

1 Running head: SPEEDED ATTENTIONAL ORIENTING

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5 **Involuntary Attentional Orienting in the Absence of Awareness**

6 **Speeds Up Early Sensory Processing.**

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Highlights

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- 3 • We used a Temporal Order Judgment to investigate automatic attentional orienting
- 4 • Compatible and incompatible cues directed spatial attention, even when non-reportable
- 5 • N1pc latency showed that compatible cues accelerate sensory processing of targets
- 6 • Incompatible cues triggered the need for reorienting, enhancing N1pc amplitude
- 7 • Bayesian analyses suggested that attentional set did not influence these effects

Abstract

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6 2 A long-standing controversy in the field of human neuroscience has revolved around the
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9 3 question whether attended stimuli are processed more rapidly compared to unattended stimuli.
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11 4 We conducted two event-related potential (ERP) experiments employing a temporal order
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14 5 judgment procedure in order to assess whether involuntary attention accelerates sensory
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16 6 processing, as indicated by latency modulations of early visual ERP components. A non-
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19 7 reportable exogenous cue could precede the first target with equal probability at the same
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21 8 (compatible) or opposite (incompatible) location. The use of non-reportable cues promoted
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24 9 automatic, bottom-up attentional capture, and ensured the elimination of any confounds related
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26 10 to the use of stimulus features that are common to both cue and target. Behavioral results
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29 11 confirmed involuntary exogenous orienting towards the unaware cue. ERP results showed that
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31 12 the N1pc, an electrophysiological measure of attentional orienting, was smaller and peaked
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34 13 earlier in compatible as opposed to incompatible trials, indicating cue-dependent changes in
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36 14 magnitude and speed of first target processing in extrastriate visual areas. Complementary
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39 15 Bayesian analysis confirmed the presence of this effect regardless of whether participants were
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41 16 actively looking for the cue (*Experiment 1*) or were not informed of it (*Experiment 2*), indicating
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43 17 purely automatic, stimulus-driven orienting mechanisms.
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53 21 Keywords: Bayesian analysis; ERPs; N1pc; spatial attention; TOJ
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23 1. Introduction

24 Titchener's law of *prior entry* states that attended stimuli are processed more rapidly than
25 unattended stimuli (Titchener, 1908). Behavioral evidence for this phenomenon comes from
26 temporal order judgment tasks (*TOJ*; Shore, Spence, & Klein, 2001; Spence & Parise, 2010), in
27 which participants subjectively report which of two stimuli, separated by variable stimulus onset
28 asynchronies (*SOAs*), appeared first. Perceptual judgments are biased towards attended stimuli,
29 particularly at short *SOAs*. However, while this behavioral effect has classically been attributed
30 to attention, alternative non-attentional interpretations have also been put forward, highlighting
31 the influence of response biases, changes in decision criteria, or sensory facilitation (Jaskowski,
32 1993; K. A. Schneider & Bavelier, 2003).

33 Event-related potentials (*ERPs*) may provide more direct evidence of the attentional nature of
34 prior entry (e.g., Spence, Shore, & Klein, 2001), and inform on the neural systems involved in
35 this effect. In spatial attention research, directional shifts along the horizontal axis have been
36 linked to a series of lateralized deflections – event-related lateralizations, *ERLs* – reflecting the
37 asymmetric representation of perceptual environments in the visual system: when attention is
38 directed towards one side of the visual field, electrical responses are increased in the
39 contralateral as opposed to the ipsilateral hemisphere (Heinze et al., 1994; Heinze, Luck,
40 Mangun, & Hillyard, 1990; Luck, Woodman, & Vogel, 2000). This asymmetry can be captured
41 by subtracting ipsi- from contralateral *ERPs*, resulting in a series of deflections (*P1pc*, *N1pc*,
42 *N2pc*, *N3pc*) which have been related to the speed and efficiency of attentional orienting
43 (Verleger, Zurawska Vel Grajewska, & Jaśkowski, 2012). In a *TOJ* task, amplitude and latency
44 modulations of these early brain responses (especially within 80-200 ms following stimulus
45 onset) would hint at increased mass synchronization of target-related neural activity in ventral

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4 46 and dorsal extrastriate visual areas (Di Russo, Martínez, & Hillyard, 2003; Hopfinger &
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6 47 Mangun, 1998), suggesting a pivotal role of attentional orienting *before* the activation of
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9 48 response-related networks. However, the only two ERP studies that used TOJ tasks to investigate
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11 49 the electrophysiological correlates of prior entry did not consider ERLs, and reported discrepant
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14 50 findings concerning more classical ERP responses. One study (McDonald, Teder-Sälejärvi, Di
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16 51 Russo, & Hillyard, 2005) used a non-predictive auditory cue to reflexively capture attention
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19 52 towards one of two peripheral red and green LEDs, which could flash simultaneously or be
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21 53 separated in time by various SOAs. Results showed cue-dependent amplitude modulations of P1
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24 54 and N1 components elicited by simultaneous visual targets, but no latency shifts. In the other
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26 55 study (Vibell, Klinge, Zampini, Spence, & Nobre, 2007), participants were required to judge the
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29 56 perceived temporal order of tactile (a tap by small plastic rods operated by solenoids attached to
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31 57 the index fingers) and visual stimuli (flashes of red light emitted by LEDs placed on the
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34 58 solenoids). P1 and N1 components elicited by the visual targets peaked on average 3-4 ms earlier
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36 59 when vision was attended compared to when touch was attended.

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38 60 It is difficult to accommodate these two studies within a coherent theoretical framework, and
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41 61 this goes beyond the obvious incompatibility of their main findings. First, the use of cross-modal
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43 62 TOJ procedures likely resulted in reduced attentional competition between targets presented in
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46 63 different sensory modalities, in accordance with numerous studies in the literature showing
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48 64 enhanced competition within but not between senses (Duncan, Martens, & Ward, 1997;
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51 65 Franconeri, Alvarez, & Cavanagh, 2013; Keitel, Maess, Schröger, & Müller, 2013; Parks,
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53 66 Hilimire, & Corballis, 2011; Porcu, Keitel, & Müller, 2014; Talsma, Doty, Strowd, & Woldorff,
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55 67 2006). A corollary of this issue is that the electrophysiological results obtained with such cross-
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58 68 modal tasks cannot directly be compared with classical unimodal cueing paradigms, which
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4 69 typically show amplitude enhancement of early visual ERP components elicited by cued targets
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6 70 without concurrent latency modulations (Hillyard, Vogel, & Luck, 1998; Hopf, Heinze,
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8 71 Schoenfeld, & Hillyard, 2009). Second, these studies used distinct experimental setups to tackle
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10 72 very different questions: the task employed by Vibell et al. (2007) required *top-down* sustained
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12 73 attention towards one sensory modality (i.e., vision or touch), whereas McDonald et al. (2005)
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14 74 used a non-predictive auditory cue to capture participants' visuospatial attention in a *bottom-up*,
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16 75 stimulus-driven fashion. A preliminary synthesis of these data appears to indicate that latency
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18 76 shifts of early ERP components can be observed only when visual stimuli are *endogenously*
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20 77 attended (Vibell et al., 2007) – perhaps because congruent with current goals determined by task
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22 78 instructions (e.g., Folk, Remington, & Johnston, 1992) –, whereas *exogenous* attentional
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24 79 orienting does not seem to affect ERP latencies (McDonald et al., 2005), at least in cross-modal
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26 80 TOJ tasks. In sum, three questions still remain unanswered: (1) Can involuntary, bottom-up
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28 81 spatial attention influence the speed of perceptual analysis in temporally challenging conditions?
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30 82 (2) Can this attention-dependent sensory acceleration be observed within one sensory modality,
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32 83 i.e., vision? (3) Would top-down attention allocation additively or interactively influence
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34 84 processing speed or, conversely, not play any role in it?
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43 85 To directly address these issues, we devised a visual TOJ task in which participants were
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45 86 required to judge the perceived temporal order of horizontal and vertical line gratings separated
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47 87 by various SOAs. An uninformative exogenous cue could occasionally appear for 20 ms,
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49 88 preceding either the first or second line grating (*compatible* and *incompatible* conditions,
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51 89 respectively). This very short presentation prevented conscious perception of the cue (see *Section*
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53 90 2.3). We reasoned that any attentional biases towards targets previously preceded by a non-
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55 91 reportable exogenous cue would provide even stronger evidence of automatic attentional
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4 92 orienting, as suggested elsewhere (McCormick, 1997; Mulckhuyse & Theeuwes, 2010; Posner &
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6 93 Snyder, 1975; Yantis & Jonides, 1990). In order to track the electrophysiological correlates of
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9 94 prior entry in our TOJ paradigm, we focused on one specific ERL component: the *N1pc*, a
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11 95 negative deflection starting at approximately 120 ms after stimulus onset, which has been shown
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14 96 to reflect the initial orienting of attention along the horizontal meridian (Verleger et al., 2012;
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16 97 Wascher, Hoffmann, Sanger, & Grosjean, 2009). In our study, N1pc amplitude ought to be
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19 98 smaller in compatible relative to incompatible targets, given that no attentional reorienting would
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21 99 be needed in such conditions (Fu, Greenwood, & Parasuraman, 2005; Gibbons, Wiegleb, &
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24 100 Stahl, 2013; Ruge & Naumann, 2006; Wascher & Beste, 2010). Crucially, any latency shifts of
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26 101 this component – i.e., earlier target-elicited N1pc for compatible as opposed to incompatible
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29 102 trials – would provide an electrophysiological indication of attention-dependent accelerated
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31 103 sensory processing (Spence et al., 2001; Vibell et al., 2007).

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33 104 Before the N1pc in response to the target stimuli, we should be able to measure another
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36 105 negative deflection in compatible trials, indicating an initial orienting response to the cued
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38 106 location. This component should be of inverted polarity (i.e., positive) in incompatible trials (see
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41 107 Casiraghi, Fortier-Gauthier, Sessa, Dell’Acqua, & Jolicœur, 2013), and absent when no cue is
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43 108 displayed on screen. Importantly, we should not be able to observe any changes in latency
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46 109 because, if this component truly reflects the first sweep of attentional capture, it could not benefit
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48 110 from any preparatory activity because nothing precedes the unpredictable cue. This would
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51 111 provide converging evidence that latency shifts of the N1pc to the first target do not result from
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53 112 carry-over effects originated by sensory refractoriness and, therefore, accelerated sensory
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56 113 processing would directly be linked to fast attentional orienting mechanisms in extrastriate visual
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4 115 In addition, we aimed at testing whether attention effects on the N1pc to cues and targets
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6 116 would be maximized when top-down attention was directed to the cues, or whether this
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9 117 automatic orienting would be insensitive to task set. To do so, we manipulated prior knowledge
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11 118 about the cues. In *Experiment 1*, participants were informed that a cue could sometimes be
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14 119 flashed at the beginning of the trial, but were explicitly told that it would not help them resolving
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16 120 the TOJ task. Cue awareness was assessed on a subset of trials, after giving the manual response
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19 121 for the TOJ. This awareness check procedure provided a more objective measure of observers'
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21 122 inability to consciously perceive the exogenous cue. We also predicted that these task demands
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24 123 would activate top-down attentional sets that may interact with stimulus-driven attentional
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26 124 capture: in fact, previous studies have shown that unconscious priming depends on successfully
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29 125 allocating attention to the time window during which the prime-target pair is presented (Kiefer &
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31 126 Brendel, 2006; Naccache, Blandin, & Dehaene, 2002). To test if any cueing effect on the speed
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34 127 or amplitude of the ERLs was only driven by this top-down attentional set, in *Experiment 2* we
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36 128 informed participants of the presence of the cue only at the end of the experimental session (see
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38 129 also Ivanoff & Klein, 2003). The absence of differences between experiments (investigated with
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41 130 a Bayesian approach) would suggest that top-down, task-induced goals do not influence initial
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43 131 attentional orienting during early stages of visual processing (Theeuwes, 2004).

45 132 **2. Materials and Methods**

48 133 *2.1. Participants*

50 134 The study met the requirements of the Declaration of Helsinki as well as of local and national
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53 135 ethics committees. Forty undergraduate students were recruited at the universities of Leipzig and
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55 136 Ghent (20 in each university, evenly distributed across experiments), and received monetary
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58 137 compensation or course credit after their participation. Informed consent was obtained for all
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4 138 participants. All volunteers were right-handed, had normal or corrected-to-normal vision, and no
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6 139 history of neurological or psychiatric disorders. Poor behavioral performance of two participants
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9 140 in Experiment 1 (i.e., absence of a reliable psychometric curve) led to their exclusion from the
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11 141 final dataset, leaving a final sample of 18 individuals (12 women, mean age 23 years, range
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14 142 18-33). In Experiment 2, three participants were excluded because they reported having seen the
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16 143 exogenous cue, leaving a total of 17 individuals (12 women, mean age 24 years, range 18-33).
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18 144 *2.2. TOJ: stimuli, procedure, and data analysis*

19 145 The study was conducted in dimly lit Faraday cages on PCs connected to 19" CRT monitors
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21 146 with screen resolution of 1024 x 768 pixels and 100 Hz refresh rate. Stimulus presentation was
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24 147 controlled with E-Prime 2.0 (W. Schneider, Eschman, & Zuccolotto, 2002). Each trial started
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27 148 with a central fixation cross (degrees of visual angle: $0.96^\circ \times 0.96^\circ$ at 60 cm viewing distance)
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30 149 and two placeholders ($4.77^\circ \times 2.86^\circ$) located on the left and right side of fixation (3.10° of
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33 150 eccentricity along the horizontal meridian), displayed on a white background (*Figure 1*). After
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36 151 2000 ms, in two-thirds of the trials, one of the placeholders (either left or right, with equal
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38 152 probability) got thicker – from 5 to 7 pixels – for 20 ms. From a perceptual standpoint, this
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41 153 particular cue was markedly dissimilar to the targets. This has two major advantages. First, any
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43 154 observed prior entry effects could not be attributed to “illusory conjunction” phenomena (K. A.
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45 155 Schneider & Bavelier, 2003; Treisman & Schmidt, 1982), i.e., perceptually “fusing” features
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48 156 shared by both cue and target, which would lead to judge a target as appearing first while, in
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51 157 reality, the cue was processed but mistakenly identified as the target. Second, we could avoid any
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53 158 influences of top-down attentional task sets that may interfere with a purely bottom-up capture of
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55 159 attention. This is particularly relevant because the cue was presented below the threshold of
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58 160 subjective awareness (Ansorge, Horstmann, & Scharlau, 2011; Kiefer et al., 2011). Forty
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4 161 milliseconds after cue offset, a line grating enclosed in an oval frame (see also Schettino, Loeys,
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6 162 & Pourtois, 2013, Experiments 4-5) appeared with equal probability (50% cue-target spatial
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8 163 contingency) either in the cued placeholder or on the opposite side (compatible and incompatible
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10 164 trials, respectively). The orientation of the lines in the first grating could either be horizontal or
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12 165 vertical, with equal probability. The second line grating (whose lines were always of opposite
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14 166 orientation relative to the first one) appeared in the other placeholder after a variable *SOA* (260,
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16 167 180, 100, or 20 ms). Both line gratings remained on screen for 100 ms, before being
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18 168 simultaneously masked until response. Participants had to perform a two-alternative forced
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20 169 choice task regarding the orientation of the grating appearing as first by pressing numbers 2 or 8
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22 170 (counterbalanced) on a standard numeric pad of a USB keyboard. This discrimination task was
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24 171 preferred over a simple detection task (i.e., judge whether the first target appeared on the left or
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26 172 right hemifield) because it directed participants' attention towards different features of cue and
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28 173 target – i.e., thickness in the former, orientation in the latter –, which further mitigates the
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30 174 influence of top-down attentional task sets that would confound a purely stimulus-driven capture
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32 175 of attention (Ansorge, Horstmann, et al., 2011; Folk et al., 1992; Kiefer et al., 2011).
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34 176 Furthermore, this procedure allowed us to dampen stimulus-response compatibility effects –
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36 177 known to seriously affect the behavioral outcome of TOJ tasks (K. A. Schneider & Bavelier,
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38 178 2003; Shore et al., 2001) – in two ways: (i) participants were required to identify the *orientation*
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40 179 of the first line grating, not its *location*; (ii) response buttons were located on the *vertical* axis,
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42 180 whereas the stimuli were presented on the *horizontal* axis (see also Schettino et al., 2013). Five
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44 181 hundred and twenty-eight trials (44 for each *SOA* and cue condition) were randomly intermixed
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46 182 in six blocks (88 trials each) of the experimental task, preceded by verbal and written instructions
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48 183 as well as a practice block (with feedback) containing 12 trials.
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4 184 Accuracy was expressed as the proportion of *horizontal first* responses (Shore et al., 2001).
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6 185 Positive SOAs refer to trials in which the horizontal line grating was presented first, whereas
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9 186 negative SOAs indicate that the vertical line grating was presented first (*Figures 2A* and *2C*).
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11 187 Responses occurring 2000 ms after the onset of the bilateral masks were discarded (Experiment
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14 188 1: $M = 3.24\%$, $SE = 0.64$; Experiment 2: $M = 2.18\%$, $SE = 0.49$; no differences between
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16 189 experiments). Individual points of subjective simultaneity (*PSS*) were obtained by: (i) converting
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19 190 the proportion of horizontal first responses into z -scores using a standardized normal distribution;
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21 191 (ii) calculating the slope and intercept of the best-fitted linear regression on these z -scores; (iii)
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23 192 calculating the *PSS* according to the formula: $PSS = -\text{slope}/\text{intercept}$ (see Moseley, Gallace, &
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26 193 Spence, 2009). Prior entry effects were subsequently assessed by comparing these values against
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29 194 0 with two-tailed one-sample t -tests.

30 31 195 2.3. Cue awareness assessment

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33 196 In Experiment 1, cue detection was assessed in 9% of the trials (equally distributed across
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36 197 compatible, incompatible, and no cue conditions). Three questions were presented in these trials
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38 198 after the TOJ response: (Q1) have you seen the cue? [yes/no]; (Q2) was it on the left or right? If
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41 199 you have not seen it, please guess [left/right]; (Q3) how clear was it? [4-point Perceptual
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43 200 Awareness Scale, *PAS* (Ramsøy & Overgaard, 2004)]. Sensitivity (d') and response bias (β)
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46 201 measures on responses to Q1 were calculated for each observer (Green & Swets, 1966; Stanislaw
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48 202 & Todorov, 1999). Two-tailed one-sample t -tests against 0 on d' values verified whether
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51 203 participants could reliably detect the exogenous cue when presented, whereas two-tailed one-
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53 204 sample t -tests against 1 on β values evaluated whether participants showed a tendency to favor
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56 205 either “yes” or “no” responses. To assess implicit cue detection, we additionally ran chi-square
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58 206 tests of independence on responses to Q2 only in trials in which the cue was present and
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4 207 observers reported not having seen it (i.e., negative responses to Q1). Finally, responses to Q3
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6 208 were used to plot the Receiver Operating Characteristic (ROC; Fawcett, 2006) and calculate the
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9 209 Area Under the Curve (AUC). AUC values close to 0.5 indicate poor discrimination between
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12 210 signal and noise (i.e., presence vs. absence of the cue, respectively).
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14 211 Participants in Experiment 2 were not informed of the cue (Ivanoff & Klein, 2003). Upon
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16 212 completion of the TOJ task, they were asked to freely report any unexpected events that they
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19 213 noticed during the experiment. Afterwards, they were shown an example of the exogenous cue
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21 214 and asked whether they believed it had been presented during the main task. Only participants
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24 215 who responded negatively to these first two questions were retained in the final analysis ($N =$
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26 216 17). A follow-up PAS (Ramsøy & Overgaard, 2004) probed the extent to which the cue had
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29 217 consciously been processed. When participants were told that the cue had in fact been presented
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31 218 to them, a 5-point Likert scale evaluated their level of surprise (from 1, not surprised at all, to 5,
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33 219 extremely surprised).
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35 36 220 *2.4. EEG recording and preprocessing*

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38 221 EEG was recorded at a sampling rate of 256 Hz from 64 Ag/AgCl electrodes fitted into an
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41 222 elastic cap using ActiveTwo amplifier systems (BioSemi, Inc., The Netherlands). Horizontal and
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43 223 vertical electrooculograms (EOGs) were monitored using four additional electrodes placed on
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46 224 the outer canthi of each eye and in the inferior and superior areas of the left orbit. Data
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48 225 preprocessing was performed offline with customized MATLAB scripts (v7.11.0; The
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51 226 MathWorks, Inc., Natick, MA) using functions included in EEGLAB v13.2.1 (Delorme &
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53 227 Makeig, 2004), ERPLAB v4.0.2.3 (Lopez-Calderon and Luck, 2014), and FASTER v1.2.3b
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55 228 (Nolan, Whelan, & Reilly, 2010) toolboxes. The continuous EEG was referenced to Cz and low-
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58 229 pass filtered (non-causal windowed-sinc finite impulse response filter, 30 Hz half-amplitude
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4 230 cutoff) after subtracting the mean value of the signal (DC offset). Epochs time-locked to the
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6 231 onset of the exogenous cue (or, in the cue absent conditions, at the corresponding time point)
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9 232 were created for each cue condition and SOA, including a 200 ms baseline (also used for
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11 233 correction) and extending to 800 ms post-cue onset. Artifact correction was performed with
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14 234 independent component analysis (Jung et al., 2000), and noisy channels were interpolated via a
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16 235 spherical spline procedure (Perrin, Pernier, Bertrand, & Echallier, 1989). ERLs were calculated
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19 236 by subtracting ipsilateral from contralateral electrophysiological activity originated by the first
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21 237 line grating, in order to identify lateralized components associated with attentional orienting
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24 238 (Verleger et al., 2012). ERLs were advantageous for two additional reasons: (i) to avoid a
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26 239 differential overlap of cue-elicited ERPs on activity related to the first target (Anllo-Vento,
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29 240 1995); (ii) to minimize the problems associated with interpreting latency shifts of peaks of ERP
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31 241 components (Luck, 2005). Importantly, in our analysis we focused exclusively on the shortest
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33 242 SOA (i.e., 20 ms), because our main objective was to quantify *competing* attentional orienting
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36 243 towards the first and second line gratings that was influenced by cue location. The other SOAs
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38 244 were included in the experimental design only to obtain a reliable estimate of prior entry at the
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41 245 behavioral level, and will not be discussed further.

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43 246 Following visual inspection of the ERLs, we extracted mean amplitude and peak latency
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45 247 values at electrodes PO7/PO8 in two time windows: 80-130 ms and 130-180 ms after first target
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48 248 onset (see Table 1). Please note that the first measurement window (80-130 ms) corresponded to
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51 249 an interval of 140-190 ms after cue onset, thus corresponding to the N1pc to the lateralized non-
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53 250 reportable cue (*N1pc-cue*). On the other hand, the second interval corresponded to the N1pc to
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55 251 the first target (*N1pc-target*)¹. Amplitude and latency differences across cue conditions were

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¹ A closer look at the grand-average ERLs (Figures 3A and 3D) revealed the presence of another, positive component 180-230 ms after first target onset, presumably reflecting attentional reorienting from the first to the

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 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

second line grating. Due to the subtraction used to calculate the ERLs locked to the first 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 Figures 3A and 3D, 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.

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4 270 inference testing (Jeffreys, 1961; Kass & Raftery, 1995). Following the procedure outlined in
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6 271 Wagenmakers (2007), we used the PASW output of the split-plot rANOVAs to derive an
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9 272 estimation of posterior probabilities of H_1 (behavioral and electrophysiological differences
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11 273 between experiments, corresponding to the *cue* x *task* interaction model) and H_0 (no task
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13 274 differences, corresponding to the simple effect of *cue*) based on the Bayesian Information
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16 275 Criterion (*BIC*; Kass and Raftery, 1995; Raftery, 1995). First, we calculated the difference
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19 276 between the BIC of H_1 and H_0 (ΔBIC_{10}) according to the formula:

$$21 \quad 277$$

$$23 \quad 278 \quad \Delta BIC_{10} = n * \log(SSE_1 / SSE_0) + (k_1 - k_0) * \log(n)$$

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29 280 where n is the number of participants, SSE_1 is the sum of squares that is not explained by the *cue*
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31 281 x *task* interaction model (i.e., the error sum of squares), SSE_0 is the sum of squares that is not
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33 282 explained by the simple effect of *cue* (i.e., the error sum of squares plus the sum of squares
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35 283 associated with the interaction model), k is the number of parameters of each model (in our case,
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38 284 $k_1 - k_0 = 1$), and *log* indicates the conversion to natural logarithm (see Wagenmakers, 2007,
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41 285 Equation 14). A positive ΔBIC_{10} would indicate lower BIC for H_0 than H_1 and, consequently, H_0
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43 286 ought to be preferred over H_1 . Note that, by following this procedure, an objective uniform prior
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46 287 distribution is hypothesized, meaning that no *a priori* preference for either H_0 or H_1 was included
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48 288 in the analysis (see also Lee & Wagenmakers, 2005). In a second step (Wagenmakers, 2007,
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51 289 Equation 12), we quantified the extent of the preference towards H_0 by estimating the posterior
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53 290 probability of H_0 given the data [$\text{Pr}_{\text{BIC}}(H_0 | D)$] according to the formula:

$$54 \quad 291$$

$$56 \quad 292 \quad \text{Pr}_{\text{BIC}}(H_0 | D) = 1 / [1 + \exp(-0.5 * \Delta BIC_{10})].$$

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

298 3. Results

299 3.1. Cue assessment

300 In Experiment 1, sensitivity (d') was at chance level ($M = 0.08$, $SE = 0.14$; $t_{17} = 0.58$, $p =$
301 $.571$, $r = .14$, $CI_{.95} [-0.17, 0.32]$), and no response bias (β) was observed ($M = 1.87$, $SE = 0.78$; t_{17}
302 $= 1.11$, $p = .281$, $r = .26$, $CI_{.95} [-0.18, 2.19]$). We also found no evidence of implicit awareness
303 for the position of the cue ($\chi^2_{1, N=473} = 2.67$, $p = .102$). Finally, AUC was 0.62 ($SE = 0.02$),
304 indicative of poor signal-noise discrimination performance.

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

313 3.2. Behavioral results

314 Average PSS values in Experiment 1 were -54.52 ms ($SE = 10.94$) when the horizontal line
315 grating was cued, 62.96 ms ($SE = 8.75$) when the vertical line grating was cued, and -2.25 ($SE =$

316 7.20) when no cue was presented (*Figure 2B*). Cued line gratings were consistently perceived as
 317 appearing first (horizontal: $t_{17} = -4.98, p < .001, r = .77, CI_{.95} [-75.56, -34.99]$; vertical: $t_{17} =$
 318 $7.20, p < .001, r = .87, CI_{.95} [47.29, 80.53]$), whereas no bias was observed in the absence of the
 319 cue ($t_{17} = -0.31, p = .758, r = .07, CI_{.95} [-15.33, 11.24]$).

320 In Experiment 2, average PSS was -46.38 ms ($SE = 7.84$) when the horizontal line grating was
 321 cued, 37.13 ms ($SE = 9.16$) when the vertical line grating was cued, and -9.10 ms ($SE = 5.52$)
 322 when no cue was presented (*Figure 2D*). Participants responded more often that the cued line
 323 gratings had appeared first (horizontal: $t_{16} = -5.92, p < .001, r = .83, CI_{.95} [-63.53, -30.85]$;
 324 vertical: $t_{16} = 4.05, p = .001, r = .71, CI_{.95} [19.78, 56.53]$), with no bias in the cue absent
 325 condition ($t_{16} = -1.65, p = .119, r = .38, CI_{.95} [-22.12, 1.43]$).

326 3.3. ERP results

327 *N1pc-cue*. In a first step, we compared against zero the amplitude values extracted in a time
 328 window 80-130 ms post-target onset (which corresponded to 140-190 ms after cue onset) across
 329 the three cue conditions. Consistent with our predictions, no detectable N1pc-cue was observed
 330 in the cue absent condition (Exp. 1: $t_{17} = -0.11, p = .916, r = .03, CI_{.95} [-0.62, 0.55]$; Exp. 2: $t_{16} =$
 331 $0.72, p = .480, r = .18, CI_{.95} [-1.00, 0.44]$), as opposed to a reliable N1pc-cue for compatible
 332 (Exp. 1: $t_{17} = -2.27, p = .036, r = .48, CI_{.95} [-2.70, -0.39]$; Exp. 2: $t_{16} = -3.24, p = .005, r = .63,$
 333 $CI_{.95} [-2.62, -0.70]$) and incompatible trials (Exp. 1: $t_{17} = 4.03, p = .001, r = .70, CI_{.95} [0.81,$
 334 $2.42]$; Exp. 2: $t_{16} = 2.29, p = .036, r = .50, CI_{.95} [0.23, 1.91]$). Mean amplitude values were also
 335 significantly different across cue conditions (Exp. 1: $F_{1.38, 23.41} = 10.26, p = .002, \eta_p^2 = .38$; Exp.
 336 2: $F_{1.47, 23.47} = 7.41, p = .006, \eta_p^2 = .32$), consistently showing the expected N1pc-cue polarity
 337 reversal for compatible as opposed to incompatible trials (Exp. 1: $t_{17} = -3.52, p = .003, r = .65,$
 338 $CI_{.95} [-4.59, -1.56]$; Exp. 2: $t_{16} = -3.08, p = .007, r = .61, CI_{.95} [-4.40, -1.16]$). Importantly,

latency analysis did not show differences across cue conditions (Exp. 1: $F_{2,34} = 0.02, p = .976, \eta_p^2 < .01$; Exp. 2: $F_{2,32} = 1.31, p = .284, \eta_p^2 = .08$), confirming no sensory acceleration due to the cue's spatial unpredictability.

N1pc-target. Activity 130-180 ms 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: $t_{17} = -3.26, p = .005, r = .62, CI_{95} [-2.18, -0.59]$; Exp. 2: $t_{16} = -2.23, p = .041, r = .49, CI_{95} [-2.27, -0.26]$). 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 (*Figure 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 ($t_{17} = 3.27, p = .004, r = .62, CI_{95} [1.23, 5.33]$), whereas activity in compatible condition was smaller than cue absent condition ($t_{17} = -3.24, p = .005, r = .62, CI_{95} [-2.62, -0.67]$) (*Figure 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 ($t_{17} = -7.24, p < .001, r = .87, CI_{95} [-23.00, -14.54]$) and cue absent ($t_{17} = 4.72, p < .001, r = .75, CI_{95} [5.64, 12.80]$) conditions. N1pc-target also peaked earlier in cue absent relative to incompatible trials ($t_{17} = -4.79, p < .001, r = .76, CI_{95} [-13.02, -5.86]$) (*Figure 3C*).

Similar results were obtained in Experiment 2 (*Figure 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

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4 362 amplitude was also observed for compatible compared to cue absent condition ($t_{16} = -2.86, p =$
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6 363 $.011, r = .58, CI_{.95} [-4.79, -1.09]$) (Figure 3E). Latencies were also significantly different across
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9 364 cue conditions ($F_{1.35, 21.58} = 5.38, p = .022, \eta_p^2 = .25$). Shorter latencies were observed for
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11 365 compatible compared to incompatible ($t_{16} = -2.55, p = .021, r = .54, CI_{.95} [-20.91, -3.91]$) and cue
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14 366 absent trials ($t_{16} = 2.65, p = .018, r = .55, CI_{.95} [2.07, 11.49]$) (Figure 3F).

16 367 3.4. Comparisons between Experiment 1 and 2

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19 368 With regards to behavioral performance, a split-plot rANOVAs on PSS values revealed no
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21 369 significant *cue x task* interaction ($F_{1.44, 47.65} = 2.09, p = .148, \eta_p^2 = .06$). Bayesian analysis
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23 370 confirmed no behavioral differences between experiments, with “weak” evidence in favor of H_0
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26 371 [$\Delta BIC_{10} \approx 1.41, Pr_{BIC}(H_0 | D) \approx 0.67$].

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29 372 Similar results were observed for our electrophysiological measures. For the N1pc-cue, no
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31 373 significant *cue x task* interaction was found either in amplitude ($F_{1.42, 47.00} = 0.05, p = .898, \eta_p^2 <$
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33 374 $.01$) or latency ($F_{2, 66} = 0.62, p = .543, \eta_p^2 = .02$). Complementary Bayesian analysis indicated
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35 375 “positive” evidence in favor of H_0 for both amplitude [$\Delta BIC_{10} \approx 3.50, Pr_{BIC}(H_0 | D) \approx 0.85$] and
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38 376 latency [$\Delta BIC_{10} \approx 2.91, Pr_{BIC}(H_0 | D) \approx 0.81$]. Separate mixed rANOVAs on N1pc-target
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41 377 amplitude and latency values also showed no significant *cue x task* interactions (amplitude: $F_{1.47,$
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43 378 $48.66 = 0.91, p = .383, \eta_p^2 = .03$; latency: $F_{1.46, 48.25} = 0.96, p = .365, \eta_p^2 = .03$). Bayesian analysis
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45 379 revealed “positive” evidence in favor of H_0 , both for amplitude [$\Delta BIC_{10} \approx 2.61, Pr_{BIC}(H_0 | D) \approx$
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48 380 0.79] and latency [$\Delta BIC_{10} \approx 2.55, Pr_{BIC}(H_0 | D) \approx 0.78$].

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50 381 In sum, behavioral and electrophysiological evidence pointed towards a reliable absence of
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53 382 differences between Experiments 1 and 2.

55 383 4. Discussion

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4 384 In two ERP experiments employing a visual TOJ task, we demonstrated that involuntary
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6 385 spatial attention accelerates perceptual processing starting around 130 ms after target onset.
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9 386 Participants were required to judge the perceived temporal order of two competing line gratings
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11 387 separated by various SOAs. In two-thirds of the trials, an uninformative, non-reportable
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14 388 exogenous cue preceded the first line grating at the same or opposite location. Behavioral results
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16 389 showed a robust bias towards the stimulus appearing at the location previously occupied by the
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19 390 unaware exogenous cue, especially at the short SOAs. Carefully controlled experimental
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21 391 parameters (see *Section 2.2*) allowed us to exclude potential confounds, such as response biases
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24 392 (Jaskowski, 1993; K. A. Schneider & Bavelier, 2003) or top-down attentional task sets (Ansorge,
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26 393 Horstmann, et al., 2011; Folk et al., 1992; Kiefer et al., 2011). Our findings are therefore
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29 394 consistent with the notion of compelling, automatic, stimulus-driven attentional orienting
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31 395 towards non-reportable exogenous cues (Fuchs, Theeuwes, & Ansorge, 2013; Jonides, 1981;
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33 396 McCormick, 1997; Mulckhuyse, Talsma, & Theeuwes, 2007; Mulckhuyse & Theeuwes, 2010;
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36 397 Posner & Snyder, 1975).

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38 398 Our ERP results further shed light on the electrophysiological correlates of this automatic
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41 399 orienting of attention towards unaware cues. First, we observed a lateralized component
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43 400 reflecting an orienting response to the cue (N1pc-cue), whose latency was similar across
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46 401 conditions. Second, amplitude and latency modulations of the N1pc component elicited by the
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48 402 first line grating (N1pc-target) indicated that the initial orienting towards the target location was
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51 403 influenced by the previous position of the cue. The amplitude of this component was smaller
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53 404 when cue and target shared the same spatial location, because reorienting was not necessary.
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56 405 Conversely, in incompatible trials, more neural resources and a longer processing time were
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58 406 needed in order to shift the attentional focus from the cued to the opposite visual hemifield, as
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4 407 evidenced by larger amplitude contralateral to the target location (Fu et al., 2005; Gibbons et al.,
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6 408 2013; Ruge & Naumann, 2006; Wascher & Beste, 2010). Crucially, N1pc-target also peaked 16
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9 409 ms earlier (on average) in compatible relative to incompatible trials, suggesting that cue-related
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11 410 processing benefits affected both the magnitude and the time course of the neural response to
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14 411 stimuli subsequently appearing at cued locations. The fact that we obtained identical results with
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16 412 parametric (rANOVAs, t-tests) as well as non-parametric (bootstrapped confidence intervals)
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19 413 statistical procedures speaks in favor of the robustness of these findings, which ultimately
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21 414 provide compelling neurophysiological evidence for the attentional nature of prior entry effects
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24 415 by revealing sensory acceleration of neural activity in extrastriate brain areas. Interestingly, these
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26 416 results are coherent with earlier behavioral and electrophysiological reports which showed, using
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29 417 classical visual cueing paradigms, improved discriminability and acceleration of information
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31 418 processing at cued locations (e.g., Carrasco & McElree, 2001; Nobre, Sebestyen, & Miniussi,
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33 419 2000). More importantly, our findings seem to suggest that target processing speed is enhanced
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36 420 from the earliest extrastriate responses, well within 200 ms following stimulus onset (Luck et al.,
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38 421 2000). Moreover, our results unequivocally demonstrate that this accelerated response can be
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41 422 functionally dissociated from the orienting response to the cues, which is temporally unaffected
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43 423 by its validity. Our amplitude analyses confirmed that attentional orienting to the eccentric non-
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46 424 reportable cue is reliably reflected in an enhanced contralateral response in the N1 interval,
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48 425 which is independent of top-down attentional set (Natale, Marzi, Girelli, Pavone, & Pollmann,
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51 426 2006; Natale, Marzi, & Macaluso, 2010).

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53 427 Under conditions of probabilistic uncertainty and temporal urgency, attention is automatically
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55 428 attracted towards locations where salient visual stimuli appear (Serences et al., 2005; Yantis &
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58 429 Jonides, 1984). These locations get prioritized, so that sensory processing of subsequent events is
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4 430 facilitated (Hopfinger & Mangun, 1998). This perceptual facilitation is carried out by means of
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6 431 sensory gain control mechanisms aimed at improving the signal-to-noise ratio of salient events
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9 432 (Hillyard et al., 1998; Luck, Chelazzi, Hillyard, & Desimone, 1997; Treue & Martínez-Trujillo,
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11 433 1999). The temporal dynamics of these mechanisms, however, are not completely understood,
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14 434 and are also not fully implemented in recent computational models of attention (e.g., Reynolds &
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16 435 Heeger, 2009; but see Spratling & Johnson, 2004). In addition, these models typically account
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19 436 for neuronal modulation exerted by top-down, voluntary attention rather than bottom-up,
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21 437 stimulus-driven attentional capture (as observed in the present study). Based on our findings, it
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24 438 may be speculated that perceptual competition between visual stimuli appearing at salient
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26 439 locations in close temporal proximity would rely more on intracortical feedback within
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29 440 extrastriate visual areas as opposed to long-range, feedforward connections (Desimone &
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31 441 Duncan, 1995; Desimone, 1998; Reynolds & Heeger, 2009). While electrophysiological studies
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33 442 in humans cannot provide conclusive empirical evidence in favor of this view due to the nature
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36 443 of the signal recorded on the scalp, this remains an important issue that should be addressed in
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38 444 future research.

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41 445 Another important finding of the present study is the absence of differences between the
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43 446 results of Experiments 1 and 2, as confirmed by Bayesian analysis. This is in accordance with
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46 447 previous behavioral results showing similar prior entry effects elicited by non-reportable cues
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48 448 regardless of task instructions (Weiß & Scharlau, 2012). More importantly, our ERP results
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51 449 suggest that the initial orienting of attention towards salient locations seems to be immune to task
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53 450 differences or changes in observers' mindset (Mulckhuyse & Theeuwes, 2010; Theeuwes, 2004).
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56 451 Instead, the presence of non-informative exogenous cues, due to their perceptual salience (Itti &
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58 452 Koch, 2000, 2001), may automatically capture spatial attention already in a time window 100-
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4 453 150 ms after onset, corresponding to the early feed-forward phase of visual processing (Lamme
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6 454 & Roelfsema, 2000).

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9 455 Of note, we do not wish to claim that top-down contingent attentional capture never plays a
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11 456 role in early visual processing: several studies, in fact, have already shown that top-down goals
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14 457 can influence attentional selection of non-reportable stimuli (e.g., Ansorge, Kiss, & Eimer, 2009;
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16 458 Ansorge, Kiss, Worschech, & Eimer, 2011; Eimer & Kiss, 2008; Kiss, Grubert, Petersen, &
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19 459 Eimer, 2012). With regards to our study, one could argue that participants might have completed
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21 460 the task by first detecting the location of the first target and subsequently recalling its lines'
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24 461 orientation. This might explain the lack of behavioral and electrophysiological differences
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26 462 between Experiment 1 and 2, since the cued dimension (location) was part of observers' task set
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29 463 in both experiments². We tried to prevent participants from (explicitly or implicitly) using this
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31 464 strategy by masking both locations soon after the presentation of the line gratings, but we cannot
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34 465 be sure that they did not rely on a short-term memory representation of the first target. This issue
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36 466 will be addressed in future experiments.

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38 467 To conclude, here we provide direct empirical evidence that, in perceptually demanding tasks,
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41 468 attention can be captured efficiently and independently from goal-related attentional sets,
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43 469 influencing early stages of stimulus processing in less than 200 ms.

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² We thank an anonymous reviewer for pointing out this alternative interpretation.
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collection, analysis, and interpretation of data; writing of the report; and decision to submit the

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article for publication. The authors declare no competing financial interests.

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Figure captions

Figure 1. Experimental procedure. Two lateral placeholders were followed (on 66% of 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.

Figure 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.

Figure 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 ms 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. *: $p < .05$; **: $p < .01$; ***: $p < .001$.

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Tables

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

5

Component	Experiment	Measure	Condition		
			Congruent	Cue absent	Incongruent
N1pc-cue	Exp. 1	Amplitude	-1.44 (0.64)	-0.04 (0.33)	1.57 (0.39)
		Latency	102.54 (4.72)	103.85 (4.03)	103.41 (3.18)
	Exp. 2	Amplitude	-1.62 (0.50)	-0.28 (0.39)	1.10 (0.48)
		Latency	105.44 (5.01)	104.75 (3.78)	97.86 (3.62)
N1pc-target	Exp. 1	Amplitude	0.25 (0.53)	-1.41 (0.43)	-2.97 (0.55)
		Latency	137.05 (2.15)	146.38 (2.24)	155.71 (2.40)
	Exp. 2	Amplitude	1.65 (0.74)	-1.17 (0.52)	-3.25 (0.67)
		Latency	138.53 (2.81)	145.42 (2.39)	151.17 (3.52)

6

Figure 1
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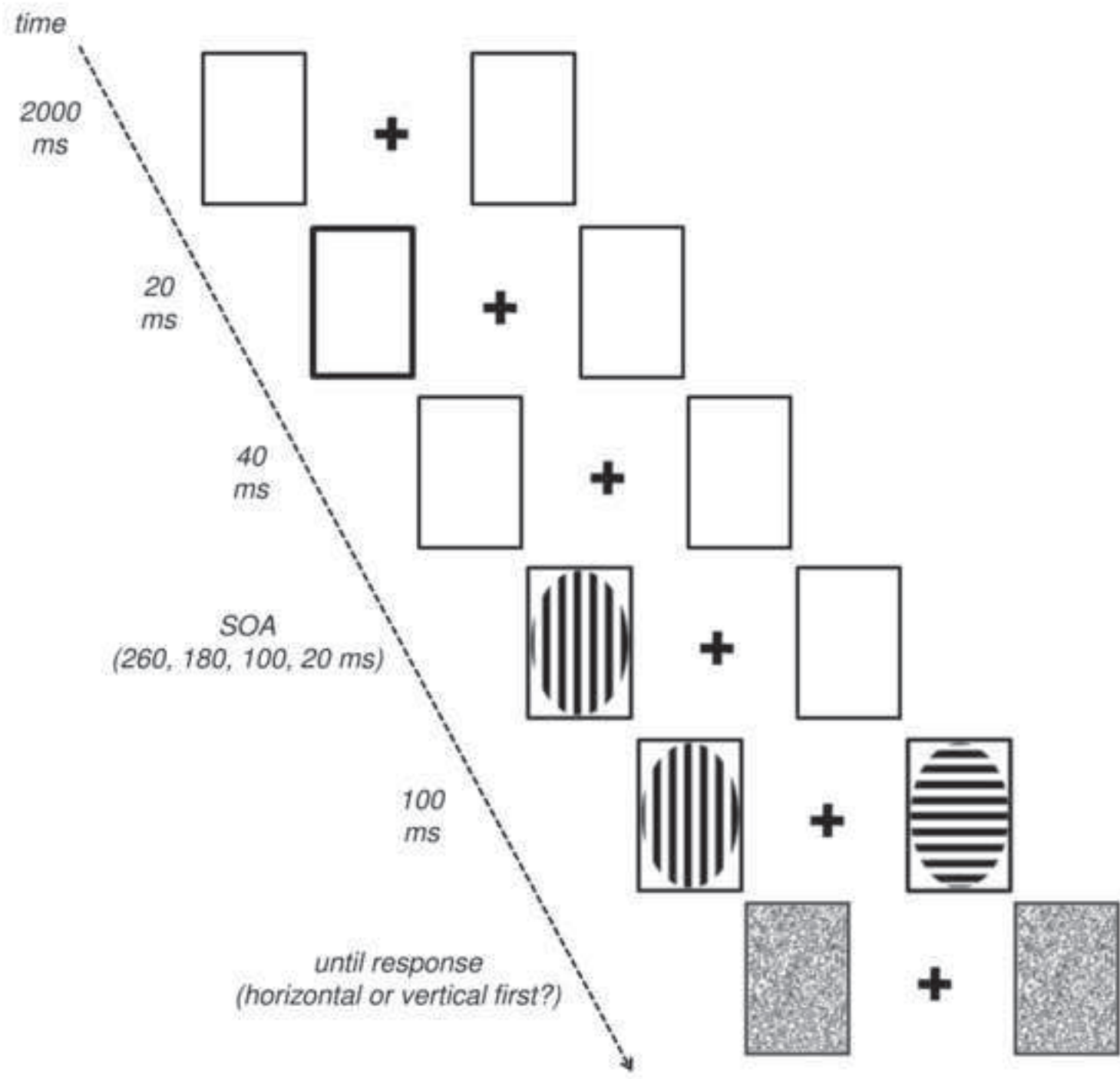


Figure 2
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