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Research report

Involuntary attentional orienting in the absence of awareness speeds up early sensory processing

Antonio Schettino [a,*,1], *Valentina Rossi* [b,1], *Gilles Pourtois* [b] *and*
Matthias M. Müller [a]

[a] *Institute of Psychology I, University of Leipzig, Leipzig, Germany*
[b] *Department of Experimental — Clinical and Health Psychology, Ghent University, Ghent, Belgium*

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ABSTRACT

A long-standing controversy in the field of human neuroscience has revolved around the question whether attended stimuli are processed more rapidly compared to unattended stimuli. We conducted two event-related potential (ERP) experiments employing a temporal order judgment procedure in order to assess whether involuntary attention accelerates sensory processing, as indicated by latency modulations of early visual ERP components. A non-reportable exogenous cue could precede the first target with equal probability at the same (compatible) or opposite (incompatible) location. The use of non-reportable cues promoted automatic, bottom-up attentional capture, and ensured the elimination of any confounds related to the use of stimulus features that are common to both cue and target. Behavioral results confirmed involuntary exogenous orienting towards the unaware cue. ERP results showed that the N1pc, an electrophysiological measure of attentional orienting, was smaller and peaked earlier in compatible as opposed to incompatible trials, indicating cue-dependent changes in magnitude and speed of first target processing in extrastriate visual areas. Complementary Bayesian analysis confirmed the presence of this effect regardless of whether participants were actively looking for the cue (*Experiment* 1) or were not informed of it (*Experiment* 2), indicating purely automatic, stimulus-driven orienting mechanisms.

1. Introduction

Titchener's law of *prior entry* states that attended stimuli are processed more rapidly than unattended stimuli (Titchener, 1908). Behavioral evidence for this phenomenon comes from temporal order judgment tasks (*TOJ*; Shore, Spence, & Klein, 2001; Spence & Parise, 2010), in which participants subjectively report which of two stimuli, separated by variable stimulus onset asynchronies (SOAs), appeared first. Perceptual judgments are biased towards attended stimuli, particularly at short SOAs. However, while this behavioral effect has classically been attributed to attention, alternative non-

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* *Corresponding author*. Institute of Psychology I, University of Leipzig, Neumarkt 9-19, 04109, Leipzig, Germany.
E-mail address: antonio.schettino@uni-leipzig.de (A. Schettino).

[1] Co-first authors.

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attentional interpretations have also been put forward, highlighting the influence of response biases, changes in decision criteria, or sensory facilitation (Jaskowski, 1993; Schneider & Bavelier, 2003).

Event-related potentials (*ERPs*) may provide more direct evidence of the attentional nature of prior entry (e.g., Spence, Shore, & Klein, 2001), and inform on the neural systems involved in this effect. In spatial attention research, directional shifts along the horizontal axis have been linked to a series of lateralized deflections – event-related lateralizations, *ERLs* – reflecting the asymmetric representation of perceptual environments in the visual system: when attention is directed towards one side of the visual field, electrical responses are increased in the controlateral as opposed to the ipsilateral hemisphere (Heinze, Luck, Mangun, & Hillyard, 1990; Heinze et al., 1994; Luck, Woodman, & Vogel, 2000). This asymmetry can be captured by subtracting ipsi-from contralateral ERPs, resulting in a series of deflections (P1pc, N1pc, N2pc, N3pc) which have been related to the speed and efficiency of attentional orienting (Verleger, Zurawska Vel Grajewska, & Jaśkowski, 2012). In a TOJ task, amplitude and latency modulations of these early brain responses (especially within 80–200 msec following stimulus onset) would hint at increased mass synchronization of target-related neural activity in ventral and dorsal extrastriate visual areas (Di Russo, Martínez, & Hillyard, 2003; Hopfinger & Mangun, 1998), suggesting a pivotal role of attentional orienting *before* the activation of response-related networks. However, the only two ERP studies that used TOJ tasks to investigate the electrophysiological correlates of prior entry did not consider ERLs, and reported discrepant findings concerning more classical ERP responses. One study (McDonald, Teder-Sälejärvi, Di Russo, & Hillyard, 2005) used a non-predictive auditory cue to reflexively capture attention towards one of two peripheral red and green LEDs, which could flash simultaneously or be separated in time by various SOAs. Results showed cue-dependent amplitude modulations of P1 and N1 components elicited by simultaneous visual targets, but no latency shifts. In the other study (Vibell, Klinge, Zampini, Spence, & Nobre, 2007), participants were required to judge the perceived temporal order of tactile (a tap by small plastic rods operated by solenoids attached to the index fingers) and visual stimuli (flashes of red light emitted by LEDs placed on the solenoids). P1 and N1 components elicited by the visual targets peaked on average 3–4 msec earlier when vision was attended compared to when touch was attended.

It is difficult to accommodate these two studies within a coherent theoretical framework, and this goes beyond the obvious incompatibility of their main findings. First, the use of cross-modal TOJ procedures likely resulted in reduced attentional competition between targets presented in different sensory modalities, in accordance with numerous studies in the literature showing enhanced competition within but not between senses (Duncan, Martens, & Ward, 1997; Franconeri, Alvarez, & Cavanagh, 2013; Keitel, Maess, Schröger, & Müller, 2013; Parks, Hilimire, & Corballis, 2011; Porcu, Keitel, & Müller, 2014; Talsma, Doty, Strowd, & Woldorff, 2006). A corollary of this issue is that the electrophysiological results obtained with such cross-modal tasks cannot directly be compared with classical unimodal cueing paradigms, which typically show amplitude enhancement of early visual ERP components elicited by cued targets without concurrent latency modulations (Hillyard, Vogel, & Luck, 1998; Hopf, Heinze, Schoenfeld, & Hillyard, 2009). Second, these studies used distinct experimental setups to tackle very different questions: the task employed by Vibell et al. (2007) required *top-down* sustained attention towards one sensory modality (i.e., vision or touch), whereas McDonald et al. (2005) used a non-predictive auditory cue to capture participants' visuospatial attention in a *bottom-up*, stimulus-driven fashion. A preliminary synthesis of these data appears to indicate that latency shifts of early ERP components can be observed only when visual stimuli are *endogenously* attended (Vibell et al., 2007) – perhaps because congruent with current goals determined by task instructions (e.g., Folk, Remington, & Johnston, 1992) –, whereas *exogenous* attentional orienting does not seem to affect ERP latencies (McDonald et al., 2005), at least in cross-modal TOJ tasks. In sum, three questions still remain unanswered: (1) Can involuntary, bottom-up spatial attention influence the speed of perceptual analysis in temporally challenging conditions? (2) Can this attention-dependent sensory acceleration be observed within one sensory modality, i.e., vision? (3) Would top-down attention allocation additively or interactively influence processing speed or, conversely, not play any role in it?

To directly address these issues, we devised a visual TOJ task in which participants were required to judge the perceived temporal order of horizontal and vertical line gratings separated by various SOAs. An uninformative exogenous cue could occasionally appear for 20 msec, preceding either the first or second line grating (*compatible* and *incompatible* conditions, respectively). This very short presentation prevented conscious perception of the cue (see Section 2.3). We reasoned that any attentional biases towards targets previously preceded by a non-reportable exogenous cue would provide even stronger evidence of automatic attentional orienting, as suggested elsewhere (McCormick, 1997; Mulckhuyse & Theeuwes, 2010; Posner & Snyder, 1975; Yantis & Jonides, 1990). In order to track the electrophysiological correlates of prior entry in our TOJ paradigm, we focused on one specific ERL component: the *N1pc*, a negative deflection starting at approximately 120 msec after stimulus onset, which has been shown to reflect the initial orienting of attention along the horizontal meridian (Verleger et al., 2012; Wascher, Hoffmann, Sänger, & Grosjean, 2009). In our study, N1pc amplitude ought to be smaller in compatible relative to incompatible targets, given that no attentional reorienting would be needed in such conditions (Fu, Greenwood, & Parasuraman, 2005; Gibbons, Wiegleb, & Stahl, 2013; Ruge & Naumann, 2006; Wascher & Beste, 2010). Crucially, any latency shifts of this component – i.e., earlier target-elicited N1pc for compatible as opposed to incompatible trials – would provide an electrophysiological indication of attention-dependent accelerated sensory processing (Spence et al., 2001; Vibell et al., 2007).

Before the N1pc in response to the target stimuli, we should be able to measure another negative deflection in compatible trials, indicating an initial orienting response to the cued location. This component should be of inverted polarity (i.e., positive) in incompatible trials (see Casiraghi, Fortier-Gauthier, Sessa, Dell'Acqua, & Jolicœur, 2013), and absent when no cue is displayed on screen. Importantly, we should not be able to observe any changes in latency because, if this component truly reflects the first sweep of attentional capture, it could not benefit from any preparatory activity because nothing precedes the unpredictable cue. This would provide converging evidence that latency shifts of the N1pc to the first target do not result from carry-over effects originated by sensory refractoriness and, therefore, accelerated sensory processing would directly be linked to fast attentional orienting mechanisms in extrastriate visual cortex.

In addition, we aimed at testing whether attention effects on the N1pc to cues and targets would be maximized when top-down attention was directed to the cues, or whether this automatic orienting would be insensitive to task set. To do so, we manipulated prior knowledge about the cues. In *Experiment* 1, participants were informed that a cue could sometimes be flashed at the beginning of the trial, but were explicitly told that it would not help them resolve the TOJ task. Cue awareness was assessed on a subset of trials, after giving the manual response for the TOJ. This awareness check procedure provided a more objective measure of observers' inability to consciously perceive the exogenous cue. We also predicted that these task demands would activate top-down attentional sets that may interact with stimulus-driven attentional capture: in fact, previous studies have shown that unconscious priming depends on successfully allocating attention to the time window during which the prime–target pair is presented (Kiefer & Brendel, 2006; Naccache, Blandin, & Dehaene, 2002). To test if any cueing effects on the speed or amplitude of the ERLs were only driven by this top-down attentional set, in *Experiment* 2 we informed participants of the presence of the cue only at the end of the experimental session (see also Ivanoff & Klein, 2003). The absence of differences between experiments (investigated with a Bayesian approach) would suggest that top-down, task-induced goals do not influence initial attentional orienting during early stages of visual processing (Theeuwes, 2004).

2. Materials and methods

2.1. *Participants*

The study met the requirements of the Declaration of Helsinki as well as of local and national ethics committees. Forty undergraduate students were recruited at the universities of Leipzig and Ghent (20 in each university, evenly distributed across experiments), and received monetary compensation or course credit after their participation. Informed consent was obtained for all participants. All volunteers were right-handed, had normal or corrected-to-normal vision, and no history of neurological or psychiatric disorders. Poor behavioral performance of two participants in Experiment 1 (i.e., absence of a reliable psychometric curve) led to their exclusion from the final dataset, leaving a final sample of 18 individuals (12 women, mean age 23 years, range 18–33). In Experiment 2, three participants were excluded because they reported having seen the exogenous cue, leaving a total of 17 individuals (12 women, mean age 24 years, range 18–33).

2.2. *TOJ: stimuli, procedure, and data analysis*

The study was conducted in dimly lit Faraday cages on PCs connected to 19″ CRT monitors with screen resolution of 1024 × 768 pixels and 100 Hz refresh rate. Stimulus presentation was controlled with E-Prime 2.0 (Schneider, Eschman, & Zuccolotto, 2002). Each trial started with a central fixation cross (degrees of visual angle: .96° × .96° at 60 cm viewing distance) and two placeholders (4.77° × 2.86°) located on the left and right side of fixation (3.10° of eccentricity along the horizontal meridian), displayed on a white background (Fig. 1). After 2000 msec, in two-thirds of the trials, one of the placeholders (either left or right, with equal probability) got thicker – from 5 to 7 pixels – for 20 msec. From a perceptual standpoint, this particular cue was markedly dissimilar to the targets. This has two major advantages. First, any observed prior entry effects could not be attributed to "illusory conjunction" phenomena (Schneider & Bavelier, 2003; Treisman & Schmidt, 1982), i.e., perceptually "fusing" features shared by both cue and target, which would lead to judge a target as appearing first while, in reality, the cue was processed but mistakenly identified as the target. Second, we could avoid any influences of top-down attentional task sets that may interfere with a purely bottom-up capture of attention. This is particularly relevant because the cue was presented below the threshold of subjective awareness (Ansorge, Horstmann, & Scharlau, 2011; Kiefer et al., 2011). Forty milliseconds after cue offset, a line grating enclosed in an oval frame (see also Schettino, Loeys, & Pourtois, 2013, Experiments 4–5) appeared with equal probability (50% cue-target spatial contingency) either

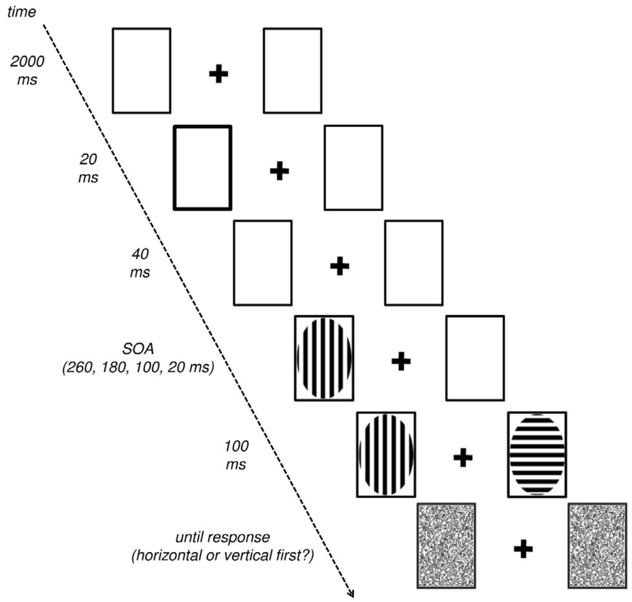

Fig. 1 – Experimental procedure. Two lateral placeholders were followed (on two-thirds of the trials) by a non-reportable exogenous cue. After a fixed cue-target interval, horizontal or vertical lines were displayed either within the cued placeholder or on the opposite side. The first stimulus stayed on screen for a variable SOA, before being followed by the second stimulus on the opposite side. Participants judged which line grating appeared first.

in the cued placeholder or on the opposite side (compatible and incompatible trials, respectively). The orientation of the lines in the first grating could either be horizontal or vertical, with equal probability. The second line grating (whose lines were always of opposite orientation relative to the first one) appeared in the other placeholder after a variable *SOA* (260, 180, 100, or 20 msec). Both line gratings remained on screen for 100 msec, before being simultaneously masked until response. Participants had to perform a two-alternative forced choice task regarding the orientation of the grating appearing as first by pressing numbers 2 or 8 (counterbalanced) on a standard numeric pad of a USB keyboard. This discrimination task was preferred over a simple detection task (i.e., judge whether the first target appeared on the left or right hemifield) because it directed participants' attention towards different features of cue and target – i.e., thickness in the former, orientation in the latter –, which further mitigates the influence of top-down attentional task sets that would confound a purely stimulus-driven capture of attention (Ansorge, Horstmann, et al., 2011; Folk et al., 1992; Kiefer et al., 2011). Furthermore, this procedure allowed us to dampen stimulus-response compatibility effects – known to seriously affect the behavioral outcome of TOJ tasks (Schneider & Bavelier, 2003; Shore et al., 2001) – in two ways: (i) participants were required to identify the *orientation* of the first line grating, not its *location*; (ii) response buttons were located on the *vertical* axis, whereas the stimuli were presented on the *horizontal* axis (see also Schettino et al., 2013). Five hundred and twenty-eight trials (44 for each SOA and cue condition) were randomly intermixed in six blocks (88 trials each) of the experimental task, preceded by verbal and written instructions as well as a practice block (with feedback) containing 12 trials.

Accuracy was expressed as the proportion of *horizontal first* responses (Shore et al., 2001). Positive SOAs refer to trials in which the horizontal line grating was presented first, whereas negative SOAs indicate that the vertical line grating was presented first (Fig. 2A and C). Responses occurring 2000 msec after the onset of the bilateral masks were discarded (Experiment 1: $M = 3.24\%$, $SE = .64$; Experiment 2: $M = 2.18\%$, $SE = .49$; no differences between experiments). Individual points of subjective simultaneity (*PSS*) were obtained by: (i) converting the proportion of horizontal first responses into z-scores using a standardized normal distribution; (ii) calculating the slope and intercept of the best-fitted linear regression on these z-scores; (iii) calculating the PSS according to the formula: PSS = –slope/intercept (see Moseley, Gallace, & Spence, 2009). Prior entry effects were subsequently assessed by comparing these values against 0 with two-tailed one-sample *t*-tests.

2.3. *Cue awareness assessment*

In Experiment 1, cue detection was assessed in 9% of the trials (equally distributed across compatible, incompatible, and no cue conditions). Three questions were presented in these trials after the TOJ response: (Q1) have you seen the cue? [yes/no]; (Q2) was it on the left or right? If you have not seen it, please guess [left/right]; (Q3) how clear was it? [4–point Perceptual Awareness Scale, *PAS* (Ramsøy & Overgaard, 2004)]. Sensitivity (d') and response bias (β) measures on responses to Q1 were calculated for each observer (Green & Swets, 1966;

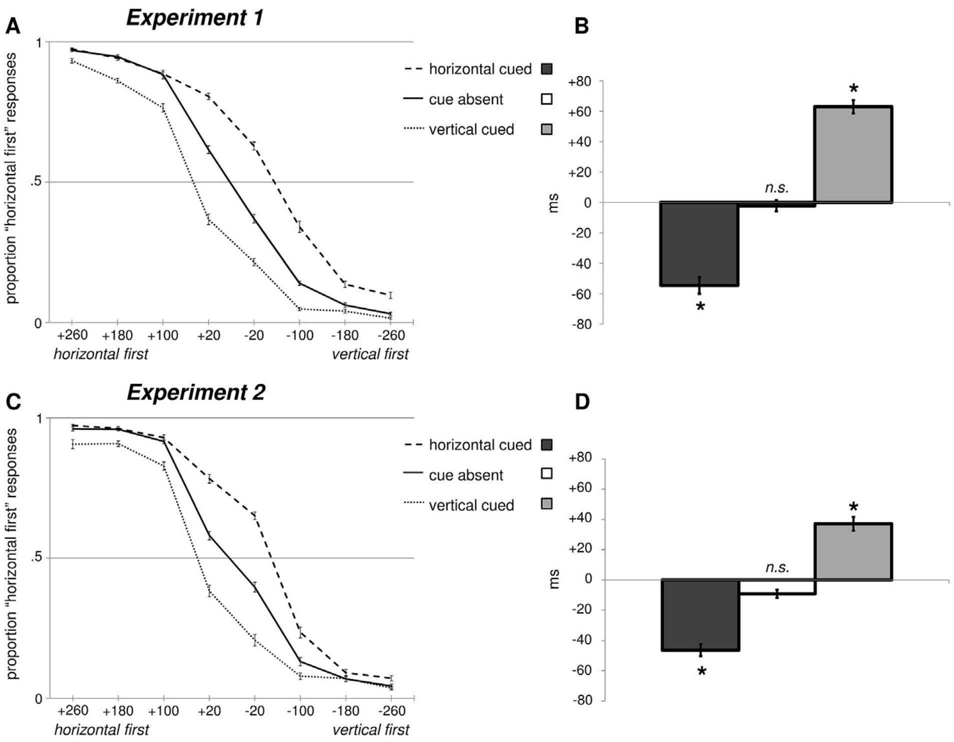

Fig. 2 – Behavioral results. Mean proportion of *horizontal first* responses as a function of SOA, separately for each cue condition, in Experiments 1 (A) and 2 (C). Horizontal shifts of the psychometric curves relative to the cue absent condition indicate prior entry effects for cued stimuli, as confirmed by PSS values significantly different from zero (B, D). Vertical bars represent standard error of the mean (SE). *: statistically different from zero; *n.s.*: non-significant.

Stanislaw & Todorov, 1999). Two-tailed one-sample t-tests against 0 on d' values verified whether participants could reliably detect the exogenous cue when presented, whereas two-tailed one-sample t-tests against 1 on β values evaluated whether participants showed a tendency to favor either "yes" or "no" responses. To assess implicit cue detection, we additionally ran chi-square tests of independence on responses to Q2 only in trials in which the cue was present and observers reported not having seen it (i.e., negative responses to Q1). Finally, responses to Q3 were used to plot the Receiver Operating Characteristic (ROC; Fawcett, 2006) and calculate the Area Under the Curve (AUC). AUC values close to .5 indicate poor discrimination between signal and noise (i.e., presence *vs* absence of the cue, respectively).

Participants in Experiment 2 were not informed of the cue (Ivanoff & Klein, 2003). Upon completion of the TOJ task, they were asked to freely report any unexpected events that they noticed during the experiment. Afterwards, they were shown an example of the exogenous cue and asked whether they believed it had been presented during the main task. Only participants who responded negatively to these first two questions were retained in the final analysis ($N = 17$). A follow-up PAS (Ramsøy & Overgaard, 2004) probed the extent to which the cue had consciously been processed. When participants were told that the cue had in fact been presented to them, a 5-point Likert scale evaluated their level of surprise (from 1, not surprised at all, to 5, extremely surprised).

2.4. EEG recording and preprocessing

EEG was recorded at a sampling rate of 256 Hz from 64 Ag/AgCl electrodes fitted into an elastic cap using ActiveTwo amplifier systems (BioSemi, Inc., The Netherlands). Horizontal and vertical electrooculograms (EOGs) were monitored using four additional electrodes placed on the outer canthi of each eye and in the inferior and superior areas of the left orbit. Data preprocessing was performed offline with customized MATLAB scripts (v7.11.0; The MathWorks, Inc., Natick, MA) using functions included in EEGLAB v13.2.1 (Delorme & Makeig, 2004), ERPLAB v4.0.2.3 (Lopez-Calderon & Luck, 2014), and FASTER v1.2.3b (Nolan, Whelan, & Reilly, 2010) toolboxes. The continuous EEG was referenced to Cz and low-pass filtered (non-causal windowed-sinc finite impulse response filter, 30 Hz half-amplitude cutoff) after subtracting the mean value of the signal (DC offset). Epochs time-locked to the onset of the exogenous cue (or, in the cue absent conditions, at the corresponding time point) were created for each cue condition and SOA, including a 200 msec baseline (also used for correction) and extending to 800 msec post-cue onset. Artifact correction was performed with independent component analysis (Jung et al., 2000), and noisy channels were interpolated via a spherical spline procedure (Perrin, Pernier, Bertrand, & Echallier, 1989). ERLs were calculated by subtracting ipsilateral from contralateral electrophysiological activity originated by the first line grating, in order to identify lateralized components associated with attentional orienting (Verleger et al., 2012). ERLs were advantageous for two additional reasons: (i) to avoid a differential overlap of cue-elicited ERPs on activity related to the first target (Anllo-Vento, 1995); (ii) to minimize the problems associated with interpreting latency shifts of peaks of ERP components (Luck, 2005). Importantly, in our analysis we focused exclusively on the shortest SOA (i.e., 20 msec), because our main objective was to quantify *competing* attentional orienting towards the first and second line gratings that was influenced by cue location. The other SOAs were included in the experimental design only to obtain a reliable estimate of prior entry at the behavioral level, and will not be discussed further.

Following visual inspection of the ERLs, we extracted mean amplitude and peak latency values at electrodes PO7/PO8 in two time windows: 80–130 msec and 130–180 msec after first target onset (see Table 1). Please note that the first measurement window (80–130 msec) corresponded to an interval of 140–190 msec after cue onset, thus corresponding to the N1pc to the lateralized non-reportable cue (*N1pc-cue*). On the other hand, the second interval corresponded to the N1pc to the first target (*N1pc-target*).[2] Amplitude and latency differences across cue conditions were analyzed by means of repeated measures ANOVAs (rANOVAs) followed by paired-sample two-tailed t-tests.

2.5. General statistical procedures

All the analyses were performed using PASW Statistics v18 (www.spss.com.hk/statistics). Significance level was set at $p = .05$. When using rANOVAs, Greenhouse-Geisser correction was applied in case of violation of sphericity, and partial eta squared (η_p^2) was used as a measure of effect size. Post-hoc comparisons were carried out by means of two-tailed paired-sample t-tests, and Pearson's r was used as a measure of effect size (Cohen, 1992; Field, 2013). T-tests were integrated by bootstrapped (5000 samples with replacement) bias-corrected and accelerated 95% confidence intervals of mean differences ($CI_{.95}$; Efron & Tibshirani, 1993; Efron, 1987).

2.6. Exploration of task differences

Split-plot rANOVAs on our behavioral and electrophysiological measures, with *cue* as within-subject factor and *task* as

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[2] A closer look at the grand-average ERLs (Fig. 3A and D) revealed the presence of another, positive component 180–230 msec after first target onset, presumably reflecting attentional reorienting from the first to the second line grating. Due to the subtraction used to calculate the ERLs locked to the fist target, this orienting component is expected to be reversed in polarity, becoming positive in response to shifts of attention towards the second target (which appeared always contralaterally to the first one). Note that the present TOJ task is created in such a way that the incompatible condition for the first line grating is, at the same time, the *compatible* condition for the *second* line grating. Thus, in this condition, we would expect no attentional reorienting towards the second line grating (i.e., lower amplitude), because the exogenous cue already attracted attention to that location. Conversely, the compatible condition for the first line grating is also the *incompatible* condition for the *second* line grating; therefore, we would expect larger amplitude due to attentional reorienting. This is exactly what can be observed in Fig. 3A and D, and it has been verified statistically. However, the concurrent overlapping ERPs elicited by the first line grating prevent us from drawing definitive conclusions. Therefore, this component will not be discussed further.

Table 1 – Mean and standard error (in parenthesis) of amplitude (in μV) and peak latency values (in ms) of the N1pc to the cue (N1pc-cue; 80–130 msec after first target) and the N1pc to the target (N1pc-target; 130–180 msec after first target) at the shortest SOA (20 msec).

Component	Experiment	Measure	Condition		
			Congruent	Cue absent	Incongruent
N1pc-cue	Exp. 1	Amplitude	−1.44 (.64)	−.04 (.33)	1.57 (.39)
		Latency	102.54 (4.72)	103.85 (4.03)	103.41 (3.18)
	Exp. 2	Amplitude	−1.62 (.50)	−.28 (.39)	1.10 (.48)
		Latency	105.44 (5.01)	104.75 (3.78)	97.86 (3.62)
N1pc-target	Exp. 1	Amplitude	.25 (.53)	−1.41 (.43)	−2.97 (.55)
		Latency	137.05 (2.15)	146.38 (2.24)	155.71 (2.40)
	Exp. 2	Amplitude	1.65 (.74)	−1.17 (.52)	−3.25 (.67)
		Latency	138.53 (2.81)	145.42 (2.39)	151.17 (3.52)

between-subject factor, were first used to assess differences between experiments. As mentioned in the *Introduction*, if N1pc modulations reflected purely stimulus-driven attentional (re-)orienting, task instructions should not play any role and, as a consequence, we should observe no differences between Experiment 1 and 2 in either N1pc-cue or N1pc-target. However, given the impossibility to accept the null hypothesis (i.e., absence of differences) with classical null-hypothesis statistical testing procedures, we turned to Bayesian inference testing (Jeffreys, 1961; Kass & Raftery, 1995). Following the procedure outlined in Wagenmakers (2007), we used the PASW output of the split-plot rANOVAs to derive an estimation of posterior probabilities of H_1 (behavioral and electrophysiological differences between experiments, corresponding to the *cue* × *task* interaction model) and H_0 (no task differences, corresponding to the simple effect of *cue*) based on the Bayesian Information Criterion (*BIC*; Kass & Raftery, 1995; Raftery, 1995). First, we calculated the difference between the BIC of H_1 and H_0 (ΔBIC_{10}) according to the formula:

$$\Delta BIC_{10} = n*\log(SSE_1/SSE_0) + (k_1 - k_0)*\log(n)$$

where n is the number of participants, SSE_1 is the sum of squares that is not explained by the *cue* × *task* interaction model (i.e., the error sum of squares), SSE_0 is the sum of squares that is not explained by the simple effect of *cue* (i.e., the error sum of squares plus the sum of squares associated with the interaction model), k is the number of parameters of each model (in our case, $k_1 - k_0 = 1$), and *log* indicates the conversion to natural logarithm (see Wagenmakers, 2007, Equation 14). A positive ΔBIC_{10} would indicate lower BIC for H_0 than H_1 and, consequently, H_0 ought to be preferred over H_1. Note that, by following this procedure, an objective uniform prior distribution is hypothesized, meaning that no *a priori* preference for either H_0 or H_1 was included in the analysis (see also Lee & Wagenmakers, 2005). In a second step (Wagenmakers, 2007, Equation 12), we quantified the extent of the preference towards H_0 by estimating the posterior probability of H_0 given the data [$Pr_{BIC}(H_0 \mid D)$] according to the formula:

$$Pr_{BIC}(H_0 \mid D) = 1/[1 + \exp(-0.5*\Delta BIC_{10})].$$

To facilitate the interpretation of these posterior probabilities, we followed the arbitrary convention proposed by Raftery (1995) and verbally described the results as reflecting "weak", "positive", "strong", or "very strong" evidence in favor of either H_0 or H_1 (see also Wagenmakers, 2007, Table 3).

3. Results

3.1. *Cue assessment*

In Experiment 1, sensitivity (*d′*) was at chance level ($M = .08$, $SE = .14$; $t_{17} = .58$, $p = .571$, $r = .14$, $CI_{.95}$ [−.17, .32]), and no response bias (β) was observed ($M = 1.87$, $SE = .78$; $t_{17} = 1.11$, $p = .281$, $r = .26$, $CI_{.95}$ [−.18, 2.19]). We also found no evidence of implicit awareness for the position of the cue ($\chi^2_{1,\, N=473} = 2.67$, $p = .102$). Finally, AUC was .62 ($SE = .02$), indicative of poor signal-noise discrimination performance.

The majority of observers in Experiment 2 ($N = 17$) did not spontaneously report having seen the cue. A follow-up PAS (Ramsøy & Overgaard, 2004) confirmed that most of them ($N = 13$) did not see the cue at all, with only 2 people having a brief glimpse and 2 having almost a clear image. When the experimenters revealed that the exogenous cue had been presented, the majority of participants were quite surprised ($N = 10$) or extremely surprised ($N = 4$). Of note, the exclusion of individuals who reported having seen the exogenous cue to some extent and/or were not very surprised did not change the pattern of results; therefore, they were retained in the analysis to have power comparable with Experiment 1.

3.2. *Behavioral results*

Average PSS values in Experiment 1 were −54.52 msec ($SE = 10.94$) when the horizontal line grating was cued, 62.96 msec ($SE = 8.75$) when the vertical line grating was cued, and −2.25 ($SE = 7.20$) when no cue was presented (Fig. 2B). Cued line gratings were consistently perceived as appearing first (horizontal: $t_{17} = -4.98$, $p < .001$, $r = .77$, $CI_{.95}$ [−75.56, −34.99]; vertical: $t_{17} = 7.20$, $p < .001$, $r = .87$, $CI_{.95}$ [47.29, 80.53]), whereas no bias was observed in the absence of the cue ($t_{17} = -.31$, $p = .758$, $r = .07$, $CI_{.95}$ [−15.33, 11.24]).

In Experiment 2, average PSS was −46.38 msec ($SE = 7.84$) when the horizontal line grating was cued, 37.13 msec ($SE = 9.16$) when the vertical line grating was cued, and −9.10 msec ($SE = 5.52$) when no cue was presented (Fig. 2D). Participants responded more often that the cued line gratings had appeared first (horizontal: $t_{16} = -5.92$, $p < .001$, $r = .83$, $CI_{.95}$

[−63.53, −30.85]; vertical: $t_{16} = 4.05$, $p = .001$, $r = .71$, $\text{CI}_{.95}$ [19.78, 56.53]), with no bias in the cue absent condition ($t_{16} = -1.65$, $p = .119$, $r = .38$, $\text{CI}_{.95}$ [−22.12, 1.43]).

3.3. *ERP results*

3.3.1. *N1pc-cue*

In a first step, we compared against zero the amplitude values extracted in a time window 80–130 msec post-target onset (which corresponded to 140–190 msec after cue onset) across the three cue conditions. Consistent with our predictions, no detectable N1pc-cue was observed in the cue absent condition (Exp. 1: $t_{17} = -.11$, $p = .916$, $r = .03$, $\text{CI}_{.95}$ [−.62, .55]; Exp. 2: $t_{16} = .72$, $p = .480$, $r = .18$, $\text{CI}_{.95}$ [−1.00, .44]), as opposed to a reliable N1pc-cue for compatible (Exp. 1: $t_{17} = -2.27$, $p = .036$, $r = .48$, $\text{CI}_{.95}$ [−2.70, −.39]; Exp. 2: $t_{16} = -3.24$, $p = .005$, $r = .63$, $\text{CI}_{.95}$ [−2.62, −.70]) and incompatible trials (Exp. 1: $t_{17} = 4.03$, $p = .001$, $r = .70$, $\text{CI}_{.95}$ [.81, 2.42]; Exp. 2: $t_{16} = 2.29$, $p = .036$, $r = .50$, $\text{CI}_{.95}$ [.23, 1.91]). Mean amplitude values were also significantly different across cue conditions (Exp. 1: $F_{1.38,\ 23.41} = 10.26$, $p = .002$, $\eta_p^2 = .38$; Exp. 2: $F_{1.47,\ 23.47} = 7.41$, $p = .006$, $\eta_p^2 = .32$), consistently showing the expected N1pc-cue polarity reversal for compatible as opposed to incompatible trials (Exp. 1: $t_{17} = -3.52$, $p = .003$, $r = .65$, $\text{CI}_{.95}$ [−4.59, −1.56]; Exp. 2: $t_{16} = -3.08$, $p = .007$, $r = .61$, $\text{CI}_{.95}$ [−4.40, −1.16]). Importantly, latency analysis did not show differences across cue conditions (Exp. 1: $F_{2,\ 34} = .02$, $p = .976$, $\eta_p^2 < .01$; Exp. 2: $F_{2,\ 32} = 1.31$, $p = .284$, $\eta_p^2 = .08$), confirming no sensory acceleration due to the cue's spatial unpredictability.

3.3.2. *N1pc-target*

Activity 130–180 msec post-target onset reflected the initial orienting of attention towards the first line grating, as evidenced by larger amplitude than baseline when no cue was presented (Exp. 1: $t_{17} = -3.26$, $p = .005$, $r = .62$, $\text{CI}_{.95}$ [−2.18, −.59]; Exp. 2: $t_{16} = -2.23$, $p = .041$, $r = .49$, $\text{CI}_{.95}$ [−2.27, −.26]). This analysis confirmed that this component was neither the sole result of sensory refractoriness nor was heavily contaminated by overlapping cue-related activity because, in this condition, no cue was presented.

In Experiment 1 (Fig. 3A), mean amplitude values of the N1pc-target were significantly different across cue conditions ($F_{1.43,\ 24.29} = 7.91$, $p = .005$, $\eta_p^2 = .32$). A larger (i.e., more negative) amplitude was found in incompatible relative to compatible trials ($t_{17} = 3.27$, $p = .004$, $r = .62$, $\text{CI}_{.95}$ [1.23, 5.33]), whereas activity in compatible condition was smaller than cue absent condition ($t_{17} = -3.24$, $p = .005$, $r = .62$, $\text{CI}_{.95}$ [−2.62, −.67]) (Fig. 3B). Importantly, latency values were also statistically different across conditions ($F_{2,\ 34} = 36.42$, $p < .001$, $\eta_p^2 = .68$). Shorter latencies were observed for compatible compared to incompatible ($t_{17} = -7.24$, $p < .001$, $r = .87$, $\text{CI}_{.95}$ [−23.00, −14.54]) and cue absent ($t_{17} = 4.72$, $p < .001$, $r = .75$,

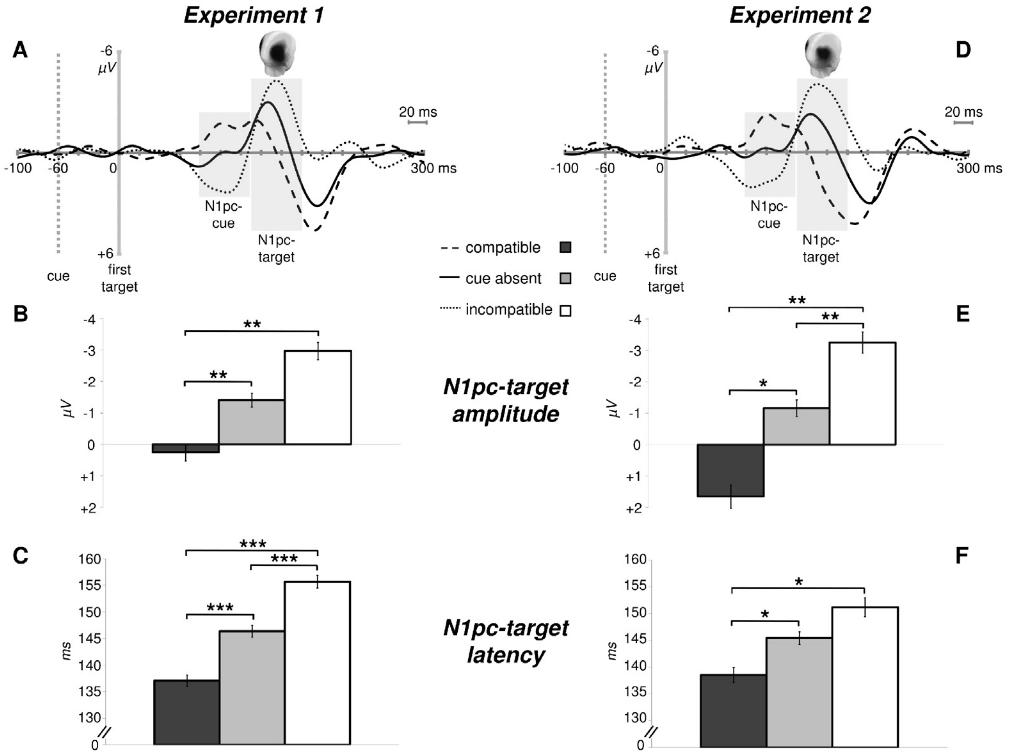

Fig. 3 – ERP results. Grand average of contra-minus ipsilateral ERPs at occipitotemporal electrodes in Experiment 1 (A) and 2 (D). Gray areas indicate amplitude and peak measurement windows of the N1pc elicited by cue and target (80–130 and 130–180 msec after first target onset, respectively). The location of the preceding unaware cue (vertical dotted line) selectively modulated the latency of the N1pc to the target (showing the characteristic occipitotemporal topography), with smaller (B, E) and earlier (C, F) activity for compatible compared to incompatible trials. Vertical bars represent SE *: *p* < .05; **: *p* < .01; *: *p* < .001.**

$CI_{.95}$ [5.64, 12.80]) conditions. N1pc-target also peaked earlier in cue absent relative to incompatible trials ($t_{17} = -4.79$, $p < .001$, $r = .76$, $CI_{.95}$ [-13.02, -5.86]) (Fig. 3C).

Similar results were obtained in Experiment 2 (Fig. 3D). N1pc-target amplitudes were significantly modulated by the exogenous cue ($F_{1.24,\ 19.88} = 12.23$, $p = .001$, $\eta_p^2 = .43$). Activity was more negative in incompatible relative to compatible ($t_{16} = 3.80$, $p = .002$, $r = .69$, $CI_{.95}$ [2.57, 7.47]) and cue absent trials ($t_{16} = 3.63$, $p = .002$, $r = .67$, $CI_{.95}$ [1.12, 3.16]). Smaller amplitude was also observed for compatible compared to cue absent condition ($t_{16} = -2.86$, $p = .011$, $r = .58$, $CI_{.95}$ [-4.79, -1.09]) (Fig. 3E). Latencies were also significantly different across cue conditions ($F_{1.35,\ 21.58} = 5.38$, $p = .022$, $\eta_p^2 = .25$). Shorter latencies were observed for compatible compared to incompatible ($t_{16} = -2.55$, $p = .021$, $r = .54$, $CI_{.95}$ [-20.91, -3.91]) and cue absent trials ($t_{16} = 2.65$, $p = .018$, $r = .55$, $CI_{.95}$ [2.07, 11.49]) (Fig. 3F).

3.4. *Comparisons between Experiment 1 and 2*

With regards to behavioral performance, a split-plot rANOVAs on PSS values revealed no significant *cue* × *task* interaction ($F_{1.44,\ 47.65} = 2.09$, $p = .148$, $\eta_p^2 = .06$). Bayesian analysis confirmed no behavioral differences between experiments, with “weak” evidence in favor of H_0 [$\Delta BIC_{10} \approx 1.41$, $Pr_{BIC}(H_0 \mid D) \approx .67$].

Similar results were observed for our electrophysiological measures. For the N1pc-cue, no significant *cue* × *task* interaction was found either in amplitude ($F_{1.42,\ 47.00} = .05$, $p = .898$, $\eta_p^2 < .01$) or latency ($F_{2,\ 66} = .62$, $p = .543$, $\eta_p^2 = .02$). Complementary Bayesian analysis indicated “positive” evidence in favor of H_0 for both amplitude [$\Delta BIC_{10} \approx 3.50$, $Pr_{BIC}(H_0 \mid D) \approx .85$] and latency [$\Delta BIC_{10} \approx 2.91$, $Pr_{BIC}(H_0 \mid D) \approx .81$]. Separate mixed rANOVAs on N1pc-target amplitude and latency values also showed no significant *cue* × *task* interactions (amplitude: $F_{1.47,\ 48.66} = .91$, $p = .383$, $\eta_p^2 = .03$; latency: $F_{1.46,\ 48.25} = .96$, $p = .365$, $\eta_p^2 = .03$). Bayesian analysis revealed “positive” evidence in favor of H_0, both for amplitude [$\Delta BIC_{10} \approx 2.61$, $Pr_{BIC}(H_0 \mid D) \approx .79$] and latency [$\Delta BIC_{10} \approx 2.55$, $Pr_{BIC}(H_0 \mid D) \approx .78$].

In sum, behavioral and electrophysiological evidence pointed towards a reliable absence of differences between Experiments 1 and 2.

4. Discussion

In two ERP experiments employing a visual TOJ task, we demonstrated that involuntary spatial attention accelerates perceptual processing starting around 130 msec after target onset. Participants were required to judge the perceived temporal order of two competing line gratings separated by various SOAs. In two-thirds of the trials, an uninformative, non-reportable exogenous cue preceded the first line grating at the same or opposite location. Behavioral results showed a robust bias towards the stimulus appearing at the location previously occupied by the unaware exogenous cue, especially at the short SOAs. Carefully controlled experimental parameters (see Section 2.2) allowed us to exclude potential confounds, such as response biases (Jaskowski, 1993; Schneider & Bavelier, 2003) or top-down attentional task sets (Ansorge, Horstmann, et al., 2011; Folk et al., 1992; Kiefer et al., 2011). Our findings are therefore consistent with the notion of compelling, automatic, stimulus-driven attentional orienting towards non-reportable exogenous cues (Fuchs, Theeuwes, & Ansorge, 2013; Jonides, 1981; McCormick, 1997; Mulckhuyse, Talsma, & Theeuwes, 2007; Mulckhuyse & Theeuwes, 2010; Posner & Snyder, 1975).

Our ERP results further shed light on the electrophysiological correlates of this automatic orienting of attention towards unaware cues. First, we observed a lateralized component reflecting an orienting response to the cue (N1pc-cue), whose latency was similar across conditions. Second, amplitude and latency modulations of the N1pc component elicited by the first line grating (N1pc-target) indicated that the initial orienting towards the target location was influenced by the previous position of the cue. The amplitude of this component was smaller when cue and target shared the same spatial location, because reorienting was not necessary. Conversely, in incompatible trials, more neural resources and a longer processing time were needed in order to shift the attentional focus from the cued to the opposite visual hemifield, as evidenced by larger amplitude contralateral to the target location (Fu et al., 2005; Gibbons et al., 2013; Ruge & Naumann, 2006; Wascher & Beste, 2010). Crucially, N1pc-target also peaked 16 msec earlier (on average) in compatible relative to incompatible trials, suggesting that cue-related processing benefits affected both the magnitude and the time course of the neural response to stimuli subsequently appearing at cued locations. The fact that we obtained identical results with parametric (rANOVAs, *t*-tests) as well as non-parametric (bootstrapped confidence intervals) statistical procedures speaks in favor of the robustness of these findings, which ultimately provide compelling neurophysiological evidence for the attentional nature of prior entry effects by revealing sensory acceleration of neural activity in extrastriate brain areas. Interestingly, these results are coherent with earlier behavioral and electrophysiological reports which showed, using classical visual cueing paradigms, improved discriminability and acceleration of information processing at cued locations (e.g., Carrasco & McElree, 2001; Nobre, Sebestyen, & Miniussi, 2000). More importantly, our findings seem to suggest that target processing speed is enhanced from the earliest extrastriate responses, well within 200 msec following stimulus onset (Luck et al., 2000). Moreover, our results unequivocally demonstrate that this accelerated response can be functionally dissociated from the orienting response to the cues, which is temporally unaffected by its validity. Our amplitude analyses confirmed that attentional orienting to the eccentric non-reportable cue is reliably reflected in an enhanced contralateral response in the N1 interval, which is independent of top-down attentional set (Natale, Marzi, Girelli, Pavone, & Pollmann, 2006; Natale, Marzi, & Macaluso, 2010).

Under conditions of probabilistic uncertainty and temporal urgency, attention is automatically attracted towards locations where salient visual stimuli appear (Serences et al., 2005; Yantis & Jonides, 1984). These locations get prioritized, so that sensory processing of subsequent events is facilitated (Hopfinger & Mangun, 1998). This perceptual facilitation is carried out by means of sensory gain control mechanisms aimed at improving the signal-to-noise ratio of salient events (Hillyard et al., 1998; Luck, Chelazzi, Hillyard, & Desimone, 1997; Treue & Martínez-Trujillo, 1999). The temporal dynamics of these mechanisms, however, are not completely understood, and are also not fully implemented in recent computational models of attention (e.g., Reynolds & Heeger, 2009; but see Spratling & Johnson, 2004). In addition, these models typically account for neuronal modulation exerted by top-down, voluntary attention rather than bottom-up, stimulus-driven attentional capture (as observed in the present study). Based on our findings, it may be speculated that perceptual competition between visual stimuli appearing at salient locations in close temporal proximity would rely more on intracortical feedback within extrastriate visual areas as opposed to long-range, feedforward connections (Desimone, 1998; Desimone & Duncan, 1995; Reynolds & Heeger, 2009). While electrophysiological studies in humans cannot provide conclusive empirical evidence in favor of this view due to the nature of the signal recorded on the scalp, this remains an important issue that should be addressed in future research.

Another important finding of the present study is the absence of differences between the results of Experiments 1 and 2, as confirmed by Bayesian analysis. This is in accordance with previous behavioral results showing similar prior entry effects elicited by non-reportable cues regardless of task instructions (Weiβ & Scharlau, 2012). More importantly, our ERP results suggest that the initial orienting of attention towards salient locations seems to be immune to task differences or changes in observers' mindset (Mulckhuyse & Theeuwes, 2010; Theeuwes, 2004). Instead, the presence of non-informative exogenous cues, due to their perceptual salience (Itti & Koch, 2000, 2001), may automatically capture spatial attention already in a time window 100–150 msec after onset, corresponding to the early feed-forward phase of visual processing (Lamme & Roelfsema, 2000).

Of note, we do not wish to claim that top-down contingent attentional capture never plays a role in early visual processing: several studies, in fact, have already shown that top-down goals can influence attentional selection of non-reportable stimuli (e.g., Ansorge, Kiss, & Eimer, 2009; Ansorge, Kiss, Worschech, & Eimer, 2011; Eimer & Kiss, 2008; Kiss, Grubert, Petersen, & Eimer, 2012). With regards to our study, one could argue that participants might have completed the task by first detecting the location of the first target and subsequently recalling its lines' orientation. This might explain the lack of behavioral and electrophysiological differences between Experiment 1 and 2, since the cued dimension (location) was part of observers' task set in both experiments.[3] We tried to prevent participants from (explicitly or implicitly) using this strategy by masking both locations soon after the presentation of the line gratings, but we cannot be sure that they did not rely on a short-term memory representation of the first target. This issue will be addressed in future experiments.

To conclude, here we provide direct empirical evidence that, in perceptually demanding tasks, attention can be captured efficiently and independently from goal-related attentional sets, influencing early stages of stimulus processing in less than 200 msec.

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