenomenology with respect to perception based on their introspection (Timmermans & Cleeremans, 2015). SDT represents a formidable tool for examining type 1 and type 2 responses because it allows for the estimation of perceptual and introspective sensitivity (i.e., the relationship of signal to noise) independently from response biases (i.e., liberal or conservative stance with respect to the amount of evidence that underlie responses tendencies). In this fashion, while *d'* estimates perceptual sensitivity, *meta-d'* corresponds to introspective sensitivity in terms of type 1 sensitivity parameter that would lead to the observed type 2 responses assuming that the observer uses the same information for producing type 1 and type 2 responses. In other words, *meta-d'* reflects the degree to which subjective judgments predict task performance independently from biases. Previous work highlights the reliability of this approach for accurately gauging introspective access to internal information by comparing *meta-d'* to *d'* since both estimates rest on the same scale; this comparison produces an index called M-Ratio (Barrett et al., 2013). Thus, when the *meta-d'* over *d* ratio (i.e., M-Ratio) equals 1, the model indicates that individuals make optimal use of perceptual sensitivity (i.e., d') to make subjective judgments. This approach also provides an estimation of response bias and subjective uncertainty based on type 1 and type 2 criteria, respectively. Hence, researchers can determine whether performance and subjective judgments result from changes in sensitivity or some form response bias. *d’* and *meta-d’* typically correlate positively, which implies that perceptual evidence impacts introspective sensitivity in a manner that allows individuals to make use of the information available to form their subjective judgments (e.g., Kepecs et al., 2008). However, despite the strong bond between perceptual and introspective sensitivities, previous work highlights experimental conditions where we can observe a dissociation between them (e.g., Lau & Passingham, 2006; however, see Peters & Lau, 2015). This dissociation suggests that type 1 and type 2 responses follow from distinct processes, rather than a single channel (Maniscalco & Lau, 2016; Rausch et al., 2018; Rausch & Zehetleitner, 2017). The present study proceeds from this framework to examine whether stimulus- and goal-driven orienting modulates these different components of perception and tests whether we can observe a similar dissociation as a function of visuospatial attention. Furthermore, our experiment will determine whether both forms of orienting operate independently or interactively at these levels of perceptual processing. Our experimental approach additionally uses a masking procedure so as to avoid floor and ceiling effects (Breitmeyer & Ögmen, 2006).

Our study addresses ongoing disputes regarding the role of attention in consciousness (Montemayor & Haladjian, 2015). Based on the SDT framework, a large body of research confirms the impacts on stimulus- and goal-driven attention on perceptual evidence and the decision bound (Carrasco, 2011; Hawkins et al., 1990; Luo & Maunsell, 2018; Rahnev et al., 2011). In turn, however, there is some contention in the field as to whether attention directly influences the subjective level of perception. Given the strong link between perceptual and introspective sensitivities, the influence of attention on the former likely impacts the latter. Still, the current study aims to determine whether attention enhances the subjective component of perception beyond that of task performance. Type 2 SDT is designed to tackle this inquiry, whereby the observation that stimulus- and goal-driven attention increases M-Ratio would imply that these forms of orienting directly interface with subjective components of perception.

The idea that attention is a prerequisite to conscious perception is quite prevalent (Cohen et al., 2012; De Brigard & Prinz, 2010; Dehaene et al., 2006; O'Regan & Noë, 2001; Posner, 1994, 2012). This view mainly follows from evidence showing that individuals typically remain unaware of unattended events (Jensen et al., 2011; Mack, 2003; Mack & Rock, 1998; Most, 2010, 2013; Most et al., 2005; Most et al., 2000; Raymond et al., 1992; Shapiro et al., 1997; Simons, 2000; Simons & Chabris, 1999; Simons & Levin, 1997). In contrast, certain findings intimate that attention and awareness reflect orthogonal processes (Brascamp et al., 2010; Koch & Tsuchiya, 2007; van Boxtel, 2017; van Boxtel et al., 2010a; van Boxtel et al., 2010b; Watanabe et al., 2011; Wyart et al., 2012; Wyart & Tallon-Baudry, 2008). Thus far, evidence from the spatial cueing procedure remains agnostic relative to these ongoing disputes. While some studies argue favorably for the primacy of goal-driven orienting (Kurtz et al., 2017; Vernet et al., 2019; Zizlsperger et al., 2012), others instead promote the centrality of stimulus-driven orienting (Chica, Botta, et al., 2012; Chica et al., 2011; Chica et al., 2010), or even favor both forms of orienting (Hsu et al., 2011). Conversely, some studies report that attention hardly influence subjective reports of perception beyond task performance and therefore undermine the attention view of consciousness (Wilimzig et al., 2008; Wyart et al., 2012; Wyart & Tallon-Baudry, 2008). Methodological and analytical differences likely account for this heterogeneous landscape. In particular, few assays control for potential biases that might plague type 2 responses. Thus, variations in subjective reports following visuospatial attention could in fact result from variations of the decision bound (Peters et al., 2016). Previous work strongly alludes to this possibility (Rahnev et al., 2011). The present work proceeds from these disputes and aims to overcome ambivalence regarding the influence of stimulus- and goal-driven attention employing the double cueing approach to tease apart the respective influence of each orienting form, while also addressing caveats relative to response biases using type 2 SDT.

Experimental Predictions

Our overarching goal is to evaluate the modularity of stimulus- and goal-driven orienting across objective and subjective dimensions of perception. In this way, a statistically reliable interaction between both forms of orienting would specify that the combined synergy between them differs from the sum of their isolated effects - a pattern that would reflect a breakdown of modularity. Conversely, the absence of an interaction would support the modular view of visuospatial attention by promoting that the combined effect of stimulus- and goal-driven attention likely corresponds to the sum of their isolated effect. Note that these interpretations assume that main effects for each form of orienting are statistically reliable.

Experiment 1 and 2

Methods

Participants. We recruited 28 and 37 participants for our first and second experiment, respectively. Each participant reported normal or corrected-to-normal vision. They received monetary compensation of $10/hour CAD for two two-hour sessions of 1536 trials each. Participants completed both sessions on different days. Each session comprised 8 blocks of 192 trials. Before each session, participants completed a series of 10 practice trials until they confirmed understanding the task. All procedures were approved by the local ethics review board.

We reasoned that sample size estimations should be considered in light of the effects of stimulus- and goal-driven attention on perceptual sensitivity. Thus, in order to properly examine our hypotheses, we determined that the sample should allow for perceptual facilitation to occur following both stimulus- and goal-driven spatial cueing. However, in the near absence of specific information regarding the effect size estimates for our methodology, we considered experiment 1 to be exploratory and based our sample size on previous experiments (see the following report for effect size estimations; Chica et al., 2014). Here, we conducted apriori power analyses for repeated measures F-tests on cueing effects for response times in the context of target discrimination tasks using G*Power3 (Faul et al., 2007). Our goal was to determine the sample size for facilitation effects of stimulus- and goal-driven orienting. At long cue-target latencies (i.e., > 500ms), a central predictive cue merely requires 6 participants to achieve a power of .8 following the large effect size observed in previous work (η^2 = .34) and an alpha of .05. Likewise, at short cue-target latencies (i.e., < 300ms), a peripheral non-predictive cue only requires 3 participants to achieve a power of .8 following a large effect size (η^2 = .84). Based on this information, and again to ensure proper evaluation of our hypotheses, our recruitment for experiment 1 was four folds greater than our estimations of goal-driven orienting and nine times greater than that of stimulus-driven orienting (Chica et al., 2014).

We determined the sample size for experiment 2 from the results of experiment 1 using hierarchical linear regression modelling through the lme4 package (Bates et al., 2015) and simulations from the SIMR package (Green & MacLeod, 2016) in R Studio (RStudio-Team, 2020). Consistent with our previous assessment, simulations revealed that 6 participants were required to achieve a power of .8 relative to the effects of stimulus- and goal-driven attention on discrimination performance when alpha was set to .05. In this regard, we observed somewhat of a large effect size when fitting both effects, *Marginal* R^2_{GLMM} = .23. (Barton & Barton, 2019; Nakagawa & Schielzeth, 2013). Having confirmed that the sample size was reliable for detecting the effects of stimulus- and goal-driven orienting, we opted for a sample size that would match that of experiment 1. Lastly, we maximized power to better assess our hypotheses by pooling data from both experiment 1 and 2. Note that our findings nevertheless replicated separately across both experiments (see supplementary material).

Three participants were excluded in each experiment due to self-attrition. We additionally excluded five participants from experiment 1 and ten from experiment 2 based on the following criteria: Elevated (> 15%) rates of either anticipation errors (Response Time < 150ms), timeout errors (Response Time >

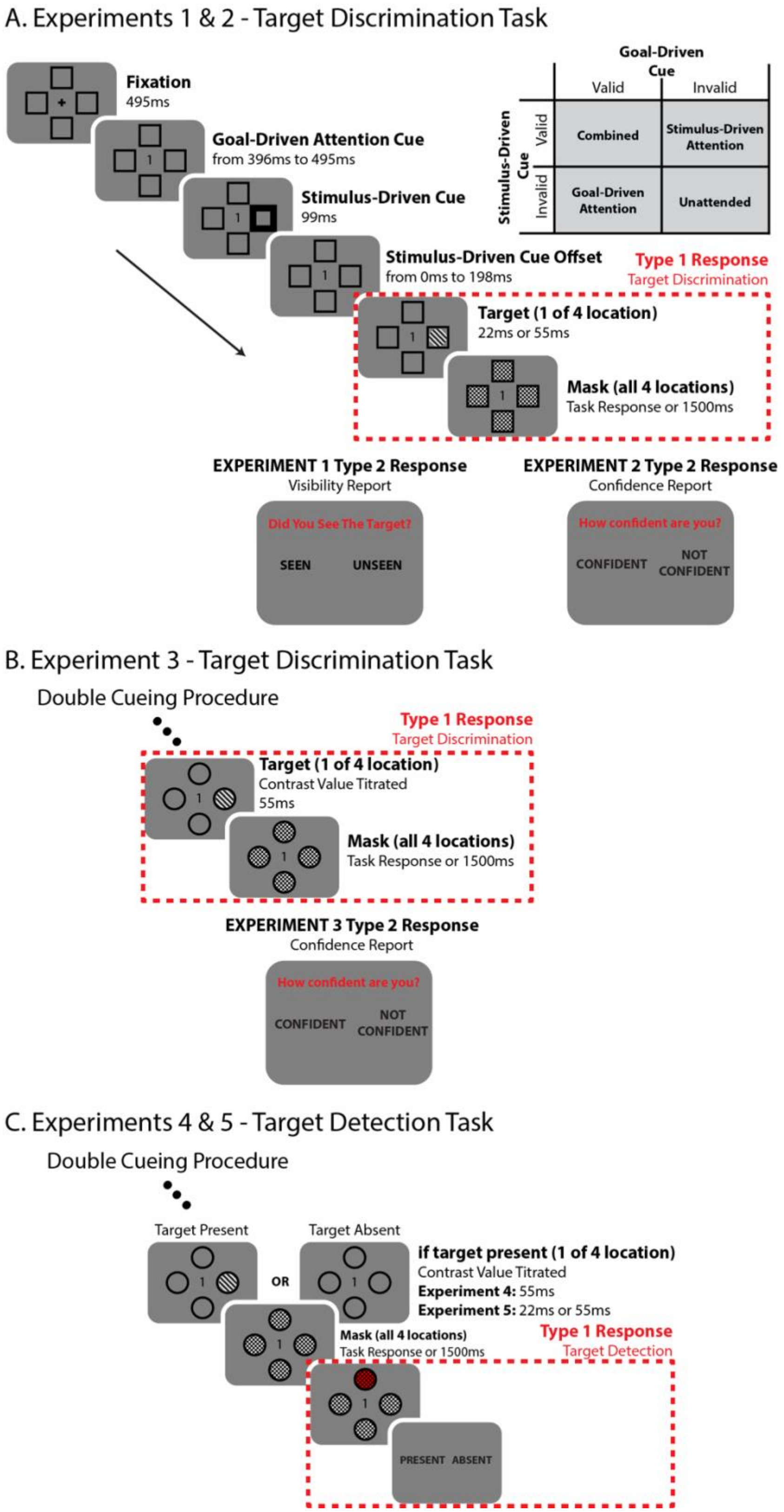
1500ms), or wrong key pressed, as well as below chance performance (< 50% accuracy), or implausible subjective report (e.g., 100% seen target). Specifically, four exclusions followed from elevated anticipation errors and one due to implausible number of seen target events in experiment 1. In turn, all ten excluded participants from experiment 2 showed elevated anticipation errors. Three of those individuals already excluded due to anticipation errors also showed elevated numbers of wrong key presses and poor discrimination accuracy. 20 participants (15 adult females; age: M = 21 y.o., SD = 1.23) were kept for experiment 1 and 24 (15 adult females; age: M = 20.54 y.o., SD = 2.36) for experiment 2. We deemed it important to remove time out errors because these responses potentially involve additional perceptual processing that may hurt the generalizability of our findings. The elevated number of exclusions we report here pose a threat to future replications. In this regard, a few participants reported that the task was particularly tedious, which could explain the pattern we observed with respect to exclusion.

Apparatus and Stimuli. All participants viewed the task on a 17.5-in CRT monitor (ViewSonic Graphics Series G90fB) sitting approximately 60 cm away. We used Psychtoolbox-3 and MATLAB (Mathworks inc. version R2015a) to display the stimuli. The screen was set to 85hz. All stimuli were made from black lines (i.e., RGB values of 0, 0, 0; 1.0 cd/m^2) against a grey background (i.e., RGB values of 128, 128, 128; 21.8 cd/m^2) except for the target gratings. The targets were circular gratings (i.e., 3° of visual angle) of alternating parallel lines (3 cpd) of black (RGB values of 0, 0, 0) and white (RGB values of 255, 255, 255; 158.3 cd/m^2) with a oriented clockwise or counter-clockwise, wherein the orientation of the targets ranged from 15° to 30° in steps of 5° degrees. However, the current analyses did not include this factor. All four target locations were marked by boxes subtending 3° of visual angles, each situated 3° of visual angle away from fixation at one of the four cardinal points. Arabic numbers “1”, “3”, “6” and “9” (i.e., 2° by 1.5° of visual angles) served as cues for goal driven attention. Note that symbolic number cues do not elicit a pure form of goal-driven orienting. This limitation follows from prior knowledge of numerical concepts and their relation to spatial representations where numbers can prompt automatic orienting responses consistent with the number line or the spatial location of numbers within clocks (e.g., the number 6 situated at the bottom of the clock; Ristic et al., 2006). It seems reasonable to assume that such numerical prior knowledge contributed to the orienting response here. We nevertheless opted for this option to engage goal-driven attention given the difficulty of the task, as the number cues were easier to process with respect to four target locations. Conversely, we cued stimulus-driven attention by briefly changing the line drawing from one of the placeholders to white. The backwards mask consisted of checkerboard patterns comprising 10 by 10 white and black squares, each mask subtended 2° visual angle.

Design. Participants viewed both cues on each trial, which entails that goal-driven and stimulus-driven attention systems were engaged throughout the experiment. Consistent with previous studies relying on a double cueing approach (see Figure 1), we presented goal-driven and stimulus-driven cues at different latencies, wherein the target would onset within a time-window corresponding to the maximal efficiency of each system (Chica et al., 2014). Number cues were predictive of the target's location, whereby the number "1" indicated that the target was 62.5% likely to onset at the top location, the number "3" indicated that the target was 62.5% likely to onset rightward, the number "6" indicated that the target was 62.5% likely to onset to the bottom location, the number "9" indicated that the target was 62.5% likely to onset leftward. The number cues were therefore task-relevant. To ensure that this peripheral cue solely engaged stimulus-driven attention, the cue-target spatial contingency was set to 25%, such that the cue was not predictive of the target's location. The experimenter informed participants about cue-target contingencies. Hence, participants were asked to guide their attention according to the number cue, while discounting the peripheral cueing event.

Critically, given cueing contingencies, sometimes both cues would indicate different target locations, other times the same location. Thus, the mixture of cueing conditions and target locations produces a two-by-two factorial albeit imbalanced design, comprising stimulus-driven (i.e., valid versus invalid) and goal-driven attention (i.e., valid versus invalid; see Figure 1). For both sessions, this task comprised 864 trials where both cues were invalid, 288 trials where the stimulus-driven cue was valid and the goal-driven cue was invalid, 1440 trials where the stimulus-driven cue was invalid and the goal-driven cue was valid, and 480 trials where both cues were valid. Our approach also relied on two distinct target-mask latencies to explore cueing effects across varying levels of signal strengths. Cueing conditions and masking latency were mixed within blocks. Cue direction and target position were equally spread across all four locations. For each trial, participants were required to input a type 1 discrimination responses by pressing the “F” key with their left index finger or “J” key with right index finger to subsequently indicate the orientation of the target. Thereafter, participants also specified a type 2 subjective report regarding target events pressing the “F” key with their left index finger or “J” key with right index finger. While type 1 responses were identical for both experiments, type 2 responses were different. For experiment 1, participants indicated whether they consciously saw the target event or not. Specifically, participants were explicitly instructed to indicate whether they had a conscious experience of seeing the target event or not. For experiment 2, they indicated whether they were confident about the response they just provided. Input keys for “Seen” and “Unseen” options, as well as “Confident” and “Not Confident”, were counterbalanced across participants.

Procedure. Every trial began with a fixation cross for 495ms, followed by the onset of a goal-driven cue at the center with its latency randomly jittered between 396 and 495ms. The stimulus-driven cue would then onset and remained on the screen for 99ms. The target appeared after a random variable delay from 0ms to 198ms. We used a uniform distribution for random latencies. Therefore, the goal-driven cue-target onset asynchrony varied between 495ms and 792ms, while the stimulus-driven cue-target onset asynchrony varied between 99ms and 297ms. The target would onset in one of the four target locations and was then subsequently masked. Target-mask onset asynchrony were 22ms and 55ms. The goal-driven cue and mask remained on the screen for 1991ms or until the participant inputted their discrimination responses relative to the target orientation. Next, a screen prompted participants to provide their subjective responses. The words “*Seen*” and “*Unseen*” for experiment 1, or “*Confident*” and “*Not Confident*” for experiment 2, appeared for 2970ms or until the participant responded a second time. The location of each word mapped onto the keys for the type 2 responses, wherein leftward location corresponded to the “F” key and the rightward location the “J” key. Participants were asked to fixate at the center of the screen throughout the experiment and input both type 1 and type 2 responses as quickly and accurately as possible.



Stimulus-Driven Cue	Goal-Driven Cue: Valid	Goal-Driven Cue: Invalid
Valid	Combined	Stimulus-Driven Attention
Invalid	Goal-Driven Attention	Unattended

Figure 1. Experimental design. We used a two-by-two double cueing experimental approach across all five experiments, involving stimulus-driven attention cueing (valid vs. invalid) by goal-driven attention cueing (valid vs. invalid). A stimulus-driven and a goal-driven cue preceded the target event, while checkerboard pattern masked all four target locations thereafter following 22ms or 55ms. See methods for detail. **A.** In Experiments 1 & 2, we instructed participants to discriminate the orientation of the grating target (i.e., clockwise vs. counterclockwise). Next, we asked them to report visual awareness of the target event in Experiment 1 (i.e., seen vs. unseen), and confidence judgments about task performance in Experiment 2 (i.e., confident vs. not confident). **B.** In Experiment 3, we again instructed participants to discriminate the orientation of the grating target (i.e., clockwise vs. counterclockwise) and then provide confidence judgments about task performance. Masking latency was fixed at 55ms. Note that we titrated the contrast value of the Gabor stimuli across attention conditions following the QUEST algorithm. The purpose was to equate performance across attention conditions, and then evaluate the direct influence of attention on confidence judgments following stimulus- and goal-driven cueing **C.** In experiment 4 and 5, we combined the double cueing experimental approach with a detection task, where the target event occurred for only half of the trials. The masking latency was set to 55ms in Experiment 4, and then 22ms and 55ms in Experiment 5. We instructed participants to indicate whether a target event had occurred (i.e., present vs. absent) at the probed location, wherein one of the masks turned red to probe a specific location.

Analysis. We pooled type 1 responses from experiment 1 and experiment 2 together. Likewise, for type 2 responses. We opted for this approach because results from each experiment separately were identical (see supplementary material).

Discrimination Responses – Type 1 Responses - Signal Detection Theory. We used signal detection theory to assess discrimination performance (Macmillan & Creelman, 2005). For type 1 responses, estimations of perceptual sensitivity *d’* and decision criterion C is computed through a direct analytic solution:

$$d' = z(\text{hit rate}) - z(\text{false alarm})$$
$$C = -0.5 * (z(\text{hit rate}) + z(\text{false alarm}))$$

where z represents the inverse of the cumulative normal distribution. Note that in simple target discrimination tasks the hit rate is defined as the correct response when the corresponding stimulus is displayed on screen (e.g., responding clockwise to clockwise stimulus), while false alarm rates is defined as the incorrect response when the other stimulus is displayed (e.g., responding clockwise to counterclockwise stimulus; Macmillan & Creelman, 2005). We applied the following correction ((2*N)-1)/(2*N), where N equals the number of trials, whenever hit rate was equal to 1; and 1/(2*N) whenever false alarm was equal to 0 (Macmillan & Creelman, 2005). Three percent of cells required such corrections.

Inferential statistics were done through hierarchical regression modelling (Gelman & Hill, 2006), as implemented by the lme4 package (Bates et al., 2015) in R Studio (RStudio-Team, 2016). Goodness-of-fit was determined in a stepwise fashion using chi-square tests. We also informed model selection using Bayesian information criterion (BIC). We estimated the effect size for the best fitting model by calculating the marginal R^2 using the MuMln R package (Barton & Barton, 2019; Nakagawa & Schielzeth, 2013) We additionally evaluated the reliability of the null hypothesis for the absence of an interaction between stimulus-driven and goal-driven cue validity by estimating Bayes factor (i.e., $Pr(data|H_0/Pr(data|H_1))$ using the BIC (Wagenmakers, 2007) following the following equation:

$$BF_{01} = e^{\Delta BIC_{10}/2}$$

Subjective Judgements – Type 2 Responses – HMeta-d. We similarly relied on the signal detection theoretic framework to assess type 2 responses in order to estimate efficacy for subjective reports across attention conditions (Maniscalco & Lau, 2012, 2014). However, contrary to type 1 SDT, the estimation of parameters for type 2 SDT does not follow from a straightforward solution and instead requires for researchers to fit estimates over the probability of being confident given a stimuli events and discrimination responses. Here, we used HMeta-d, a MATLAB toolbox (Mathworks inc. version R2017a; note that the toolbox is also available in R) designed to estimate type 2 SDT parameters at the group-level, while taking into account subject-level uncertainty, through the exploration of parameters spaces via Bayesian statistics and Markov-Chain Monte-Carlo (MCMC) sampling strategy as implemented in JAGS (Plummer), as well as given the specifications of the model and the data (Fleming, 2017; https://github.com/metacoglab/HMeta-d). This analytic approach provides statistical inference through Bayesian computations of posterior densities that estimate parameters values for type 2 SDT, including type 2 responses efficiency, herein the log of M-Ratio (i.e., log (meta-d’/d’)). Furthermore, we extended this analytic strategy to estimate parameter values of linear regression models for examining how stimulus-driven attention, goal-driven attention, and their interaction predict log M-Ratio. We included these beta parameters in a stepwise fashion through different models. Note, however, that we performed this analysis separately for early (i.e., 22ms) and late (i.e., 55ms) masking latency to avoid appending additional parameters and hurting the interpretation due to the complexity of the models. This approach was consistent with hypothesis for type 2 SDT and the influence of attention on conscious perception. Although we compared the different models based on deviance information criterion (DIC), we nevertheless examined the full models across both masking latencies:

Log M-Ratio ~ β0 + β1[Stimulus-Driven cue validity] + β2[Goal-Driven cue validity] + β3[Stimulus-driven cue validity **X** Goal-driven cue validity]

Parameter estimation relied on 3 MCMC chains of 100,000 samples with burn-in of 1000 samples and thinning of 10 samples, while using the standard prior values from the toolbox. We evaluated convergence of the model by inspecting MCMC chains and by ensuring that the Gelman-Rubin diagnostic metrics (R-hat) were below 1.1 for all parameter estimations (Gelman & Rubin, 1992). We used the 95% high-density interval (HDI) from the posterior samples to assess the parameter estimates (Kruschke, 2015). We used the same approach to evaluate how stimulus- and goal-driven orienting operate at the level of the Type 2 criteria (see supplementary material).

Results

Objective performance (type 1 response) in experiment 1 and 2. Following the target discrimination task, we computed SDT estimates for each participant across the masking and attention conditions, and then relied on hierarchical linear regression modelling to evaluate the influence of each experimental variable. Our step-wise approach to determine the best fitting model first included masking latency (i.e., early and late), then stimulus-driven attention (i.e., valid and invalid), followed by goal-driven attention (i.e., valid and invalid), as well as their interactions as fixed factors, with subjects as random factors.

Our results are consistent with the modular view of visuospatial attention where both stimulus- and goal-driven orienting influenced perceptual sensitivity across both masking latencies yet did not interact (Figure 2). According to our stepwise approach, the best fitting model (see Tables 1 and 2 in supplementary material; *Marginal* $R^2_{GLMM} = .46$) conveys that masking latency ($\beta = 0.82$, SE = 0.11, 95% CI [0.61, 1.04]), stimulus-driven cue validity ($\beta = 0.55$, SE = 0.09, 95% CI [0.38, 0.73]), goal-driven cue validity ($\beta = 0.96$, SE = 0.09, 95% CI [0.78, 1.13]), and masking latency by goal-driven cue validity interaction ($\beta = 0.31$, SE = 0.13, 95% CI [0.06, 0.56]) represent reliable predictors. Thus, all three variables improved discrimination performance, while the benefits of goal-driven increases slightly for the longer masking latency. Critically, the full model comprising the interactions between stimulus-driven cue validity and goal-driven cue validity, as well as the three-way interaction between masking latency, stimulus-driven cue validity, and goal-driven cue validity, failed to improve the fit of the data ($\chi^2(2) = 1.67$, $p = 0.434$). Here, the stimulus-driven cue validity by goal-driven cue validity two-way interaction ($\beta = -0.12$, SE = 0.18, 95% CI [-0.47, 0.23]) and the masking latency by stimulus-driven cue validity by goal-driven cue validity three-way interaction ($\beta = -0.07$, SE = 0.25, 95% CI [-0.57, 0.42]) both proved statistically unreliable predictors (see Figure 2). Evidence therefore indicates that stimulus- and goal-driven orienting operate separately in boosting the perceptual signal. We further evaluated this hypothesis by assessing evidence favoring the null hypothesis (i.e., the best fitting model) versus the alternative hypothesis (i.e., the best fitting model with the stimulus-driven by goal-driven two-way interaction, and again with the three-way masking latency by stimulus-driven by goal-driven interaction) using Bayes factors. This analytical strategy weights both hypotheses against the data and provides additional information for interpreting null findings (Aczel et al., 2018). Our results favored the null hypothesis in both cases, wherein the analyses returned $BF_{01} = 8.5$ when we included the stimulus-driven by goal-driven two-way interaction in the alternative model, and BF_{01} = 10.23 when we included the masking latency by stimulus-driven by goal-driven three-way interaction in the alternative model. Note that we corroborated these results for experiment 1 and 2 separately (see Tables 3 and 4 in supplementary material). We similarly assessed the decision criterion parameter of the SDT model. The best model solely involved masking latency as a predictor (see Tables 5 and 6 in supplementary material; β = -0.06, SE = 0.03, 95% CI [-0.11, -0.004]; *Marginal* R^2_{GLMM} = .003).

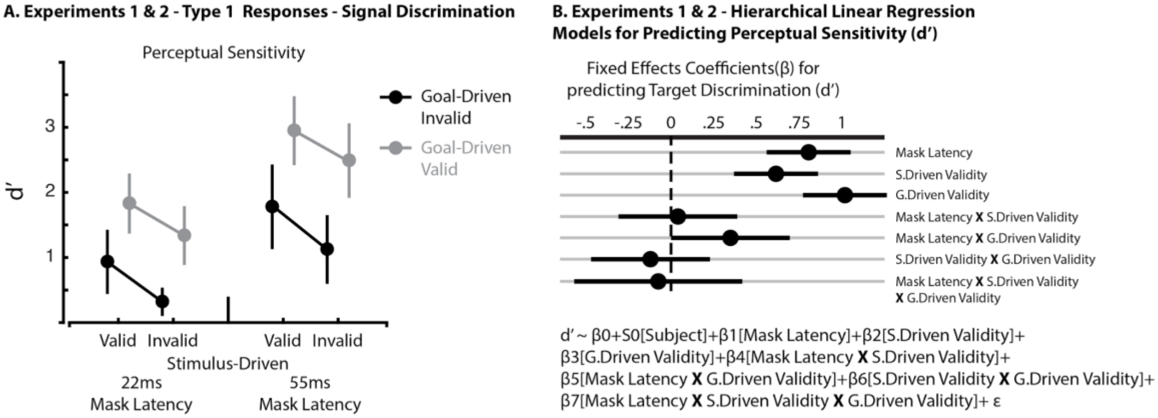


Figure 2. Type 1 signal detection analysis for the discrimination response in Experiment 1 and 2. A. Averaged perceptual sensitivity estimates (d') across stimulus- and goal-driven cueing through 22ms and 55ms masking latencies. **B.** We fitted hierarchical linear regression models to predict perceptual sensitivity (d') and therefore evaluate the effects of stimulus- and goal-driven attention, as well as masking latencies. Here, we plot fixed effects β parameters of the full model. Error bars represent 95% CI.

Note that we also evaluated median correct response times and found no evidence of a speed-accuracy tradeoff (see Supplementary Figure 1; Tables 7 and 8 in supplementary material).

*Subjective judgments (type 2 responses) for experiment 1 and 2***.** The assessment of M-Ratio through hierarchical Bayesian modelling revealed the limited influence of attention processing on subjective judgments of perception. Visual assessment of the MCMC samples and Gelman-Rubin diagnostic (i.e., R-Hat < 1.1) confirmed convergence of the models (see supplementary Figure 3). The DIC varied marginally across models for both early and late masking latencies (Figure 3), which entails that more complex models failed to improve the fit compared to the baseline model (Spiegelhalter et al., 2002). Here, we observe that the 95% HDI of the posterior densities for the beta estimates in the full models encompassed zero across early and late masking latencies (Figure 3). For early mask latency, the intercept of the model conveyed that the M-Ratio approximated 1 for the unattended condition as (μ of β0 = 1.14, 95% HDI [.94 1.36]), which indicates that participant based their subjective judgments on the perceptual information available regardless of attention processing. Note that, since our attention variables were dummy coded, the intercept estimates the M-Ratio at baseline (i.e., the unattended condition). Importantly, both stimulus-driven and goal-driven attention failed to improve M-Ratio (μ of β1[Stimulus-Driven Cue Validity] = -.002, 95% HDI [-.263 .261]; μ of β2[Goal-Driven Cue Validity] = -.014, 95% HDI [-.225 .196]), while their interaction was also statistically unreliable (μ of β3[Stimulus-Driven Cue Validity **X** Goal-Driven Cue Validity] = -.0195, 95% HDI [-.341 .281]). We observed a similar pattern for the late masking latency, although participants showed a marginal benefit of the M-Ratio at baseline (μ of β0 = 1.21, 95% HDI [1.08 1.34]). Again, however, we observed that stimulus- and goal-driven orienting failed to improved type 2 response sensitivity (μ of β1[Stimulus-Driven Cue Validity] = .011, 95% HDI [-.145 .167]; μ of β2[Goal-Driven Cue Validity] = .096, 95% HDI [-.035 .228]); and likewise for the interaction parameter (μ of β3[Stimulus-Driven Cue Validity **X** Goal-Driven Cue Validity] = -.014, 95% HDI [-.211 .179]). Plotting the corresponding estimated averaged M-Ratio per conditions across each participant corroborated our assessment and revealed little variations across attention conditions (see Figure 3). Note that we observe the same results for experiment 1 and experiment 2 separately (see supplementary Figures 4 and 5). Altogether, our type 1 and type 2 SDT analyses demonstrate how visuospatial orienting of attention fails to increase introspective sensitivity beyond that of perceptual sensitivity, which implies that attention influences the subjective components of perception through lower level processing. This outcome entails that the locus of stimulus- and goal-driven orienting therefore appears limited to the perceptual level of processing and that both forms of orienting indirectly interface with the subjective level of perception. Note that stimulus- and goal-driven orienting, as well as their interaction, were also statistically unreliable for the type 2 criteria (see supplementary Figures 6 and 7).

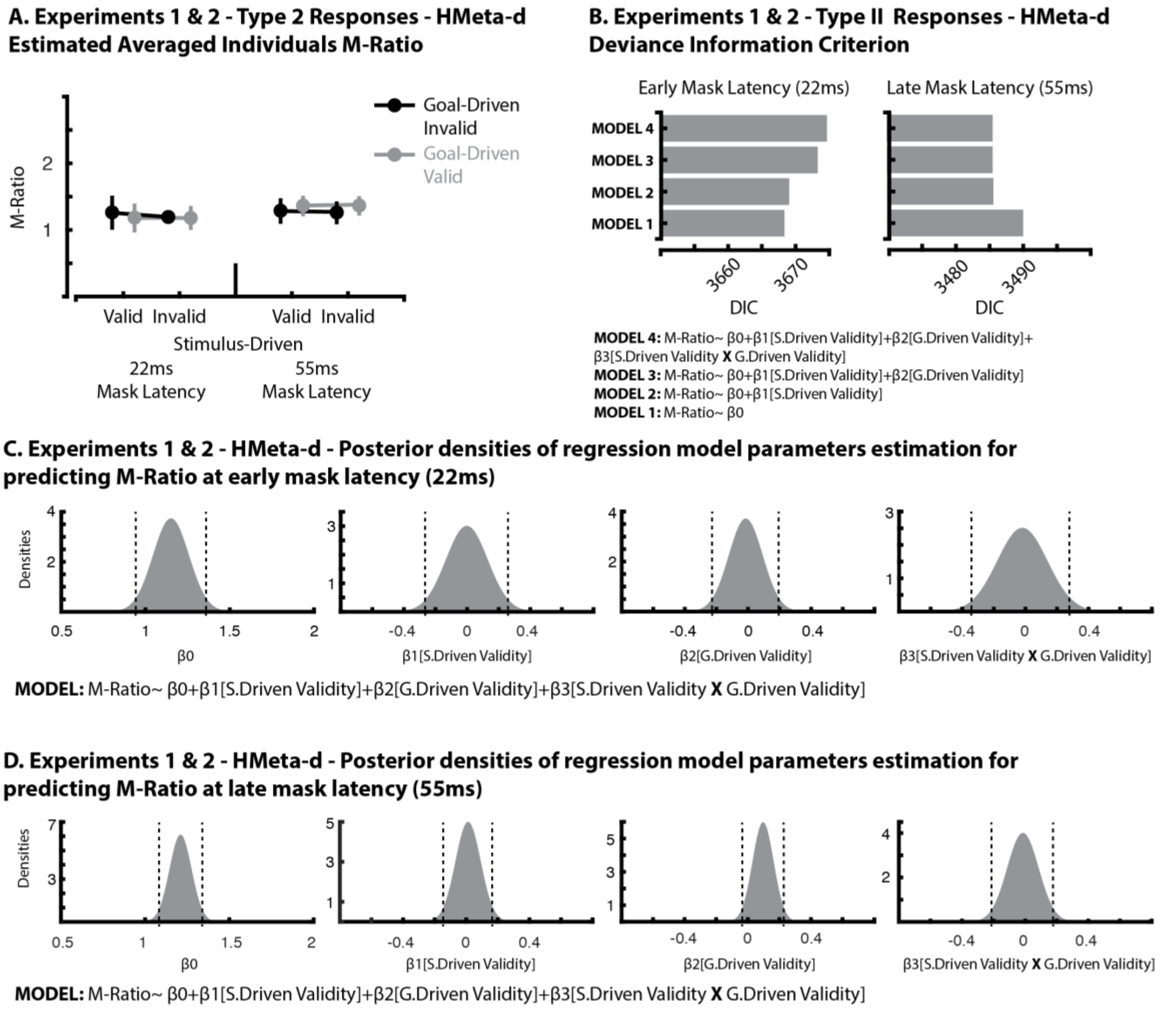


Figure 3. Type 2 signal detection analysis for subjective judgments in Experiment 1 and Experiment 2. A. Averaged values for estimated individual values for type 2 responses efficiency (i.e., M-Ratio) from MCMC modelling across stimulus- and goal-driven cueing through 22ms and 55ms mask latencies. Error bars represent bootstrapped 95% C.I. **B.** Deviance information criterion that corresponds to the four linear regression models that were fitted to the data to estimate M-Ratio from Experiments 1 and 2 as a function of stimulus- and goal-driven orienting. We fitted models separately for 22ms and 55ms masking latencies. **C.** Posterior densities for parameter estimates of the full linear regression model for predicting type 2 responses efficiency (i.e., M-Ratio) at 22ms masking latency. The dotted lines represent 95% HDI. **D.** Posterior densities for parameter estimates of the full linear regression model for predicting type 2 responses efficiency (i.e., M-Ratio) at 55ms masking latency. The dotted lines represent 95% HDI.

The results from experiments 1 and 2 inform the current research in two ways. First, our findings support the modular of visuospatial orienting by showing that stimulus- and goal-driven orienting enhance perceptual sensitivity with limited interaction. Both forms of orienting therefore parallel each other at this level of processing. Second, evidence did not support the idea that attention directly interfaces with the subjective components of perception. However, both of these interpretations rest on null hypotheses, which could raise concerns regarding type 2 error. Our approach has already addressed such worries here. In particular, we observed that evidence supports our null hypotheses despite the reliable effects of stimulus- and goal-driven attention on perceptual processing. Therefore, following a-priori power analyses, the absence of evidence needs to be explained while both forms of orienting clearly benefited perception. Furthermore, we should also consider that we replicated these null results in each experiment individually (see Supplementary Material). In other words, we combined data from both installments to maximize power, but nevertheless observed the same pattern in experiment 1 and 2. Lastly, we evaluated whether evidence supports these null hypotheses using Bayes statistics instead of solely relying on null hypothesis testing (Dienes, 2014; Gallistel, 2009; Wagenmakers, 2007). Here, lack of power would convey some form of ambiguity. And yet, evidence clearly favored null hypotheses. Altogether, our approach provides a solid basis for arguing in favor of null hypotheses.

As mentioned in the introduction, one caveat that often besets the field of consciousness studies pertains to the impact of task performance on subjective reports (Irvine, 2013). The main issue is that, despite their strong bond, subjective components of perception are distinct from task performance (Lau & Passingham, 2006; Weiskrantz, 1986), which emphasizes the need to delineate both processes to precisely gauge changes in conscious perception independently from those of task performance. The relative blindsight approach represents an experimental strategy designed to remove the influence of performance on subjective judgments across variables of interests (Lau & Passingham, 2006; Samaha, 2015). This outcome is achieved by matching performances across conditions via a titration procedure so that type 2 responses may vary while performance remains constant. Hence, in contrast to type 2 SDT where variations of subjective judgements and introspective sensitivity are isolated through analytical means, relative blindsight achieves the same goal via experimental means. We adopted this methodology in our third experiment to corroborate our previous results, and thereby validate our findings beyond type 2 SDT. Our goal was to replicate our findings about how attention relates the subjective components of perception using the relative blindsight approach and therefore corroborate our current interpretation.

Experiment 3

Method

Participants. We recruited 33 participants for the third experiment. They received a monetary compensation of $10/hour CAD for two sessions of 1728 trials. Participants completed both sessions on different days. Each session comprised 12 blocks of 144 trials. Participants completed a series of 10 practice trials until they understood the task. Given that our objective was to replicate outcomes from experiments 1 and 2, we aimed for a similar sample size.

Five participants were excluded due to elevated (> 15%) anticipation errors (Response Time < 150ms). 28 participants (17 adult females; age: M = 22.44 y.o, SD = 3.6) were included in this experiment.

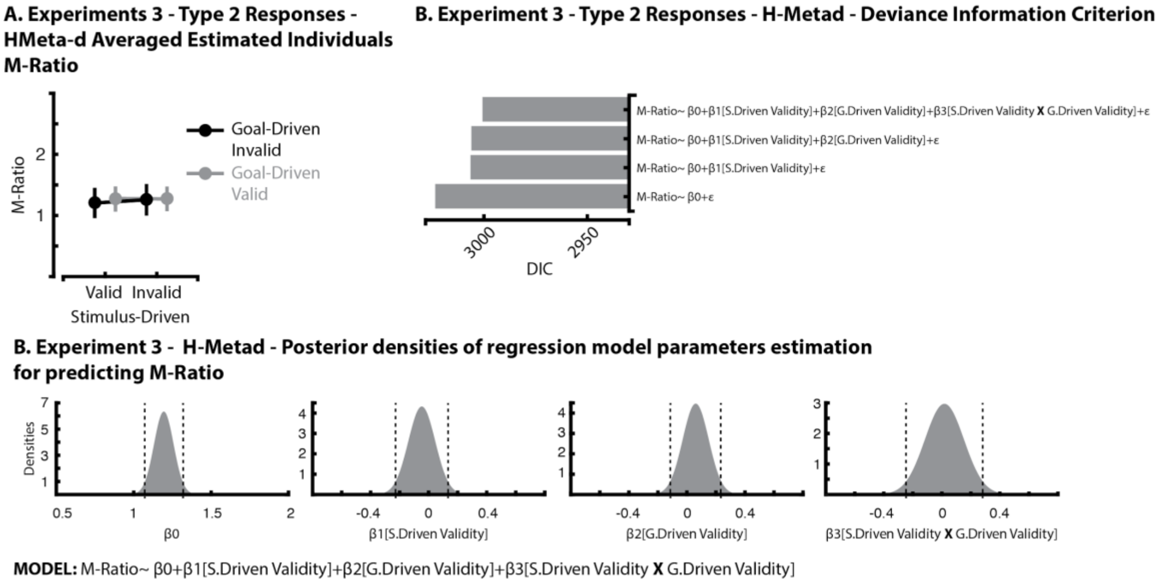
Apparatus and Stimuli. The apparatus and stimuli were similar to the first two experiments, with the following exceptions (see Figure 1). All four target-placeholders, as well as the masking stimulus, were changed from squares to circles. We also switched the target stimulus from a circular grating to a Gabor patch (i.e., a sinusoidal pattern combined with a Gaussian envelope) subtending 3° of visual angle, 3 cpd; while orientation was fixed to 15° or -15°. Moreover, the purpose of this third experiment was to directly evaluate the effects of stimulus-driven and goal-driven attention on subjective reports using the relative blindsight approach where we control for task performance. We relied on the QUEST algorithm to achieve this experimental strategy (Watson & Pelli, 1983), wherein the Michelson contrast value of the Gabor target would vary as a function of attention conditions. Thus, we equalized type 1 response performance across the unattended, stimulus-driven, goal-driven, and combined attention conditions.

Design & Procedure. The design and procedure were similar to previous experiments, with the following exceptions. While we kept the reliability of the peripheral cue at chance level (i.e., 25%), we made the central number cue predictive of the target location at 50%. Due to our unbalanced trial matrix following the combination of spatial cueing procedures, this modification allowed us to increase the overall number of unattended and stimulus-driven trials. Our instructions to participants emphasized the need to use the central number cue regardless of its reliability. (Analyses confirm their compliance with our directives.) Identical to the second experiment, we asked participants to discriminate the orientation of targets and then provide confidence judgments. Mask latency was fixed to 55ms. Moreover, we used the QUEST staircase procedure to titrate task performance at ~75% accuracy by varying the target's Michelson contrast values. The initial contrast value was set to .10. Each testing session comprised two parts: a first one aiming to find the accurate contrast thresholds for type 1 performances across all attention conditions, and a second one where we assumed that these performances were stable enough for applying our analyses. Thus, we relied on the first 480 trials of the titration procedure to determine the contrast thresholds for each participant. This process involved 180 unattended trials, 60 stimulus-driven trials, 180 goal-driven trials, and 60 combined attention trials. During this phase, participants were solely required to indicate the orientation of the target. In the second phase, participants were asked to also input their confidence judgments at the end of each trial. In total, for the second phase, participants completed 936 unattended trials, 312 stimulus-driven trials, 936 goal-driven trials, and 312 combined trials. While we assumed that the titration procedure reached a stable threshold in the first phase, we nonetheless applied the QUEST algorithm throughout the second half of the experiment to safeguard against factors that may influence type 1 performance.

Results

Objective performance (type 1 response) in experiment 3. We evaluated the reliability of our titration procedure across attention conditions by estimating perceptual sensitivity *d'* for each participant in each attention condition (Supplementary Figure 6). Again, we used hierarchical linear regression models. While the titration procedure properly controlled performance for stimulus-driven orienting, we observed a small benefit for goal-driven orienting over perceptual sensitivity (Supplementary Figure 6; Tables 7 and 8 in supplementary material; β = 0.39, SE = 0.07, 95% CI [0.24, 0.53]). Conversely, we observed no effect of attention on the decision criterion (Supplementary Figure 6 and Table 9 in supplementary material). The QUEST algorithm was therefore unable to perfectly match performances across all attention conditions. This outcome likely follows from the demanding experimental context comprising the combination of a double cueing strategy with visual masking during a target discrimination task. Nevertheless, the titration procedure eliminated the influence of stimulus-driven orienting on perceptual sensitivity, and strongly curtailed the effects of goal-driven orienting paving the way for the application of type 2 SDT to subjective judgments.

*Subjective judgments (type 2 response) for experiment 3**.*** The current results replicate those of experiment 1 and 2. Experimentally controlling for task performance across attention yielded the same pattern. Again, visual assessment of MCMC chains and the Gelman-Rubin diagnostic (i.e., R-Hat < 1.1) confirmed convergence of the models across all parameter estimates (see supplementary Figure 7). Likewise, the DIC only varied marginally across models (Figure 4), thereby conveying that more complex models hardly improved the fit compared to the baseline model. These results replicate our previous findings and verify the lack of influence of stimulus- and goal-driven orienting over the M-Ratio. In particular, the 95% HDI of the posterior densities for the betas of the full models revealed that participants displayed a marginal gain in type 2 efficiency beyond task performance during the unattended condition (μ of β0 = 1.19, 95% HDI [1.07 1.32]), while the model indicates that stimulus-driven and goal-driven again failed to heighten the M-Ratio (μ of β1[Stimulus-Driven Cue Validity] = -.047, 95% HDI [-.226 .136]; μ of β2[Goal-Driven Cue Validity] = .061, 95% HDI [-.112 .237]). Likewise, their interaction was also obviously statistically unreliable (μ of β3[Stimulus-Driven Cue Validity **X** Goal-Driven Cue Validity] = .018, 95% HDI [-.244 .283]). The third experiment therefore replicates our previous results and verifies the limited influence of visuospatial attention on confidence reports. Visual inspection of the projected M-Ratio values (Figure 4) confirm this assessment, where we see the absence of attention modulation.



A. Experiments 3 - Type 2 Responses - HMeta-d Averaged Estimated Individuals M-Ratio

B. Experiment 3 - Type 2 Responses - H-Metad - Deviance Information Criterion

B. Experiment 3 - H-Metad - Posterior densities of regression model parameters estimation for predicting M-Ratio

MODEL: M-Ratio~ β0+β1[S.Driven Validity]+β2[G.Driven Validity]+β3[S.Driven Validity **X** G.Driven Validity]

Figure 4. Type 2 signal detection analysis for subjective judgments in Experiment 3 A. Averaged values for estimated individual values for type 2 responses efficiency (i.e., M-Ratio) from MCMC modelling across stimulus- and goal-driven cueing through 22ms and 55ms mask latencies. Error bars represent bootstrapped 95% C.I. **B.** Deviance information criterion that corresponds to the four linear regression models that were fitted to the data to estimate M-Ratio from Experiments 3 as a function of stimulus- and goal-driven orienting. **C.** Posterior densities for parameter estimates of the full linear regression model for predicting type 2 responses efficiency (i.e., M-Ratio). The dotted lines represent 95% HDI.

The same pattern emerged for type 2 criteria, where we similarly observed no influence of attention (see supplementary Figure 8). Note that recent report indicates how relative blindsight may lead to inflated type 2 efficiency – a caveat that hinders this experimental approach (Rahnev & Fleming, 2019). However, we did not observe any such pattern here across attention conditions.

Thus far, our results support the modular view of visuospatial attention at the level of perceptual sensitivity, yet also highlight the limited influence of stimulus- and goal-driven orienting at subjective level of perception. Through all attention conditions, type 2 sensitivity equated type 1 sensitivity – a pattern suggesting that the loci of these attention systems are restricted to early processing of perceptual evidence, which in turn determines the emergence of perceptual information at the subjective level. Both stimulus- and goal-driven orienting therefore influence conscious perception and metacognition in a parallel and indirect fashion. In contrast, however, the current body of findings provides little information concerning the decision bound. This lacuna contrasts with previous work that emphasizes the impact of spatial attention over this component (Hawkins et al., 1990; Luo & Maunsell, 2018; Rahnev et al., 2011). We accordingly examined the modularity of attention within the context of target detection paradigm to evaluate the joint and isolated influence of stimulus- and goal-driven orienting over the decision bound. This parameter of the SDT model informs current views on the threshold of target awareness (Jachs et al., 2015). In particular, the decision bound reflects an internal bias relative to the amount of evidence required for committing to the occurrence of the signal. This parameter therefore denotes whether individuals adopt more liberal or conservative stances with respect to the decision process and the perceptual evidence available. While a liberal tendency shows a propensity for committing to the presence of the signal with limited evidence, a conservative tendency instead reflects a propensity to require more evidence before making such commitments. Hence, in addition to perceptual sensitivity, visuospatial orienting may also induce heightened tendencies to report awareness of target, which would account for previous reports of elevated conscious perception as a function of attention (e.g., Hsu et al., 2011).

Experiment 4

Method

Participants. We recruited 44 participants for the fourth experiment. They received a monetary compensation of $10/hour for one two-hour session of 1728 trials (i.e., 648 unattended trials, 216 stimulus-driven cueing trials, 648 goal-driven cueing trials, 216 combined cueing trials). Participants completed a series of 10 practice trials until they understood the task.

Again, we relied on previous research (Chica et al., 2014) and G*Power3 to assess the sample size following estimates for repeated measures F-tests on cueing effects for response times in the context of target detection tasks. For a central predictive cue at long cue-target latencies (i.e., > 500ms), we required a sample of 9 participants to achieve a power of .8 based on a large effect size ($\eta^2 = .23$) and an alpha value of .05. For a peripheral non-predictive cue at short cue-target latencies (i.e., < 300ms), we needed 5 participants to attain a power of .8 based on the rather large effect size ($\eta^2 = .44$) at an alpha level of .05.

Six participants were excluded due to poor accuracy (< 50%) and high number of trials without a response (> 15%). 38 participants (26 adult females; age: M = 21.61 y.o, SD = 3.46) were kept.

Apparatus and Stimuli. The apparatus and stimuli were similar to the previous experiments, except for the following differences (Figure 1). The purpose of this fourth installment was to evaluate the effect of stimulus-driven and goal-driven attention on target detection. We relied on the QUEST algorithm to avoid ceiling and floor effects. Again, this algorithm titrates the Michelson contrast value of the Gabor target as a function of detection performance in the unattended condition so that participants would perform at approximately 70% accuracy in that experimental condition. The calibration procedure allowed stimulus- and goal-driven orienting to facilitate perception while avoiding ceiling effects.

Design & Procedure. The design and procedure were similar to previous experiments, as we kept validity of the peripheral cue at chance level (i.e., 25%) and the central number cue at 50%. Again, our instructions to participants emphasized the need to use the central number cue, and forthcoming analyses confirm their compliance with our directives. Critically, we employed a target detection task instead of a target discrimination task. The target was present for half of the trials and participants were informed of this contingency. We asked them to indicate whether a target event had occurred at a probed location. We kept the masking latency to 55ms and used the QUEST staircase procedure throughout the experiment to titrate task performance in the unattended condition at ~70% detection accuracy by varying the target's Michelson contrast values. We used this titration procedure to avoid floor and ceiling effects following attention orienting. The initial value was set to .10, while the mean contrast value during the task was .38 (SD = .26). For data analysis, we removed the first block of trials (i.e., 144 trials) for each participant to allow the QUEST algorithm to stabilize properly and reach dependable contrast values. Combining spatial cueing with a target detection task is challenging due to the difficulty of categorizing target absent trial relative to attention conditions – i.e., in the absence of a target event one cannot determine cue validity. We overcame this issue by matching the contingencies of the cues to the probing of a particular location following the mask onset on each trial. In this way, the location of the probe determined cue validity. Hence, we would probe the location of the stimulus-driven attention cue 25% of the time (i.e., chance-level non-predictive cueing), and the location of the goal-driven cue 50% of the time (i.e., predictive cueing). Also, note that the target event, which was present for only half of the trials, and could only occur at the probed location. Participants were aware of these specificities. Given that the probe conveyed no information about the likelihood of a target event across our experimental conditions, the effects of attention were orthogonal to the probing procedure. One of the four masks would turn red (i.e., RGB values of 255, 0, 0; 37.7 cd/m^2) after 198ms and served as the probe. Participants were then required to indicate whether the target stimulus was present or absent as quickly and accurately as possible following its onset.

Detection Response - Signal Detection Theory. We used signal detection theory to assess detection performance. We calculated perceptual sensitivity *d'* and decision criterion C. We applied the following correction ((2*N)-1)/(2*N), where N equals the number of trials, whenever hit rate was equal to 1; and 1/(2*N) whenever false alarm was equal to 0. Less than 2% of cells required such corrections.

Results

Objective performance (type 1 detection response) in experiment 4. Unexpectedly with respect to our hypotheses, the current analysis reveals that only goal-driven attention benefited perceptual sensitivity (Figure 5). This outcome contrasts with previous literature in that stimulus-driven orienting did not boost perceptual evidence. Hierarchical linear regression models validated this observation (see Tables 10 and 11 in supplementary material; *Marginal* $R^2_{GLMM} = .02$), wherein goal-driven cue validity was the sole predictor ($\beta = 0.29$, $SE = 0.07$, 95% CI [0.15, 0.44]). Bayes factor analysis confirmed this pattern by providing positive evidence for the null hypothesis regarding stimulus-driven orienting, $BF_{01} = 12$. This unexpected result suggests that the influence of stimulus-driven over perceptual evidence might be limited in the context of signal detection whenever goal-driven is also engaged. Conversely, however, we found that both systems influenced the decision criterion, and both contributed to a reduction in conservative tendencies (Figure 5). The best fitting model (see Tables 12 and 13 in supplementary material; *Marginal* $R^2_{GLMM} = .25$) confirmed this by showing that both stimulus-driven ($\beta = -0.77$, $SE = 0.09$, 95% CI [-0.94, -0.6]) and goal-driven cue validity ($\beta = -0.29$, $SE = 0.09$, 95% CI [-0.46, -0.12]) were reliable predictors. Hence, both forms of orienting lessened response biases. Critically, our analyses were again consistent with the modular view of visuospatial attention. While both stimulus- and goal-driven orienting altered the criterion, our analysis shows limited interaction between them. Here, the full model comprising the interaction parameter did not improve the fit ($\chi^2(1) = .004$, $p = .95$; Figure 5). Bayes factor analysis provided further support for this view by favoring the null hypothesis relative to the interaction model, $BF_{01} = 12.3$. In sum, both stimulus- and goal-driven attention alter response biases in a parallel manner. Here, we observed that participants adopt a conservative stance relative to the detection of target events at unattended locations, while both forms of orienting reduced this particular bias independently of each other.

Response times for detection response. We examined response times (RTs) from the onset of the probe to confirm the reliability of the cueing procedure over performance in the context of target detection. This analysis aimed to ensure that each cue produced facilitation. Here, different patterns of RTs emerged across attention conditions as a function of the target's contingency (i.e., present or absent). We accordingly evaluated the effects of attention separately for target present and target absent trials (see Figure 5). We used median reaction times of accurate trials (i.e., hits and correct rejections only) and once again applied hierarchical linear regression model in a stepwise fashion by including stimulus-driven attention cue validity, goal-driven attention cue validity, and their interaction as fixed factors, and participants as a random factor. For correct rejections, we observed a small effect of stimulus-driven attention (see Tables 14 and 15 in supplementary material; *Marginal* R^2_{GLMM} = .004), wherein the main effect of stimulus-driven cue validity produced faster response times (β = -17.62, SE = 6.98, 95% CI [-31.35, -3.9]). However, this effect is not statistically significant when we fit the full model (Figure 5), which suggests that the influence of stimulus-driven attention remains somewhat marginal in the context of target absent trials. A different pattern emerged for hits (i.e., target present). Here, the best fitting model (see Table 15 and 16 in supplementary material; *Marginal* R^2_{GLMM} = .09) revealed facilitations for response times across both stimulus-driven (β = -48.39, SE = 10.04, 95% CI [-68.06, -28.72]) and goal-driven attention (β = -49.77, SE = 10.04, 95% CI [-69.44, -30.09]), which corroborates the validity of the double cueing procedure in the context of target detection. Participants were therefore faster to respond as a function of cue validity in both attention conditions. Importantly, the full model did not improve the fit ($\chi^2(1) < .3$), thus providing further evidence for parallel processing between stimulus-driven and goal-driven attention in this particular experimental context (Figure 5). Bayes factor analysis supported this construal, as evidence backed the null hypothesis (i.e., best fitting model) with respect to the interaction model (i.e., best fitting model and the interaction), BF_{01} = 11.02. These results therefore highlight how some of the effects of attention are contingent to the presence of the target signal. Furthermore, evidence is consistent with our previous findings and shows an additive pattern.

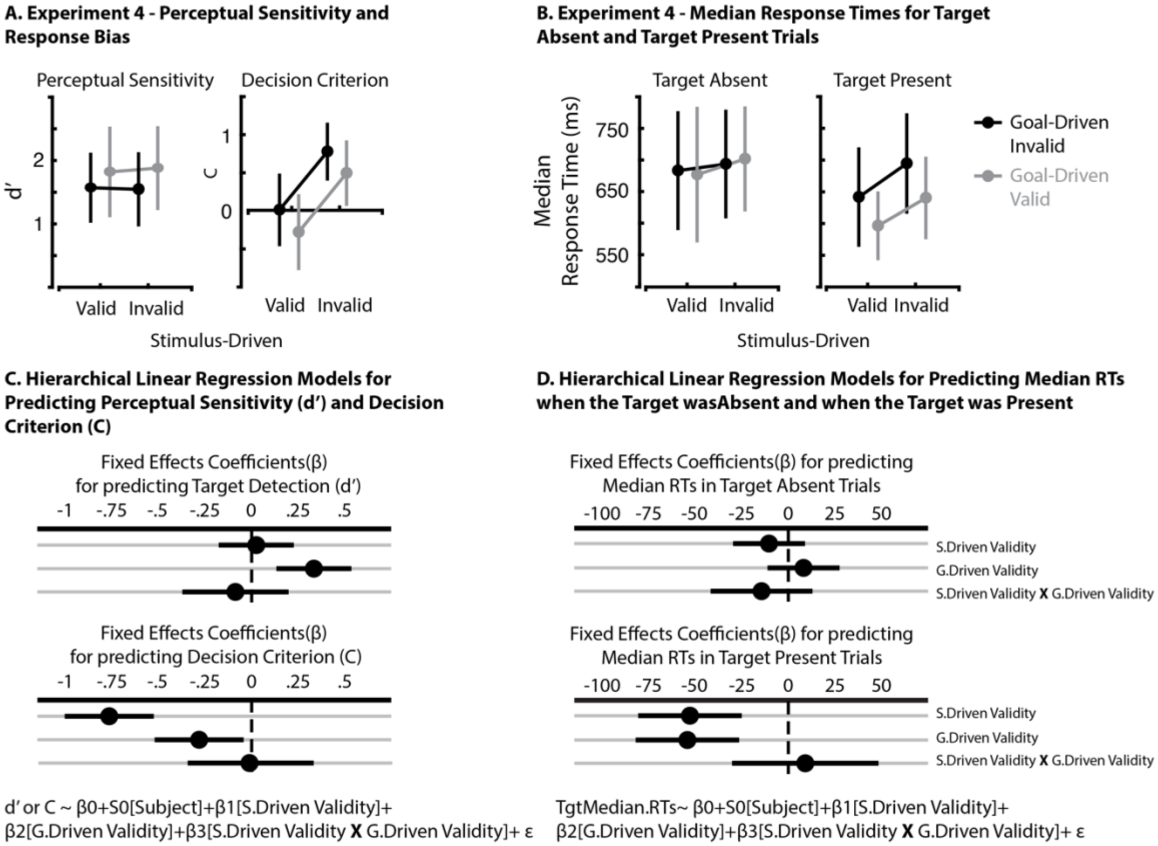


Figure 5. Response time and signal detection analyses in Experiment 4. A. Signal detection perceptual sensitivity (d'), as well as decision criterion (C) as a function of stimulus- and goal-driven attention. **B.** median reaction times for target absent and target present trials as a function stimulus-driven and goal-driven attention. **C.** We fitted hierarchical linear regression models to predict perceptual sensitivity (d') and the criterion (C) to evaluate the effects of stimulus- and goal-driven attention. Here, we plot fixed effects β parameters of the full model. Error bars represent 95% CI. **D.** We fitted hierarchical linear regression models to predict median response times for target present and target absent to evaluate the effects of stimulus- and goal-driven attention. Here, we plot fixed effects β parameters of the full model. Error bars represent 95% CI.

The unexpected outcome regarding the impotence of stimulus-driven orienting over perceptual sensitivity led us to replicate our findings in a fifth and final experiment. We detail how we replicated the current results in supplementary material. Specifically, this last installment corroborated the absence of an effect for stimulus-driven attention over perceptual sensitivity, as well the modularity of visuospatial attention over response times for hits and over the decision criterion.

Discussion

Attention is multifaceted, which means that the selection of information comprises multiple components operating alongside each other, including different forms of orienting. Based on this account, the present study examined how the modularity of visuospatial attention modulate several aspects of perception, including signal detection and discrimination, visual awareness, and metacognition. To this end, we tested the isolated and joint influence of stimulus- and goal-driven attention across type 1 and type 2 SDT using a double cueing approach through multiple installments. Our findings are manifold. Previous work argues that the signal detection theoretic framework corresponds a hierarchical architecture, wherein type 1 SDT reflects to lower-level processes and type 2 SDT higher-order ones (Fleming & Daw, 2017; Maniscalco & Lau, 2016). Assuming the validity of this framework, our findings demonstrate how functional modules of visuospatial attention solely influence lower-level processes, while failing to directly impact higher-order processes. Moreover, both stimulus- and goal-driven orienting boosted perceptual evidence during target discrimination with minimal interaction, thus upholding the modular view at this level of processing. In turn, neither influenced subjective judgments of perception once task performance was factored out, per type 2 SDT analyses and the relative blindsight approach. The current body of results accordingly challenges the notion that visuospatial attention directly interfaces with conscious perception, and instead aligns with previous work that downplays the role of selection in the emergence of consciousness (Brascamp et al., 2010; van Boxtel, 2017; van Boxtel et al., 2010b; Watanabe et al., 2011; Wilimzig et al., 2008; Wyart et al., 2012; Wyart & Tallon-Baudry, 2008). In lieu of a tight relationship, our research implies that visuospatial attention indirectly relates to subjective dimensions of perception through its influence on perceptual sensitivity. In this way, both stimulus- and goal-driven orienting boost visual awareness and metacognition by increasing the amount of evidence available at the perceptual level. We replicated this pattern across several experiments. Likewise, our results support the modular view at the level of the decision bound, where both forms of orienting lessened conservative tendencies independently of each other. Because response biases impact subjective reports of conscious perception (Peters et al., 2016), this outcome implies that both stimulus- and goal-driven attention likely influence subjective judgments of perception through this component as well, consistent with previous work (Rahnev et al., 2011). In sum, our findings submit a comprehensive account that limits the scope of visuospatial attention to boosting perceptual evidence and reducing response biases, while evidence corroborated the modular view.

A large body of research emphasizes the centrality of signal enhancement and noise reduction for the efficient selection of information during perception (Carrasco et al., 2000; Dosher & Lu, 2000a, 2000b; Hawkins et al., 1990; Hillyard et al., 1998; Lu & Dosher, 1998; Lu et al., 2002; Luck, 1995; Luck et al., 1997; Luck et al., 2000). Hence, both mechanisms likely shape the influence of stimulus- and goal-driven on conscious perception via lower-level processing. Consistent with this hypothesis, previous work in electroencephalography relates early sensory gains to visual awareness (Koivisto & Revonsuo, 2010), while other reports relate confidence judgments to the amount evidence available during perceptual decisions, as opposed to the relative amount of signal to the noise (Koizumi et al., 2015; Samaha et al., 2016; Zylberberg et al., 2012). These findings support the notion that visuospatial orienting contributes to changing conscious perception through signal enhancement (Carrasco et al., 2004; Liu et al., 2009). Conversely, the influence of noise reduction mechanisms on subjective judgements of perception seems more limited (Vernet et al., 2019). Altogether, previous studies suggest that stimulus- and goal-driven orienting alter reports of awareness and confidence by boosting the amount of sensory evidence available at the perceptual level of processing. In the present work, this benefit transpired as increased discrimination sensitivity (i.e., type 1 sensitivity) in our different experiments, which then resulted in greater awareness and metacognitive sensitivity (i.e., type 2 sensitivity). Furthermore, because both forms of orienting contribute to this sensory outcome in parallel, the modular view promotes the idea that the attentional route to conscious perception is multifaceted.

The SDT framework defines the criterion parameter as the amount of evidence that underlies perceptual decisions for reporting the presence of a particular signal (Macmillan & Creelman, 2005). Accordingly, this item estimates response biases, which ultimately relates to the subjective appraisal of individuals (Peters et al., 2016). In this way, two individuals may show the same degree of perceptual sensitivity, yet report different experiences following such biases. Several factors dictate how the perceptual system establishes this threshold, including spatial attention (Chica et al., 2011; Downing, 1988; Hawkins et al., 1990; Luo & Maunsell, 2018; Müller & Rabbitt, 1989; Rahnev et al., 2011; Sridharan et al., 2017). Consistent with this previous work, the current study indicates that while individuals were inclined to adopt a conservative stance whenever we probed at unattended locations, stimulus- and goal-driven orienting mitigated this bias independently of each other. These findings further expand our framework by showing that, in addition to improving the signal-to-noise ratio in the context of discrimination, both forms of orienting impact how the perceptual system sets the decision bound. Previous work relates changes in criterion setting during perception to variations in neuronal excitability, as indexed by the power of alpha oscillations in the posterior region of the brain (Iemi & Busch, 2018; Iemi et al., 2017; Kloosterman et al., 2019). Given that spatial attention induces relative changes in alpha waves across sensory regions (Foxe & Snyder, 2011), attending to a particular hemifield likely influences the criterion by increasing overall neuronal excitability in the contralateral sensory cortex.

Our results contrast with the findings from a previous study showing that attention induces conservative shifts of the criterion, as opposed to the liberal one we observe in the present work (Rahnev et al., 2011). According to the authors of this previous report, their results are consistent with the idea that individuals adopt a unified decision bound across attention conditions (Gorea & Sagi, 2001), while attention decreases trial-by-trial variance of the perceptual signal. This pattern ultimately leads to a reduction of false alarm rates, thereby producing a conservative pattern in the perceptual decision process. Importantly, this interpretation entails that the criterion is not dynamically adjusted as a function of attention processing. However, note that this previous research occurred in the context of the relative blindsight methodology where noise levels were greater for attended stimuli than for unattended ones so as to allow task performance to be equated across both conditions. One can therefore argue that the conservative stance reported in this work follows from elevated noise levels for attended events (Vernet et al., 2019), although additional experiments in this particular report dispute this interpretation. And yet, recent findings similarly challenge the idea that individuals adopt a fixed decision criterion across different contexts of attention (Denison et al., 2017). This work instead demonstrates that considerations pertaining to the attentional state of individuals influence how they calibrate the decision bound, which essentially means that the criterion is adjusted in a dynamical fashion. In light of this interpretation, evidence from the present study further demonstrates that these dynamical adjustments occur separately following stimulus- and goal-driven orienting. This outcome therefore supports the modular view.

In contrast to the first and second experiments where stimulus-driven attention improved perceptual sensitivity during target discrimination, we observed no such facilitation following stimulus-driven orienting in the context of target detection. While this outcome might seem unexpected, previous studies report similar findings at low target contrast values (Prinzmetal et al., 2008). In fact, our results align with previous assessments showing that non-predictive peripheral cues hardly improve perceptual sensitivity for signal detection despite reliable cueing effects over response times and the decision criterion (Chica et al., 2011). Perceptual benefits in the context of spatial cueing seem to emerge only when cues are made informative (i.e., predictive) about the target's possible location, thereby engaging goal-driven control of attention. A possible explanation for the limitations of stimulus-driven attention over target detection is the emergence of inhibition of return (IOR). The engagement and subsequent disengagement of stimulus-driven attention to a peripheral location typically causes a decrease in performance for target events occurring at this previously attended site, the IOR phenomenon (Klein, 2000). The presence of IOR seems like a reasonable explanation for the absence of perceptual benefits here. In fact, previous work indicates that successive events at the same peripheral location can enhance the potency of this phenomenon (Dukewich & Boehnke, 2008). Given that our experimental approach involves such consecutive events (i.e., peripheral cue, target stimulus on half of the trials, mask stimulus, and finally the probe stimulus), it increases the likelihood of IOR. However, note that our findings show a cueing effect over response times for stimulus-driven orienting following the presence of target events, which weakens this interpretation. Ultimately, this particular outcome provides additional support to the idea that stimulus- and goal-driven orienting operate differently: While the latter produced perceptual benefits for both signal discrimination and detection, the former was only reliable over discrimination sensitivity. The absence of benefits following stimulus-driven attention for target detection therefore demonstrates that both forms of orienting are not bounded by the same parameters. This perspective aligns with previous work that emphasizes distinct selection mechanisms for stimulus- and goal-driven attention (Dosher & Lu, 2000a, 2000b; He et al., 1996; Lu & Dosher, 1998).

One might argue that our results can be explained through a unitary process of attention, such that the absence of an interaction would in fact reflect the outcome of a single process engaged by both cues. However, several points undermine this competing account. First, the list of qualitative differences that characterize the dichotomous view of spatial attention dispute the idea that single all-encompassing orienting system underlies both forms of orienting (Chica et al., 2013). Furthermore, our experimental design and cueing strategies rest on a dense literature that emphasizes how different patterns arise from stimulus- and goal-driven cueing (Chica et al., 2014). A unique system account therefore runs counter to a broad body of research. In particular, the idea that goal-driven attention might be engaged by both cues seems implausible because it would entail that the deployment of this alleged unitary goal-driven process occurs at multiple locations while incurring minimal cost. Furthermore, the short cue-target latency for peripheral onset (i.e., from 99ms to 297ms) would hardly leave enough time for the concurrent re-deployment of goal-driven attention on trials where both cues indicate separate locations. Evidence for this possibility remains contentious (Jans et al., 2010; however, see Eimer & Grubert, 2014). The current findings therefore seem nearly impossible to reconcile with a unitary process account.

One smaller challenge to the interpretation of the current results concerns our usage of number cues, whereby previous reports show that this form of cueing includes some form of automatic and overlearned orienting responses due to associations between numeral knowledge and the spatial organization of clocks (Ristic et al., 2006). Our cueing methodology could therefore have introduced some form of combined cueing responses that would comprise both goal-driven and automatic orienting, as opposed to a pure form of goal-driven orienting (Ristic & Kingstone, 2006; Ristic & Landry, 2015). Note, however, that research on number cues also uncovered similar effects for the number line where lower values (e.g., the number “3”) facilitate left orienting and higher ones (e.g., the number “9”) right orienting. Certain numbers (e.g., the number “3”) could therefore ignite opposing automatic responses depending on whether the overlearned component here reflects numerical knowledge relative to clocks (i.e., automatic orienting to the right) or the number line (i.e., automatic orienting to the left. Task set and higher-order processes likely mediate between these conflicting processes (Egner & Hirsch, 2005). Nevertheless, our results are consistent with previous findings in showing that this potential combined effect of goal-driven orienting and automaticity remains largely independent of stimulus-driven orienting responses (Ristic & Kingstone, 2012; Ristic et al., 2012). Another possible limitation concerns the usage of a binary scale for subjective reports when, perhaps, a four options scale would provide a better resolution to uncover the effect of attention on subjective judgments of perception (Sandberg et al., 2010). Here, we relied on a binary scale to ease task difficulty for participants and allow them to perform it at a higher tempo. Each session was already tedious, therefore going from a two options objective response to a four options subjective scale would have slowed them down significantly.

Lastly, the fact that our explanation rests on null hypotheses regarding the interaction of stimulus- and goal-driven orienting for type 1 responses and the absence of an attention effect for type 2 responses raises the prospect of a type II error (Dienes, 2014; Gallistel, 2009; Wagenmakers, 2007). However, our experimental approach mitigates these concerns through different means. First, we confirmed the validity of the cueing procedure for engaging both forms of orienting. In fact, we report facilitation for both stimulus- and goal-driven orienting for at least one estimate in all of our experiments. Thus, null findings do not follow from the absence of an effect of stimulus- and goal-driven orienting on perception. Second, we replicated each finding across different installments of our methodology. Third, we relied on Bayesian statistics to support null hypotheses (Dienes, 2014). Considered together, these different steps make it unlikely that our interpretation is invalid due to type II error.

Conclusion

The current study investigated the multifaceted view of attention through type 1 and type 2 SDT. Relying on the double cueing approach to concurrently engage stimulus- and goal-driven orienting, our findings support the modularity of visuospatial attention. In particular, our study shows that both systems modulate perceptual evidence and the decision criterion independently from one another. Conversely, we found little evidence that attention directly interfaces with the subjective dimensions of perception. Accordingly, the dynamics between visuospatial attention and human consciousness appear to rest on indirect connections, which complicates the story. Our research therefore provides a comprehensive account that opens new research avenues for exploring the various points of contact between the components of attention and perception.

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Contributions

M.L. designed and implemented the study. M.L. analyzed the data. M.L., J.D.C, J.S. and A.R wrote the manuscript. A.R secured funding for this research project.

Competing Interests

All authors declare no competing interest

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