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Voluntary and involuntary spatial attentions interact differently with awareness

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ABSTRACT

Although the nature of the relationship between attention and awareness is actively debated, the possibility that different forms of attention might interact differently with awareness has never been directly tested. We examine here whether voluntary and involuntary spatial attentions, two forms of attention that were distinguished by manipulating the predictability of central arrow cues, interact in the same way with visual awareness. Conscious perception was enhanced by both voluntary and involuntary attentions, and to a similar extent, suggesting volition may not be an essential feature for awareness. However, the influence of attention was dependent on the awareness of the target stimulus: Voluntary attention shortened reaction times and improved discrimination accuracy of cued relative to uncued stimuli, but only when the stimuli were consciously perceived. Involuntary attention shortened reaction times for cued relative to uncued target stimuli, but only when the stimuli were not consciously perceived. Our results imply that the nature of the relationship between attention and awareness is not a simple one but depends on the type of attention involved. More specifically, our results suggest that the aware or unaware status of the stimulus could determine whether attentional facilitation is driven by voluntary or involuntary mechanisms, a proposal that goes in the opposite direction of the classical view that attention controls awareness. Because voluntary attentional benefits were observed in aware trials but involuntary attentional benefits were observed in unaware trials only, our results also argue against the idea that attentional effects on conscious and unconscious processing are fundamentally of the same nature.

1. Introduction

Attention has long been held to be a prerequisite for perceptual awareness: to consciously experience a stimulus, one must pay attention to it. This intuitively appealing view is supported by numerous experimental findings, from spatial orienting (Carrasco, Ling, & Read, 2004; Merikel, 1997; Posner, 1994) to inattentional (Mack & Rock, 1998) or change blindness (Simons & Rensink, 2005) studies. Accordingly, current models and theories posit that conscious perception is associated with the top-down fronto-parietal activity amplified by attention (Baars, 1988, 1997; Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006). However, attentional cues do not always enhance conscious detection sensitivity (Smith, 2000; Solomon, 2004). Moreover, there is growing evidence showing that attention and awareness can be in some cases partially or fully dissociated either at the behavioral (Kentridge, Nijboer, & Heywood, 2008; Koch & Tsuchiya, 2007; van Boxtel, Tsuchiya, & Koch, 2010) or at the neural level (Schurger, Cowey, Cohen, Treisman, & Tallon-Baudry, 2008; Wyart & Tallon-Baudry, 2008). However, the links between attention and awareness are bound to be complex and multiple, since both notions are multifaceted, encompassing different types of processes.

Indeed, the distinction between conscious and unconscious processing can tap into perceptual aspects, such as the contrast between seen and unseen stimuli, or into more cognitive aspects, such as the contrast between intentional and unintentional processes (Bargh & Morsella, 2008). Similarly, attention is not a unitary concept either. It has been conceptualized in many different ways in the literature, for example, spatial- versus feature- or object-based attention (Maunsell & Treue, 2006; Yantis & Serences, 2003), or endogenous versus exogenous attention (Jonides, 1981; Posner, 1980), etc. In addition, attention affects a number of different processes, including expectation, perceptual saliency and decision making.

Among the many concepts found under the umbrella term of attention, we chose to focus on voluntary attention, volitionally controlled according to internal goals (Jonides, 1981), and invol-

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untary attention, which can be automatically triggered (Posner, 1980). The dichotomy between voluntary and involuntary attentions seems most relevant when it comes to the interactions between attention and awareness. Indeed, volitional processes could be tightly linked to consciousness, since voluntarily directing one's thought or actions seems to be a hallmark of conscious awareness (Jack & Shallice, 2001) and involves the notion of the self (Haggard, 2008; Zhu, 2004). However, how do voluntary and involuntary attentions interact with awareness? Do they both facilitate conscious processing, or is one more efficient than the other? Conversely, do the influences of voluntary and involuntary attentions, indexed by the shortening of reaction times at the cued location, depend on the awareness of target stimuli?

Experimentally, voluntary spatial attention has been often studied in Posner cueing tasks with central arrow cues. When cues are *predictive* of stimulus location, this task is considered to tap mainly into the mechanism of voluntary attention (Jonides, 1981; Posner, Snyder, & Davidson, 1980). The standard result is that reaction times (RTs) in response to subsequently presented targets are shortened at the cued relative to the uncued location. Central cues have been traditionally conceived to give rise only to voluntary attention because interpretation is required to extract the positional information, and cueing effects were initially observed for predictive cues only. However, there is growing evidence that an attentional shortening of RT is obtained even when the central cue is *not predictive* of the target location (Doricchi, Macci, Silvetti, & Macaluso, 2010; Eimer, 1997; Hommel, Pratt, Colzato, & Godijn, 2001; Ristic, Friesen, & Kingstone, 2002; Ristic & Kingstone, 2002; Tipples, 2002), implying that involuntary attention can also be triggered by central arrow cues. Manipulating the predictability of a central arrow cue therefore allows to distinguish between voluntary and involuntary attentions. Indeed, by capitalizing on cue predictability, prior literature has shown that voluntary attention could shorten RTs and increase accuracy performance at the cued relative to uncued locations, whereas involuntary attention only affects RTs (Prinzmetal, McCool, & Park, 2005; Prinzmetal, Zvinyatskovskiy, Gutierrez, & Dilem, 2009). To account for such distinct behavioral differences, Prinzmetal et al. (2005) proposed that voluntary attention enhances the perceptual representation of incoming stimuli at cued locations, leading to faster and more accurate responses. By contrast, involuntary attention would affect a post-perceptual process rather than the perceptual representation, leading to a shortening of RTs while leaving accuracy unchanged. It should be underlined that the concepts of voluntary versus involuntary attention triggered by central predictive or non-predictive cues are related to, but not necessarily identical to the well-known distinction between endogenous and exogenous attentions (Jonides, 1981; Posner et al., 1980) that relies on the comparison between central and peripheral cueing.

In the current study, a modified Posner central cueing task was used (Fig. 1A). First, two central arrow cues, rather than only one, were used to trigger involuntary attention more effectively (Tipples, 2002). Second, we used target stimuli that were at threshold for conscious detection: faint grating targets were physically the same across all trials but were consciously seen only half of the time, as assessed on a trial-by-trial basis. After target presentation, participants had first to discriminate the orientation of the target and then to report whether they thought a target had been presented. Attention and awareness effects could thus be operationally defined based on the results from the above two tasks: the shortening of reaction times in the orientation task was considered as a behavioral measure of spatial attention, whereas subjective reports of visual experience were taken as a measure of visual awareness. Crucially, within the same experimental paradigm and using identical stimuli, central arrow cues were made predictive (65% validity) in the voluntary condition but not predictive (50% validity) in the involuntary condition (Fig. 1B). These manipulations thus allowed us to investigate the interplay between awareness and voluntary/involuntary attention.

2. Experiment 1: voluntary and involuntary conditions

2.1. Methods

2.1.1. Participants

Two distinct groups of 14 right-handed participants without past neurological or psychiatric history participated in the voluntary condition (11 females, mean age = 22.3 years, range = 18–24) and in the involuntary condition (7 females, mean age = 24.2 years, range = 20–30). All had normal or corrected-to-normal vision and gave their written informed consent to take part in the study.

2.1.2. Stimuli

The targets were binary circular grating stimuli (patch size of 1.5° visual angle, spatial frequency of 5 cycles per degree of visual angle, cut-off = 2 cpd) created with Matlab (MathWorks, Natick, MA) and the Psychtoolbox (Brainard, 1997; Pelli, 1997). From trial to trial, the orientation of the gratings was randomly chosen from one of 20 equally spaced angles (between 0° and 180°). Vertical and horizontal orientations were excluded. The centre of the gratings was placed at 1.5° of visual angle from fixation and at a 30° declination below the horizontal meridian in the left or right lower quadrant. Arrows were created using Photoshop (Adobe systems, San Jose, CA). The arrow pair subtended a horizontal visual angle of 1.5° and a vertical visual angle of 1° around the fixation cross. These two arrows were rotated 30° from the horizontal line, pointing either to the left or to the right lower quadrant. All stimuli were presented against a grey background (luminance: 30.06 cd/m^2) at the centre of a calibrated computer screen (resolution, 1024 × 768 pixels; refresh rate, 60 Hz). The viewing distance was 76 cm.

2.1.3. General procedure

The general experimental procedure used throughout all the experiments reported here is depicted in Fig. 1A. Each trial began with a central fixation of 0.8–1 s, immediately followed by a pair of arrows for 0.6 s. A faint grating, at threshold for conscious detection, appeared for 0.4 s. The grating target could appear in either the left or right lower quadrant. Cue validity varied between experimental conditions (see Section 2.1.4). After stimulus presentation, participants had to answer two questions. They first had to identify the orientation of the previously displayed grating target by making a two alternative forced choice as quickly as possible. They had up to 3 s to respond. The orientation of one of the grating choices was identical to the target. The orientation of the other grating choice was at ±60° away. Participants were then requested to report within 3 s whether or not they believed that a grating target had been presented during the trial. The positions of all those choices were randomized across trials. Note that participants were explicitly required to perform the orientation discrimination task even though they did not believe that a grating was presented during the trial. Finally, an inter-trial interval between 2 and 3 s was introduced. Participants had to complete three runs. Each run consisted of 69 trials. The order of the trials within each run was randomized.

2.1.4. Experimental conditions (Fig. 1B)

In the *voluntary condition*, participants were informed that a grating target would appear more often at the lower quadrant indicated by the arrows. The validity of the arrow cues was 65%. Thirteen percent of the total trials were catch trials, in which no grating appeared. In other words, in each run, there were 39 validly cued target-present trials, 21 invalidly cued target-present trials, and 9 target-absent trials. In the *involuntary condition*, cue validity was set at 50%. Participants were explicitly informed that the cue was not informative, i.e., that a grating was equally likely to appear at the cued or at the uncued location. Note that the two experimental conditions were performed by two different groups of participants.

2.1.5. Estimation of contrast threshold

Prior to the experiment, contrast threshold was established for each participant. This calibration session was designed to estimate threshold contrasts of the targets so that approximately only half of the presented gratings would be reported as "present" (thus consciously seen) in the subsequent experiments. The calibration session included two randomly interleaved psychophysical staircases corresponding to the cued and uncued locations respectively. One-up one-down staircases were employed in order to converge at a detection rate of 50%. The experimental procedure during threshold estimation was the same as described above, except that the contrast of the grating varied from trial to trial depending on the previous present–absent report in the corresponding staircase. Threshold contrasts (voluntary task: cued location 1.70 ± 0.29%, uncued 2.40 ± 0.43%; involuntary task: cued 1.26 ± 0.42% uncued 1.33 ± 0.28%) were averaged across the cued and uncued locations for each participant, and this contrast value was used during the experiment. As expected, at contrast threshold, participants were aware of the presence of a target in about half of the target-present trials (voluntary condition: 49.05 ± 2.37%; involuntary condition: 56.29 ± 3.25%).

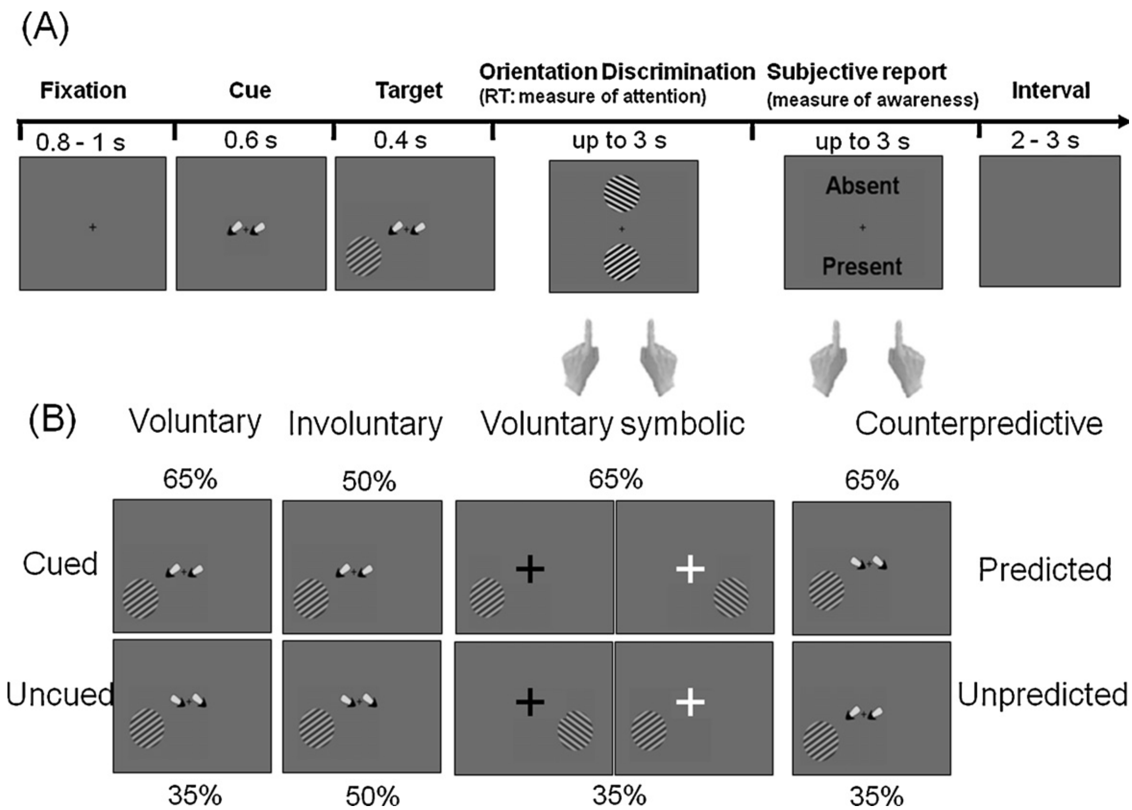

Fig. 1. General paradigm and experimental tasks. (A) General paradigm. Following fixation, a pair of central arrow cues was presented pointing to the lower left or lower right visual quadrant. A physically constant faint grating, at threshold contrast for conscious detection, appeared at the location indicated by the cues or at the location *opposite* to the one indicated by the cues. Participants had first to discriminate the orientation of the grating (2 alternative force choice). A shortening of reaction times at this question was taken as an operational measure of attention. Subjects then had to report whether they thought a stimulus had been presented or not. This subjective report was taken as an operational measure of awareness. (B) Experimental conditions. Four different conditions were tested in different groups of participants: *voluntary condition*, in which the arrows predicted the location of the grating in 65% of the trials; *involuntary condition*, in which the arrows were not predictive (50% validity); *voluntary symbolic condition*, in which in 65% of the trials, the black/white cue indicated that the grating would appear at the lower left/right quadrant (the color-location association was reversed in the other half of participants); *counterpredictive* condition, in which the grating appeared at the location opposite to the one indicated by the arrow cues in 65% of the trials.

2.2. Results

2.2.1. Subjective and objective measures of awareness

Because the measure of awareness used here was based only on participants' subjective reports, it is worth examining whether this subjective measure was corroborated by more objective ones. First, participants did not respond at random about the presence or absence of the stimulus: in both tasks, participants reported the presence of a grating target much more often when the grating was actually present than when it was absent (false alarm rate: voluntary condition, 11.9 ± 2.52%, mean ± SEM; involuntary condition, 6.08 ± 1.58%), corresponding to statistically significant d' in both tasks (voluntary: 1.27 ± 0.34, t test against zero, $t(13) = 8.33$, $p < 0.001$; involuntary: $d' = 1.75 \pm 0.12$, $t(13) = 14.45$, $p < 0.001$). Sensitivity d' was significantly larger in the involuntary than the voluntary condition (unpaired t test, $t(13) = 2.44$, $p < 0.05$), but criteria were not significantly different (voluntary: $\beta = 0.93 \pm 0.25$; involuntary: $\beta = 1.34 \pm 0.17$; $t(13) = 1.64$, $p = 0.11$). It should be noted that when participants made a false alarm, it could not be specified whether they saw a target at the cued or the uncued locations. For that reason, d' and criterion could not be computed separately for cued and uncued locations, and the analysis of attentional influences on conscious detection relied solely on hit rates. Second, participants' accuracy performance at the orientation discrimination question was high when they reported being aware of the stimuli (voluntary: 77.9 ± 3.66%; involuntary: 83.8 ± 3.21%), but at chance level when they reported not being aware of the stimuli (voluntary: 51.26 ± 0.13%, binomial test, $p = 0.42$; involuntary: 52.5 ± 1.50%, $p = 0.18$). Last, in both conditions, participants responded much faster at the orientation discrimination question when they were unaware of the stimuli than when they were aware (voluntary: unaware trials, 748.96 ± 69.09 ms, aware trials, 947.60 ± 60.52 ms, paired t test $t(13) = 3.71$, $p < 0.01$; involuntary: unaware trials, 734.59 ± 36.01 ms, aware trials, 1039.90 ± 50.47 ms, $t(13) = 6.12$, $p < 0.0001$). Together with the chance-level accuracy in unaware trials, these observations suggest that participants were indeed guessing the orientations of the targets when unaware. In all, two awareness states (aware versus unaware) were distinctly characterized in the current study.

2.2.2. Influence of attention on conscious detection

The proportions of trials for which participants reported the presence of a stimulus (i.e., conscious detection) were computed at the cued and uncued locations. In the voluntary condition (Fig. 2A, left), participants reported the presence of validly cued targets significantly more often than they did for uncued targets (valid: 55.5 ± 3.15%, mean ± SEM; invalid: 37.1 ± 4.67%; paired t test, $t(13) = 3.01$, $p < 0.01$). Similarly in the involuntary condition (Fig. 2B, left), participants reported seeing the targets significantly more often when they appeared at the cued (60.2 ± 3.50%) than the uncued locations (49.0 ± 4.14%, $t(13) = 2.91$, $p < 0.05$). Such advantages for conscious detection at the cued versus uncued locations were of similar size in the voluntary and involuntary conditions (unpaired t test, $t(13) = 0.99$, $p = 0.33$).

Although conscious detection was enhanced in both voluntary and involuntary conditions, the facilitation of conscious detection at the cued location was not systematically accompanied by bet-

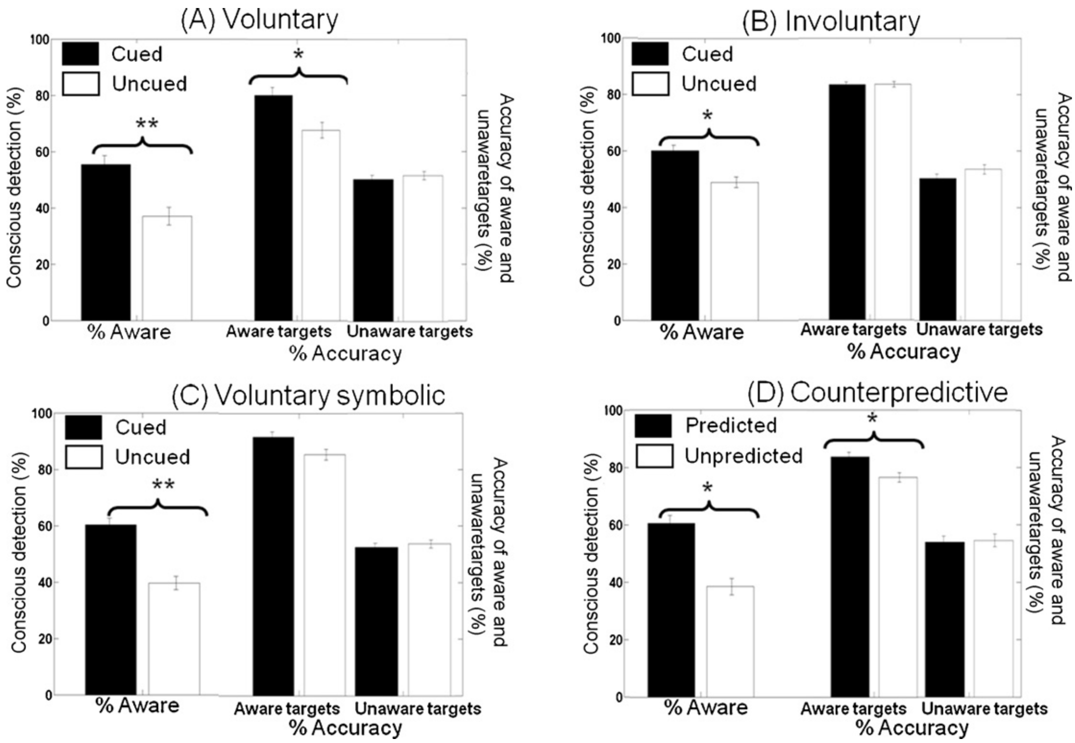

Fig. 2. Each panel presents the proportion of consciously perceived targets at the cued and uncued locations (2 left bars) and the orientation discrimination accuracy for those aware and unaware targets at the cued and uncued locations (2 right bars), respectively in the (A) voluntary condition, (B) involuntary condition, (C) voluntary symbolic condition, and (D) counterpredictive condition. Asterisks indicate a significant difference between the attended and the unattended locations (* $p < 0.05$; ** $p < 0.01$). Error bars indicate the 95% within-participant confidence intervals.

ter performance at discriminating the orientation of the grating. In the voluntary condition (Fig. 2A, right), enhanced conscious detection at the cued location was accompanied by improved accuracy performance when the target was consciously perceived (aware trials, cued: 80.01 ± 3.81%, uncued: 67.64 ± 5.26%; paired *t* test, $t(13) = 2.18$, $p < 0.05$). By contrast accuracy performance did not differ between the cued and the uncued location when the target was not consciously perceived (unaware trials, cued: 50.28 ± 1.86%, uncued: 51.71 ± 2.07%; $t(13) = 0.48$, $p = 0.64$). In the involuntary condition, no sign of improved accuracy at the cued location could be found neither in aware (Fig. 2B, right; cued: 83.49 ± 3.39%, uncued: 83.65 ± 3.44%; $t(13) = 0.08$, $p = 0.94$) nor in unaware trials (cued: 50.34 ± 1.98%, uncued: 53.56 ± 2.28%; $t(13) = 1.00$, $p = 0.34$). These results thus indicate that voluntary attention facilitated conscious detection as well as increased orientation discrimination accuracy at the cued location, while involuntary attention facilitated conscious detection to the same extent but left accuracy unchanged.

2.2.3. *Influence of awareness on attentional RT effects*

The attentional effect was measured as the gain in reaction times for cued relative to uncued targets in the orientation discrimination task. To estimate how awareness could influence the attentional effect, we computed the RT difference between the cued and uncued location separately for trials in which participants were aware of the targets and trials in which participants were unaware of the target. Because accuracy performance was high in aware trials and at chance in unaware trials, we analyzed the RT results of correct trials only when participants reported being aware of the stimuli, but collapsed the RT results of both correct and incorrect trials when subjects reported being unaware. Reaction times shorter than 200 ms or that deviated from the mean by more than 2 standard deviations were excluded from the analysis (less than 5% of the total trials for each participant). In the voluntary condition (Fig. 3A), participants discriminated the gratings much faster at the cued (883.29 ± 49.98 ms, mean ± SEM) than at the uncued location (1011.90 ± 79.49 ms; paired *t* test, $t(13) = 2.59$, $p < 0.05$). However, this pattern of results helds true only in aware trials. No significant RT difference between the cued and the uncued locations was found in unaware trials (cued: 750.19 ± 70.91 ms, uncued: 747.73 ± 68.65 ms; $t(13) = 0.13$, $p = 0.9$). In other words, voluntary attention shortened RTs, but only when targets were consciously perceived. A very different pattern of results was observed for involuntary attention (Fig. 3B). Here, participants responded faster at the cued than at the uncued location in *unaware* trials only (cued: 720.25 ± 33.78 ms, uncued: 748.92 ± 38.99 ms; $t(13) = 2.46$, $p < 0.05$). No attentional advantage was observed in aware trials (cued: 1036.00 ± 52.32 ms, uncued: 1043.90 ± 50.13 ms; $t(13) = 0.60$, $p = 0.56$). As a result, targets that were consciously perceived could benefit from voluntary attention, while targets that were not consciously perceived could benefit from involuntary attention.

2.2.4. *Control analysis*

Participants exhibited significantly larger d' values in the involuntary compared to the voluntary condition ($d' = 1.75 \pm 0.12$ versus 1.27 ± 0.34, $t(13) = 2.44$, $p < 0.05$). Therefore, we checked whether our findings could be explained by this confounding factor. In each condition, we correlated the conscious detection differences between the cued and uncued locations with participants' d' values. No significant correlation was found (voluntary: $r = 0.12$, $p = 0.68$; involuntary: $r = 0.08$, $p = 0.79$). Participants' d' sensitivity correlated neither with the RT attentional effect obtained in aware trials in the voluntary condition ($r = 0.29$, $p = 0.31$) nor with the RT attentional effect in unaware trials in the involuntary condition ($r = 0.38$, $p = 0.18$). It therefore seems unlikely that the different pattern of

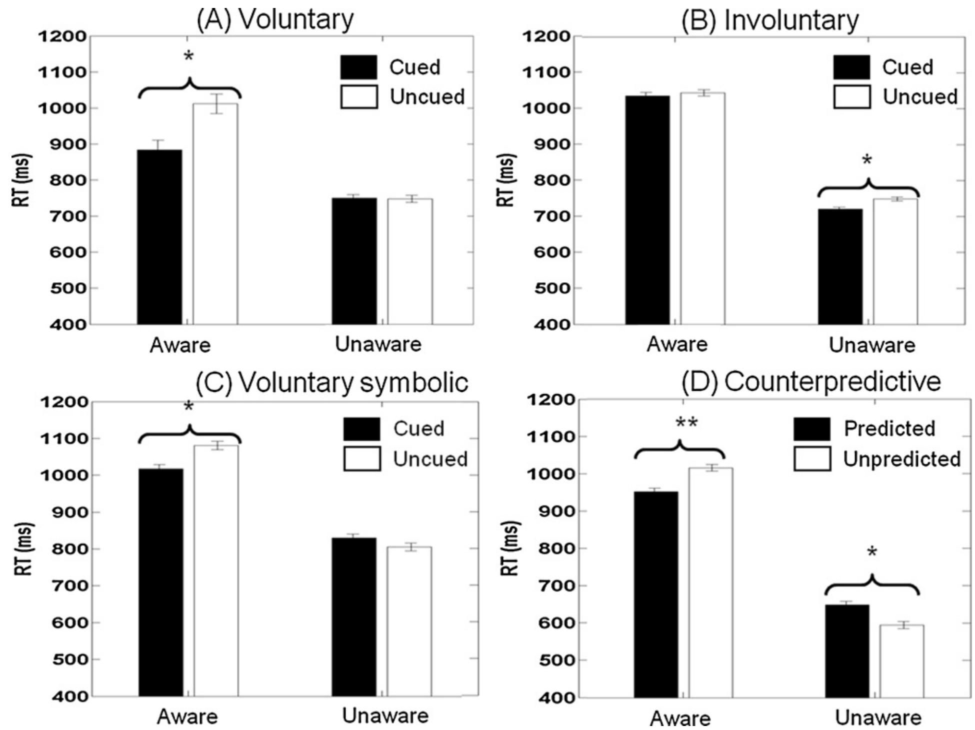

Fig. 3. Reaction times to the orientation discrimination question as a function of awareness and spatial location in the (A) voluntary condition, (B) involuntary condition, (C) voluntary symbolic condition, and (D) counterpredictive condition. For each condition, the asterisks indicate a significant difference between the attended and the unattended location (*p < 0.05; **p < 0.01). Error bars indicate the 95% within-participant confidence intervals.

results for the voluntary and involuntary conditions could be due to the difference in d' between these two conditions.

Rather than being due to involuntary attention per se, the shorter reactions times at the cued location in unaware trials could be due to a greater certainty that no stimulus was presented and in turn a faster guessing. To test for this alternative hypothesis, we analyzed the reaction times during the present/absent question: If indeed subjects had greater confidence that no stimulus was presented at the cued than at the uncued location, they should answer "absent" faster at the cued location. However, this was not the case: When participants reported not seeing the targets, no significant RT difference between the cued and uncued locations was found at the second present/absent question (mean ± SEM, cued: 630.02 ± 23.82 ms, uncued: 629.92 ± 25.89 ms, paired t test $t(13) = 0.07$, $p = 0.99$). This analysis thus suggests that confidence was unlikely to significantly contribute to the RT effect observed in unaware trials at the orientation discrimination task in the involuntary condition.

Finally, threshold contrasts were averaged across the cued and uncued locations and subsequently used in the experimental conditions, but there were large differences in the estimated threshold contrasts between cued and uncued targets in the voluntary condition. Those differences tended to be smaller in the involuntary attention. In other words, uncued targets were more often below detection threshold in the voluntary than in the involuntary condition. Could this be the reason why no attentional RT benefits were observed in voluntary unaware trials? We conducted a correlation analysis to test whether when participants were unaware of targets, attentional RT benefits could be found in those participants exhibiting smaller threshold differences between the cued and uncued locations. However, no significant correlation was observed ($r = 0.15$, $p = 0.60$), suggesting that the lack of RT benefits in the voluntary unaware trials was unlikely due to large differences in the estimated thresholds between cued and uncued locations.

2.3. Discussion

Both voluntary and involuntary attentions facilitated access to awareness, as conscious detection was comparably enhanced at the cued relative to the uncued location in both conditions. However, these two forms of attention did not facilitate awareness in the same way, as consciously perceived targets were also more accurately discriminated in the voluntary condition only. The reason that no improved accuracy was observed in unaware trials might be due to a floor effect in performance (accuracy at chance). Reciprocally, whether or not a target was consciously perceived differentially affected the attentional RT effects induced by voluntary and involuntary: an attentional RT benefit for *consciously* seen targets was found in the *voluntary* condition, whereas an attentional RT benefit for *unconsciously* processed targets was observed in the *involuntary* condition.

In the voluntary condition, we assumed that predictive arrow cues engaged voluntary attention mechanisms. However, it has been suggested that predictive arrow cues could trigger a combination and possibly an interaction between voluntary and involuntary attention (Ristic & Kingstone, 2002). In addition, the arrow cues used in this study displayed a black and white contrast which seemed offset in the direction that the arrows were cueing. Could this contrast trigger automatically attentional processes? In Experiment 2, we addressed these issues by replacing arrow cues with symbolic color cues to engage voluntary attention only.

3. Experiment 2: voluntary symbolic condition

3.1. Methods

3.1.1. Participants

Fourteen right-handed participants (9 females, mean age = 22.47 years, range = 19–32) without past neurological or psychiatric history took part in the experiment. All had normal or corrected-to-normal vision and gave their written informed consent to take part in the study.

3.1.2. Stimuli and procedure

The stimuli and the procedure from the previous voluntary condition were used, except that the arrows were replaced by color cues (Fig. 1B). In brief, after the fixation, a white or black cue appeared on the centre of the screen. Half of the participants were instructed that when a black cue appeared, they should shift attention to the lower left quadrant, and when a white cue appeared, they should shift it to the lower right. The color-location association was reversed in the other half of participants. A grating target at threshold for conscious detection was then presented at either the cued or the uncued location with 65% cue validity. The threshold contrasts of the targets for the cued (1.71 ± 0.24%) and uncued (2.19 ± 0.38%) locations were estimated during the calibration session, as what has been done in Experiment 1. The averaged threshold contrast across cued and uncued locations was used during the subsequent experimental session.

3.2. Results

3.2.1. Subjective and objective measures of awareness

The overall results were analogous to those obtained in the voluntary condition with arrow cues. Participants reported the presence of a grating target much more often when the grating was actually present than absent (false alarm rate, 6.61 ± 1.70%), as revealed by a statistically significant $d' = 1.66 \pm 0.16$ (t test against zero, $t(13) = 10.22$, $p < 0.001$) and $\beta = 1.31 \pm 0.20$ ($t(13) = 6.64$, $p < 0.001$). Participants' accuracy in the orientation discrimination task was high when they reported being aware of the stimuli (90.47 ± 2.31%), but at chance level when they reported not being aware of the stimuli (53.26 ± 1.72%, binomial test, $p = 0.18$). Reaction times were shorter in unaware (817.02 ± 70.74 ms) than in aware trials (1049.22 ± 49.30 ms) (paired t tests, $t(13) = 5.04$, $p < 0.001$), further confirming that participants were guessing when they reported not seeing targets.

3.2.2. Mutual influence between attention and awareness

We first analyzed the influence of attention on conscious detection. As expected, voluntary attention triggered by symbolic color cues facilitated conscious detection (Fig. 2C), with higher detection rate at the cued (60.32 ± 3.9%) than at the uncued location (39.68 ± 3.49%, paired t test, $t(13) = 4.41$, $p < 0.001$). The magnitude of such conscious enhancement triggered by predictive arrow cues (voluntary condition of Experiment 1) and predictive color cues used here was not significantly different (unpaired t test, $t(13) = 0.29$, $p = 0.78$). In unaware trials, conscious enhancement at the cued location was not accompanied by any sign of improved accuracy performance (cued: 52.61 ± 2.32%, uncued: 53.79 ± 2.58%; $t(13) = 0.42$, $p = 0.68$). When targets were consciously detected, target orientation tended to be more accurately discriminated at the cued location (91.63 ± 2.06%) relative to the uncued location (85.35 ± 4.48%) although the difference did not reach statistical significance (paired t test, $t(13) = 1.69$, $p = 0.11$).

Awareness also influenced voluntary symbolic attention (Fig. 3C). When participants reported consciously seeing the target, they discriminated it faster at the cued (1017.22 ± 53.3 ms) compared to the uncued location (1081.23 ± 47.87 ms; paired t test, $t(13) = 2.74$, $p < 0.05$). By contrast, no attentional RT effect was observed when participants did not report seeing a target (cued: 829.22 ± 75.18 ms, uncued: 804.82 ± 67.69 ms, $t(13) = 1.15$, $p = 0.27$). We also compared the size of the attentional RT effects induced by the predictive arrow cues and the symbolic color cues. The results showed that the effects were comparable for both types of predictive cues (unpaired t test, $t(13) = 0.29$, $p = 0.77$).

3.3. Discussion

Using predictive color cues instead of arrows cues, the same pattern of relationship between voluntary attention and awareness was replicated. First, voluntary attention triggered by either the symbol or the arrow cues facilitated conscious detection to a similar extent. Second, comparable attentional effects (RT difference between the cued and the uncued location) were obtained only when participants were subjectively aware of the targets. The absence of RT benefits in unaware trials suggests that no additional automatic attention was involved when the arrow cues were predictive. In sum, the current findings provided further support that the paradigm employed in the voluntary condition of Experiment 1 did gauge the processing of voluntary attention.

4. Experiment 3: counterpredictive condition

The data obtained so far seem to suggest that voluntary and involuntary attentions interact differently with awareness. However, these data were obtained in separate experiments involving distinct groups of participants. What would happen when voluntary and involuntary attentions are combined in the same paradigm? Would there be a competition between them, or would they trigger separate attentional effects in aware and unaware trials respectively? In addition, we observed a distinct pattern of interactions with awareness for voluntary and involuntary attentions in different groups of participants. It is therefore also worth checking that the between-group effect did not contribute to the differences obtained in Experiment 1 regarding how voluntary and involuntary attentions interact with awareness.

To probe these issues, a counterpredictive task was designed in which both voluntary and involuntary attention processes were engaged together. In this task, participants were required to shift their attention to the location opposite to that indicated by the arrow cues because targets would appear there most often. In the light of previous research (Friesen, Ristic, & Kingstone, 2004; Posner, Cohen, & Rafal, 1982; Tipples, 2008), we reasoned that the RT advantage at the predicted location (the location opposite to where arrows indicated) would reflect the influence of voluntary attention, whereas any RT advantage at the unpredicted location (the location indicated by the arrows) would reflect the influence of involuntary attention.

4.1. Methods

4.1.1. Participants

Fourteen right-handed participants (11 females, mean age = 23.46 years, range = 19–25) without past neurological or psychiatric history took part in the experiment. All had normal or corrected-to-normal vision and gave their written informed consent.

4.1.2. Stimuli and procedure

Stimuli and procedure were identical as before (Fig. 1), except that a grating target would be more likely to appear at the location *opposite* to where the arrow cues pointed (predicted location, 65% probability) than at the location indicated by the arrows (unpredicted location). Threshold contrasts at the predicted (1.34 ± 0.16%) and unpredicted (1.67 ± 0.26%) locations were estimated during the calibration session, and averaged to set contrast threshold for the experiment.

4.2. Results

4.2.1. Subjective and objective measures of awareness

Participants reported the presence of a grating target much more often when the grating was actually present than absent (false alarm rate, 9.26 ± 1.68%) as revealed by a statistically significant $d' = 1.48 \pm 0.12$ (t test against zero, $t(13) = 10.95$, $p < 0.001$) and $\beta = 1.01 \pm 0.14$ ($t(13) = 6.54$, $p < 0.001$). Besides, accuracy at the orientation discrimination task was higher when subjects reported seeing grating targets (82.2 ± 4.86%) than not seeing them (54.29 ± 1.70%). Accuracy in unaware trials was close to being significantly different from chance level (binomial, $p = 0.06$). Whether such close-to-above-chance performance had any impact on the results will be further addressed in Section 4.2.3. As before, reaction times in the orientation discrimination task were much shorter in unaware (621.82 ± 53.32 ms) than in aware trials

(983.60 ± 37.73 ms) (paired *t* test, $t(13) = 6.67$, $p < 0.0001$), suggesting that participants were making random guesses when unaware.

4.2.2. Mutual interactions between attention and awareness

As shown in Fig. 2D, participants were better at detecting the presence of a grating at the predicted (60.4 ± 3.84%) relative to the unpredicted location (38.4 ± 5.22%; paired *t* test, $t(13) = 2.91$, $p < 0.05$). Awareness was therefore facilitated by voluntary attention here. Because involuntary attention would have had an opposing effect (facilitated detection at the unpredicted location), we tested whether the attentional enhancement of conscious detection in the counterpredictive task was reduced compared to the condition in which voluntary attention operated alone. The result showed that the magnitude of conscious enhancement was not significantly different from the one observed in the voluntary condition of Experiment 1 (unpaired *t* test, $t(13) = 0.43$, $p = 0.67$) and in the voluntary symbolic condition of Experiment 2 ($t(13) = 0.19$, $p = 0.85$). In addition, enhanced conscious detection at the predicted location was accompanied by improved accuracy performance when the target was consciously perceived (predicted: 83.64 ± 5.02%, unpredicted: 76.53 ± 4.99%; paired *t* test, $t(13) = 2.18$, $p < 0.05$), but no difference in accuracy performance was observed when the target was not consciously perceived (predicted: 54.54 ± 5.02%, unpredicted: 53.93 ± 1.94%; $t(13) = 0.14$, $p = 0.89$). These results thus showed that voluntary attention facilitated conscious detection as well as increased accuracy at the orientation discrimination task at the predicted location.

The pattern of the attentional RT effects showed a clear dissociation depending on whether the stimulus was consciously experienced or not (Fig. 3D). When participant reported being aware of the target, they discriminated the gratings much faster at the predicted location (951.82 ± 36.07 ms) compared to the unpredicted location (1015.40 ± 41.27 ms; $t(13) = 3.59$, $p < 0.01$). This result replicated the finding from the voluntary condition in Experiment 1, indicating the involvement of voluntary attention in the processing of consciously seen targets. We further compared the size of effects with those obtained in the voluntary condition and found that the effects were comparable in both experiments (unpaired *t* test, $t(13) = 0.91$, $p = 0.37$). When targets were not consciously seen, shorter RTs were found at the *unpredicted* location (594.77 ± 54.22 ms) compared to the *predicted* location (648.88 ± 54.12 ms; $t(13) = 2.82$, $p < 0.05$), suggesting that involuntary attention drove the effect. The size of the RT effect obtained from the unaware trials in the counterpredictive condition was similar to the one observed when only involuntary attention was engaged in Experiment 1 (unpaired *t* test, $t(13) = 1.14$, $p = 0.27$).

4.2.3. Control analysis

Because the accuracy rate of the unaware trials in this experiment was close to above chance, we ran a correlation analysis to test whether the attentional effects observed in the unaware trials could be attributed to the participants with high accuracy performance. The results showed that the RT differences between predicted and unpredicted locations did not correlate with accuracy performance ($r = 0.083$, $p = 0.78$). In other words, when participants were unaware of the stimuli, those who exhibited better accuracy performance had comparable attentional effects compared to those who performed less well.

In the present study, we consistently found a shortening of RTs in unaware trials by involuntary attention. Is it possible that accuracy effects might not be revealed because of a floor effect in accuracy performance when participants reported not seeing the stimuli. To probe this possibility, we selected 7 participants who had above-than-chance performance in unaware trials. We then compared their accuracy performance at the predicted and unpredicted locations in unaware trials but found no significant effect of involuntary attention on accuracy data (unpredicted: 57.96 ± 2.4%, predicted: 55.19 ± 1.8%, paired *t* test, $t(6) = 1.10$, $p = 0.31$). By contrast, these participants showed a strong trend to respond faster at the unpredicted (666.30 ± 101.50 ms) relative to the predicted (710.65 ± 101.87 ms) location (paired *t* test, $t(6) = 2.19$, $p = 0.07$), indicating the presence of RT benefits by involuntary attention. To summarize, this pattern of results lends further support to the idea that involuntary attention influenced RTs, not accuracy, in unaware trials.

4.3. Discussion

Taken together, the counterpredictive task employed in this experiment faithfully reflected our previous findings regarding how awareness influenced attention. Attentional effects driven by voluntary attention were obtained in aware trials, whereas attentional effects triggered by involuntary attention were observed in unaware trials. Moreover, the size of these effects seems to be comparable with those found previously when voluntary and involuntary attentions were manipulated independently in different tasks (Experiment 1). In other words, the pattern of RT results might simply be an additive combination of those from the voluntary and involuntary conditions. The current data could therefore suggest that awareness influenced these two attentional mechanisms in an independent, additive manner, rather than in an interactive manner.

The pattern of results concerning the influence of voluntary and involuntary attentions on awareness was quite different. In the counterpredictive task used here, voluntary and involuntary attentions exerted their influence at opposite spatial locations. One might therefore expect that at least, the effect of voluntary attention on conscious detection should be reduced due to the influence of involuntary attention. Instead, we found that the size of the attentional facilitation of conscious detection at the predicted location was not significantly different from the one observed in the voluntary condition. Thus, this suggests that involuntary attention, when competing with voluntary attention, has little impact on guiding awareness. However, involuntary attention did not simply disappear in the counterpredictive task. Indeed, we were still able to observe an attentional shortening of RT at the unpredicted location in unaware trials, similar to the signature of the influence of involuntary attention found in the involuntary condition of Experiment 1.

5. General discussion

We aimed at testing whether or not voluntary and involuntary attentions interact in a different manner with awareness. It should be underlined that in this study, awareness was defined by subjective reports of visibility. By manipulating cue predictability, we could isolate voluntary and involuntary forms of attention as well as combine them in the same design. Both voluntary and involuntary attentions facilitated conscious detection at the cued location, and to a similar extent, although probably through distinct mechanisms. Sorting out trials according to their subjective aware or unaware status revealed that awareness has a deep impact on attentional influences. On the one hand, voluntarily attended targets were processed faster and with higher accuracy, but only when they were consciously perceived. On the other hand, involuntarily attended targets were processed faster, without any accuracy improvement, and only when they were not consciously perceived.

5.1. Distinction between voluntary and involuntary attentions

Although both voluntary and involuntary attentions shortened reaction times and facilitated conscious detection, they appeared here as two different processes with distinct behavioral consequences. First, attentional benefits were obtained in aware trials for voluntary attention, but in unaware trials for involuntary attention, a surprising dissociation that will be fully discussed in Section 5.2. A second important distinction between the two types of attention is that improved accuracy performance was found in the case of voluntary attention only. This finding is congruent with the proposal that voluntary attention acts upon perceptual representations, making them not only easier to access but also more accurate, and that involuntary attention rather affects decisional processing (Prinzmetal, Ha, & Khani, 2010; Prinzmetal et al., 2005), possibly at response selection or execution stages (Sumner, Tsai, Yu, & Nachev, 2006). More specifically, after perceptual evidence has been accumulated, involuntary attention would mainly affect a readout stage by biasing the system to begin the readout of the accumulator at the cued location, resulting in shorter reaction times at the cued location. Because the speed of the read-out stage does not depend on whether the accumulator is indeed filled with relevant information, the shortening of reaction times by involuntary attention is not necessarily accompanied by an improvement in accuracy, especially when participants are not under speed pressure (Prinzmetal et al., 2005, 2010). Interestingly, the accumulator model has been found to be particularly relevant to account for involuntary attention influence when the difficulty of the task is to decide whether a stimulus was present or not (Prinzmetal et al., 2005, 2010).

Altogether, although technically speaking, the current paradigm was not a speeded task in the sense that participants had to wait until a response screen appeared before they could answer, the distinct patterns of RT and accuracy performance induced by voluntary and involuntary attentions closely agree with previous literature. Therefore, our results demonstrated that voluntary and involuntary attentions could successfully be isolated by manipulating cue predictability, and suggested that these two types of attention operate via perceptual and post-perceptual mechanisms respectively (Prinzmetal et al., 2005, 2010). Our results further extend these previous findings by suggesting that the effects of voluntary and involuntary attentions on reaction times are likely to be independent ones, because when both voluntary and involuntary were simultaneously operating as in the counterpredictive condition in Experiment 3, RT effects were similar to those obtained in Experiment 1 when voluntary and involuntary attentions operated in isolation.

5.2. The shortening of RTs by voluntary and involuntary attentions depends on awareness

The main result of this series of experiments is that the behavioral influence of voluntary and involuntary attentions, as measured by reaction times in the orientation discrimination task, depends on whether or not the stimulus was consciously perceived. When participants reported seeing the target, the RT benefit was due to voluntary attention. When participants reported *not* seeing the target, the RT effect was due to involuntary attention. Further experiments ruled out that these distinct patterns of results could be attributed to different groups of participants (Experiment 3: counterpredictive condition) or to a mixture of voluntary and involuntary processes in the voluntary condition (Experiment 2: voluntary symbolic condition).

There are known cases when voluntary attention can operate on stimuli that remain invisible to participants. Kentridge et al. (2008) showed that the processing of a masked, invisible prime can be modulated by voluntary spatial attention. This result could seem at odds with our own finding that voluntary spatial attention influenced RTs in aware trials only. However, there are three major differences between the two studies. First, in Kentridge et al. study, primes were rendered invisible by metacontrast masks, while here stimuli were at threshold. Second, in Kentridge et al.'s study, participants responded to a mask that was visible in all trials, whereas in the present experiment, they responded to an unseen stimulus in unaware trials. Third, distractors were present, while they were absent from the present study. Determining which factor is the relevant one leading to such discrepancy is far beyond the scope of the present study. Overall, it should be noted that our finding that voluntary attention, in the experimental conditions reported here, did not affect unconscious stimulus processing, cannot be generalized to all types of experimental conditions.

The shortening of RTs by involuntary attention in *unaware* trials might appear surprising at first. However, it is actually closely in line with recent evidence, showing that exogenous attention, triggered by non informative peripheral cues, may affect orientation discrimination (Bahrami, Carmel, Walsh, Rees, & Lavie, 2008) or priming effects (Marzouki, Grainger, & Theeuwes, 2007; Sumner et al., 2006) *outside* the conscious domain. Although the exact nature of the relationship between involuntary attention triggered by central cues and exogenous attention triggered by peripheral cues remains largely unknown, some similarities between the two processes have already been underlined (Bonato, Priftis, Marenzi, & Zorzi, 2009). Probably the most puzzling aspect of our results is that the influence of involuntary attention on RTs was observed for unseen but not for seen stimuli. This could simply be a mechanistic consequence of shorter RTs in unaware trials: Since involuntary attention influence dissipates rapidly with time (Friesen et al., 2004; Ristic & Kingstone, 2002), it would influence only those trials with short RTs – and short RT trials happen to be in unaware trials. In addition, a previous study (Tipples, 2002) has shown that involuntary attention influence on consciously perceived stimuli were most effective at SOAs (stimulus onset asynchrony) of 100 and 300 ms. Accordingly, the 600 ms SOA adopted in the current paradigm might additively reduce the processing of *seen* targets. From this perspective, it is also possible that involuntary attention had differential influence on seen and unseen stimuli, as the influence on unseen stimuli was more sustained. In any case, the sustained time-course of involuntary attention in unaware trials stands in contrast with the typical short time-window in which exogenous attention operates, suggesting these two forms of attention are functionally distinct.

Whatever the reason for the observed dissociation, last but not least, our behavioral results raise the intriguing possibility that it is the aware or unaware status of the stimulus that determines the type of attentional modulation that can be applied. The direction of this proposal (awareness determining attention) stands in contrast with the classical view that attention controls awareness.

The finding that the influence of voluntary attention is best revealed in aware trials and that the influence of involuntary attention is best revealed in unaware trials stands in contrast with the idea that attentional effects on conscious and unconscious processing are fundamentally of the same nature. Indeed, it has long been held that the more the response to a stimulus is amplified by attention, the more likely this stimulus reaches awareness. In this view, attentional modulations of conscious and unconscious stimuli would fundamentally be of the same nature, with strong attentional enhancement leading to awareness. An alternative, more recent view, supported by both behavioral (Kentridge et al., 2008; Sumner et al., 2006) and neural (Schurger et al., 2008; Wyart & Tallon-Baudry, 2008) data, is that attention and awareness can operate independently from each other. Our data are in line with this latter view, with distinct patterns of interactions between attention and awareness depending on which type of attention is involved. In addition, the findings that voluntary attention can sometimes operate on unseen stimuli (as reported in Kentridge et al., 2008) and sometimes does not, as in the present experiment, further suggests that voluntary attention and perceptual awareness are best considered as two separate processes, which may interact in different ways depending on experimental context.

It is worth noting that we did not observe any influence of involuntary attention on *accuracy*, only on RTs, in unaware trials. As discussed above, this result is consistent with the literature about the lack of accuracy modulation by involuntary attention. However, a negative result should always be considered cautiously. In all our experiments, accuracy was at chance in unaware trials. Therefore, an absence of accuracy modulations by involuntary attention might be due to a floor effect. To further probe this possibility, we ran a control analysis on those subjects who had above than chance performance in unaware trials (Experiment 3), and found again evidence for an influence of involuntary attention on RTs only, not on accuracy. Although the results seem to be compatible with our overall findings, the number of subjects in the control analysis was small ($n = 7$), and therefore statistical power was weak. As a consequence, the possibility that a floor effect leads to the lack of an involuntary effect on accuracy performance in unaware trials cannot be completely ruled out.

5.3. *Voluntary and involuntary attentions facilitate awareness via different mechanisms*

Conscious detection was facilitated by both voluntary and involuntary attentions when these two forms of attention operated in isolation (Experiment 1). This facilitation was measured as an increase in hit rates at the cued location relative to the uncued location. Because d' and criterion could not be computed separately for these two locations, we cannot determine whether the facilitation of awareness by voluntary or involuntary attention was due to a greater sensitivity, a criterion shift, or both. However, there are several reasons why our results suggest that the facilitation of detection by voluntary and involuntary attentions involved different mechanisms. First, consciously perceived targets were more accurately discriminated in the voluntary condition but not in the involuntary condition, as revealed in Experiment 1. Second, when voluntary and involuntary attentions were combined, conscious detection was facilitated by voluntary attention (Experiment 3). If both forms of attention were involved in the *same* mechanism that interacts with conscious detection, one might expect that when voluntary and involuntary attentions operate simultaneously but are opposed to each other, as in the counterpredictive condition, the influence of *both* voluntary and involuntary attentions on conscious detection should be somewhat cancelled out, and thereby diminished. Rather, although the influence of involuntary attention was reduced in this context, as participants did not exhibit any better conscious detection of the targets at the location pointed by arrow cues, a facilitation of conscious detection could still be obtained at the predicted location, indicating the act of voluntary attention.

Based on our previous work using a task similar to the voluntary condition adopted here (Schurger et al., 2008; Wyart & Tallon-Baudry, 2008), it is likely that voluntary attention is able to facilitate conscious detection because attentional enhancement triggered by voluntary attention adds up with awareness-related activity. The nature of the neural mechanism by which involuntary attention facilitates awareness remains more elusive. It is possible that involuntary attention biases the system toward reading the accumulated sensory evidence at the cued location first, as previously suggested and discussed in Section 5.1 (Prinzmetal et al., 2005, 2010). As a result, a target would be more likely to be consciously detected at the cued location. However, the facilitation of conscious detection by involuntary attention would disappear while competing with voluntary attention, possibly because in that case, voluntary attention would affect an earlier perceptual stage, yielding ceiling effects on the readout component of the model.

6. Conclusion

Both voluntary and involuntary spatial attentions facilitate conscious detection, and to a similar extent, suggesting that volition may not be a critical feature for perceptual awareness. Whether participants consciously perceived the targets or not determined that the attentional RT effects were triggered by voluntary or involuntary attention. Our data therefore indicate that different forms of attention interact differently with awareness, a point that should be taken into account when attempting at defining the relationships between attention and awareness. Our results also imply that in addition to the classical influence of attention on awareness, whether or not a stimulus is consciously perceived can determine which type of attentional modulation can take place.

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