BIROn - Birkbeck Institutional Research Online

A dissociation between selective attention and conscious awareness

in the representation of temporal order information

Martin Eimer* and Anna Grubert

*Corresponding author

Department of Psychological Sciences, Birkbeck College, University of London,

Malet Street, London WC1E 7HX, UK

Phone: 0044 20 76316358

Fax: 0044 20 76316312

Email: m.eimer@bbk.ac.uk

Short title: Attention and awareness of temporal order

Abstract

Previous electrophysiological studies have shown that attentional selection processes are highly sensitive to the temporal order of task-relevant visual events. When two successively presented colour-defined target stimuli are separated by a stimulus onset asynchrony (SOA) of only 10 ms, the onset latencies of N2pc components to these stimuli (which reflect their attentional selection) precisely match their objective temporal separation. We tested whether such small onset differences are accessible to conscious awareness by instructing participants to report the category (letter or digit) of the first of two target-colour items that were separated by an SOA of 10, 20, or 30 ms. Performance was at chance level for the 10 ms SOA, demonstrating that temporal order information which is available to attentional control processes cannot be utilized for conscious temporal order judgments. These results provide new evidence that selective attention and conscious awareness are functionally separable, and support the hypothesis that attention and awareness operate at different stages of cognitive processing.

Keywords: selective attention, consciousness, visual awareness, temporal order judgments, event-related brain potentials

1. Introduction

Selective attention and conscious awareness are assumed to be closely linked. Phenomena such as inattentional blindness (e.g., Simons, 2000) and change blindness (e.g., Rensink, 2002) demonstrate that the appearance of salient visual stimuli or stimulus changes often goes undetected when attention is directed elsewhere. Such cases suggest that visual events need to be selectively attended in order to become consciously accessible, and that attention might act as the 'gatekeeper' for conscious awareness. These intimate links between attention and awareness have led to the suggestion that these two domains might in fact be identical (e.g., Posner, 1994; O'Reagan & Noe, 2001): What we are aware of at any given moment is determined by what is currently in the focus of selective attention. However, other authors have argued that attention and awareness are functionally distinct (e.g., Lamme, 2003; Koch & Tsuchiya, 2007). Evidence for the separability of attention and awareness is provided by cases where selective attention to a particular stimulus does not give rise to conscious awareness (e.g., He, Cavanagh, & Intriligator, 1996), cases where masked invisible stimuli attract attention when their features match a currently active task set (e.g., Scharlau & Ansorge, 2003; Ansorge, Kiss, & Eimer, 2009), and cases where conscious object classification can occur in the near absence of attention (e.g., Li, VanRullen, Koch, & Perona, 2002).

An area in which links between attention and awareness have not yet been studied systematically is the processing of temporal relationships between perceptual events. It is well-known that sensory stimuli have to be separated by a minimum time interval in order to be consciously perceived as non-simultaneous or successive (Exner, 1875; Hirsh & Sherrick, 1961). If perceptual awareness and sensory attention are closely linked, such thresholds for the conscious perception of temporal order might directly reflect a fixed temporal resolution limit of selective attention. Sensory events are perceived as simultaneous when their objective temporal separation is too small to be detected by attentional processes. They are experienced as successive when they are separated by a time interval that exceeds the temporal threshold for their individuation by selective attention. To test this hypothesis, the temporal resolution of selective attention needs to be determined independently from observers' ability to make conscious temporal order judgments.

In a recent series of experiments (Eimer & Grubert, 2014; Grubert & Eimer, in press), we developed new experimental procedures to demonstrate that focal attention can be allocated extremely rapidly and independently to different target objects, and that the temporal resolution of attentional control processes is remarkably high. In the original study (Eimer & Grubert, 2014), two search displays with coloured alphanumerical items (digits and letters) were presented in rapid succession (see Figure 1 for an illustration of the stimulation procedures). Both displays contained a colour-defined target and a distractor object in a different colour on opposite sides. Participants were told that there would be one target item in a particular colour (e.g., red) in both displays, and that their task was to attend to both of these targets in order to identify them and to report whether the two target items belonged to the same alphanumerical category (two letters, two digits) or not (one letter and one digit). To determine how rapidly attention could be allocated to each of the two target objects when these objects appear in rapid succession, the stimulus onset asynchrony (SOA) separating the two displays was varied between 10 ms and 100 ms. To perform the task, participants had to direct attention initially to the target object in the first display, and then allocate attention to the target in the second display. To track the time course of these two attentional processes, we measured N2pc components of the event-related potential in response to these objects. The N2pc is an enhanced negativity that typically emerges 180-200 ms after stimulus onset at posterior electrodes contralateral to the visual field of a target object in multi-stimulus visual displays, and reflects the attentional selection of candidate target objects among distractors in visual search (e.g., Luck & Hillyard, 1994; Eimer, 1996; Woodman & Luck, 1999). Because the N2pc is computed by comparing contralateral and ipsilateral ERP waveforms to targets in the left versus right visual field, no N2pc is elicited for target objects that appear on the vertical meridian (Woodman & Luck, 1999; Hickey, McDonald, & Theeuwes, 2006; Eimer, Kiss, & Nicholas, 2011). To measure the N2pc to one of the two targets independently of the N2pc to the other target, we presented one target/nontarget pair on the horizontal meridian and the other stimulus pair on the vertical meridian (Eimer & Grubert, 2014; see Figure 1). Trials where the horizontal display preceded the vertical display (horizontal target first: H1 targets) and trials where this order was reversed (horizontal target second: H2 targets) were randomly intermixed.

When both displays were separated by a 100 ms SOA, the N2pc to H1 targets preceded the N2pc to H2 targets by almost exactly 100 ms. Critically, when the SOA

between the two displays was 10 ms, the latency difference of the N2pc components to the two targets again mirrored this objective time interval precisely, as the N2pc to H2 targets emerged 10 ms later than the N2pc to H1 targets. This is illustrated in Figure 2 (top panel, One Colour Task), which shows ERPs at lateral posterior electrodes PO7 and PO8 contralateral and ipsilateral to a horizontal target-colour object, separately for trials where this object appeared in the first display (H1) or in the second display (H2). Figure 2 also shows the corresponding N2pc difference waveforms that were obtained by subtracting ipsilateral from contralateral ERPs. The point in time when N2pc components to H1 and H2 targets reach a pre-defined onset threshold (-1μV) is indicated by filled circles. The observation that these two N2pc components were equal in size and overlapped in time demonstrates that focal attention can be allocated rapidly and in parallel to several target objects, with each selection process following its own independent time course. Most critically, the fact that the onset latency difference between the N2pc to H1 and H2 targets perfectly matched the objective SOA between the two displays (10 ms) provides new insights into the temporal resolution of selective spatial attention in vision. It shows that the top-down control processes responsible for the allocation of spatial attention to target objects are highly sensitive to very small temporal separations between these objects.

In a follow-up study (Grubert & Eimer, in press), we perfectly replicated this temporal pattern of N2pc components to two successive targets in the same colour that were separated by a 10 ms SOA. We also investigated whether the allocation of attention to successively presented targets remains tuned to the objective time delay between these targets when their selection can no longer be guided by a unique colour-specific top-down task set. In the new Two Colour task, the two targets could have one of two possible colours, and there was always a colour change between the first and second target on each trial. The target colour sequence (e.g., red -> green or green -> red) varied unpredictably across trials, so that participants could no longer predict the colour of the first target. When both displays were separated by a 10 ms SOA, the onset latencies of N2pc components to H1 and H2 targets still matched the objective onset delay between the two displays quite closely. This is illustrated in Figure 2 (bottom panel), which shows ERPs to H1 and H2 targets at contralateral and ipsilateral posterior electrodes in this Two Colour task, together with the corresponding N2pc difference waveforms (as reported in Grubert & Eimer, in press). The onset latency difference between the N2pc to H1 and H2 targets was now 31 ms, which

is only about 20 ms longer than the objective SOA between the two displays (10 ms). This demonstrates that attentional control processes remain sensitive to very small onset delays between successive target stimuli even when their selection cannot be based on a single colour-specific attentional task set. The fact that the interval between the onsets of the two N2pc components to H1 and H2 targets was longer in the Two Colour task relative to the One Colour task (as shown in Figure 2) is likely to be due to competitive interactions between two simultaneously active attentional task sets in the former task (see Grubert & Eimer, in press, for a detailed discussion).

Overall, the N2pc results from our previous studies (Eimer & Grubert, 2014; Grubert & Eimer, in press) demonstrate that control processes involved in the allocation of selective visual attention are highly sensitive to temporal relationships between successively presented task-relevant visual stimuli. Even when these stimuli arrive within 10 ms of each other, their onset asynchrony is accurately reflected by the onset of neural processes involved in their spatially selective attentional processing. In other words, precise information about the temporal sequence of successive visual events is available to attentional control processes, and this information affects the time course of allocating attention to these events in a way that matches their objective temporal separation. The fact that early stages of focal-attentional processing that are reflected by the N2pc component are sensitive to very small onset delays between successive visual events raises the important question whether this temporal information is also available to guide conscious perceptual temporal order judgments. If selective attention and conscious awareness are identical (e.g., Posner, 1994), small stimulus onset delays that are detected by attentional control processes should in principle also be accessible to awareness. In this case, it should be possible to utilize these attentional signals for explicit judgments of temporal order. Under experimental conditions like the ones used in our previous N2pc studies, observers should therefore be able to report with above-chance accuracy that the first target precedes the second target object, even when they are separated by an SOA of only 10 ms.

This prediction could not be tested in our previous experiments (Eimer & Grubert, 2014; Grubert & Eimer, in press), where participants made same/different category judgments to the two successively presented target objects, and the temporal order in which they were presented and perceived was not reported. However, previous

investigations on the perception of temporal order within and across different sensory modalities (e,g., Hirsh & Sherrick, 1961; Zampini, Shore, & Spence, 2003; Hendrich, Strobach, Buss, Müller, & Schubert, 2012) indicate that an SOA of 10 ms between successive stimuli may be insufficient for above-chance temporal order judgments. For example, Hirsh and Sherrick (1961) reported that above-chance judgements of successiveness were possible once two stimuli are separated by SOAs of approximately 20 ms, and that performance was at or close to chance for shorter SOAs. Interestingly, these authors found that this threshold for temporal order judgments was more or less constant for vision, audition, and touch, as well as for judgements across sensory modalities. These observations suggest that the SOA of 10 ms between two visual target stimuli that was used in our previous N2pc experiments (Eimer & Grubert, 2014; Grubert & Eimer, in press) may not allow above-chance conscious judgments of temporal order. However, the stimulus procedures used in our previous work and those employed in the classic experiments of Hirsh and Sherrick (1961) were quite different. In the latter study, two flashes of light were presented successively in the left versus right or upper versus lower visual field, and observers had to report the location of the first of these flashes. Moreover, Hirsh and Sherrick (1961) defined the threshold for successful temporal order judgments as the time interval where responses were correct on 75% of all trials, which may have overestimated the minimal SOA required for above-chance performance.

To find out whether observers are able to detect the temporal order of two successively presented visual objects with above-chance accuracy when stimulus procedures are the same as those used in our two earlier N2pc studies, we ran a behavioural experiment where participants were required to make an explicit temporal order judgment on each trial. The stimulus setup was identical to our previous experiments (Eimer & Grubert, 2014; Grubert & Eimer, in press). On each trial, two stimulus displays (20 ms duration) with a colour-defined target and a nontarget item on opposite sides were presented successively. These two displays were separated by SOAs of 10 ms, 20 ms, or 30 ms, with SOA varied randomly across trials. The first stimulus pair appeared on the vertical meridian and the second on the horizontal meridian, or vice versa (see Figure 1), and this also varied randomly. In contrast to our earlier experiments, the two target-colour objects now always differed in their alphanumerical category (one letter and one digit). This change was introduced because temporal order judgments require that the two to-be-judged

stimuli differ on a particular dimension, so that observers can use this dimension to indicate which of them came first or second (see Hirsh & Sherrick, 1961). Participants' task was to report on each trial whether the first of the two target-colour objects was a letter or a digit. Performing this task with above-chance accuracy requires access to information about the temporal order in which the two target-colour stimuli were presented. Our earlier N2pc studies have shown that this information is accessible to attentional control processes, even for SOAs of 10 ms. If observers are able to utilize this information for explicit temporal order judgments, task performance should be above chance for all three SOAs tested. In contrast, if a 10 ms SOA is too short for successful judgments of temporal order, as suggested by earlier findings (Hirsh & Sherrick, 1961), performance will be at chance level for an SOA of 10 ms, and should improve when SOA is increased.

In one earlier study (Grubert & Eimer, in press), we found that the interval between N2pc components to H1 and H2 targets was longer in a Two Colour task where the two target items differed in their colour than in a One Colour task where both targets always had the same colour (as shown in Figure 2). If the time delay between these two N2pc components represents an on-line attentional temporal order signal that can be directly accessed by explicit temporal order judgments, these judgments may be more accurate when the two to-be-compared visual stimuli always have a different colour. To test this possibility, we asked participants to judge the category of the first target-colour item in two blocked task conditions where target colour was either constant (One Colour task) or changed across the two successive displays (Two Colour task; see Figure 1). Finally, in order to assess whether the judgment of temporal order improves as a result of practice, we compared task performance between the first and second half of experimental blocks in the One and Two Colour tasks.

2. Methods

2.1. Participants

Twelve paid participants took part in this experiment. They were aged between 23 and 41 years (mean age 31.4 years). Six were female, and three were left-handed. They all

had normal or corrected-to-normal vision and normal colour vision, as measured with the Ishihara colour vision test (Ishihara, 1972).

2.2. Stimuli and procedure

Participants were seated in a dimly illuminated test booth and viewed the stimuli on a 22-inch Samsung wide SyncMaster 2233 LCD monitor (resolution of 1280x1024 pixels, 100 Hz refresh rate; 16 ms black-to-white-to-black response time, as verified with a photodiode) at a distance of approximately 100 cm. Stimulus presentation, timing, and response recollection were controlled by a LG Pentium PC running under Windows XP, using the Cogent 2000 toolbox (www.vislab.ucl.ac.uk/Cogent/) for MATLAB (Mathworks, Inc.).

Stimuli were coloured uppercase letters (B, H, S, or T) or digits (1, 2, 3, or 4), measuring 0.9 x 0.9 degrees of visual angle. They were presented against a black background at an eccentricity of 2.4° from central fixation, which was marked by a continuously present grey fixation point (CIE colour coordinates: .321/.352; 0.2° x 0.2° of visual angle). Each trial contained two successively presented search displays. Each display consisted of one stimulus in a target colour and another in a nontarget colour (Figure 1). The four possible stimulus colours were red (.637/.329), green (.264/.556), blue (.179/.168), and yellow (.423/.461). All colours were equiluminant (~7.5 cd/m2). One target/nontarget pair was presented on the horizontal meridian (left and right of fixation), while the other pair appeared on the vertical meridian (above and below fixation). The presentation sequence (horizontal pair first, or vertical pair first), and the actual positions of the targets in the two displays (left/right; top/bottom) were equiprobable. These four presentation conditions were independently determined in each trial and were presented randomly intermixed in each block.

On each trial, four out of the eight stimulus identities were randomly selected, with the restriction that one of the two target items had to be a digit, and the other one a letter. Participants' task was to report whether the target colour stimulus of the first display was a digit or a letter by pressing the corresponding one of two purpose-built vertically aligned response keys. The response-to-key and the hand-to-key mapping were counterbalanced across participants. Trials requiring a 'digit first' or a 'letter first' response were equiprobable and randomly intermixed in each block.

On all trials, the two successive stimulus displays were presented for 20 ms each. One critical manipulation concerned the SOA between the two stimulus displays, which was 30 ms, 20 ms, or 10 ms (as shown in Figure 1). In SOA30 trials, a 10 ms blank interval was present between the two stimulus displays. In SOA20 trials, the two stimulus displays followed each other immediately. In SOA10 trials, where the onset of the first display preceded the onset of the second display by only 10 ms, both displays overlapped for 10 ms. These three SOA conditions were randomly intermixed in each block. The interval between the offset of the second display and the onset of the first display on the next trial was 1900 ms.

The other critical manipulation concerned target colour, with two blocked colour task conditions. In the One Colour task, all targets were defined by the same colour (e.g., participants had to decide whether the red digit or the red letter was presented first). Each of the four colours (red, green, blue, or yellow) served as target colour for three participants, and the other three colours served as nontarget colours. In the Two Colour task, there were two possible target colours, and the two successively presented targets always differed in colour (e.g., participants had to decide whether the red digit or the green letter was presented first). The order in which these two target colours appeared was randomly determined for each trial, so that the colour sequence and the colour of the first target on each trial were unpredictable. For six participants, target colours were red and green, and nontarget colours were yellow and blue, and this order was reversed for the other six participants. These target/nontarget mappings were chosen to ensure that the two target colours were not linearly separable in colour space from the two nontarget colours. For each participant, the target colour of the One Colour task served as nontarget colour in the Two Colour task (e.g., participants who searched for red targets in the One Colour task would search for yellow and blue targets in the Two Colour task).

The experiment contained eight blocks, with 96 trials per block. For each block, there were four trials for each combination of first target identity (digit or letter), first target location (left, right, top, or bottom) and SOA condition (30, 20, or 10 ms). The One Colour and Two Colour tasks were each run in four successive blocks. Six participants started the experiment with the One Colour task, and the other six with the Two Colour task. Participants were free to take breaks between the blocks, and had one additional break

after 48 trials of each block. Participants were familiarised with the visual and temporal properties of the displays by passively viewing 10 trials before the start of the experiment.

2.3. Data analysis

Mean percentage correct of the three SOA conditions (SOA10, SOA20, and SOA30) in both task conditions (One Colour, Two Colour) were analysed by means of one-way ANOVAs. Significant effects were followed up in terms of two-tailed *t*-tests. All *p*-values were Bonferroni corrected.

3. Results

Figure 3 (left panel) shows the percentage of trials where participants correctly reported the category of the target item in the first display in the three SOA conditions, separately for the One Colour and the Two Colour task. As expected, accuracy improved as the SOA between the two displays was increased. A repeated-measures ANOVA with the factors task (One Colour, Two Colour) and SOA (SOA10, SOA20, SOA30) revealed a main effect of SOA, $F(2,22) = 40.4$, $p < .001$, with better performance for longer SOAs (51.7%, 57.5%, and 66.0% correct responses in the SOA10, SOA20, and SOA30 conditions, respectively). There was no effect of task, $F(1,11) < 1$, and no interaction between task and SOA, $F(2,22) = 1.2$, $p = .330$, indicating that participants' ability to detect temporal order did not differ between the One and Two Colour tasks.

The critical question was whether participants were able to report the category of the first target with above-chance accuracy in all three SOA conditions. Because there were no significant effects involving the factor task, performance in the SOA10, SOA20, and SOA30 conditions was pooled across the One and Two Colour tasks to increase the signal-to-noise ratio. When the SOA between the two displays was 20 ms or 30 ms, accuracy was reliably above chance (50%), both $t(11) > 5.5$, both $p < .001$. In contrast, performance in the SOA10 condition did not differ significantly from chance, $t(11) = 1.8$, p = .300, demonstrating that participants were unable to detect the temporal order of the two target displays.

Additional *t*-tests showed that accuracy was significantly better with an SOA of 20 ms relative to the SOA10 condition, $t(11) = 4.2$, $p = .003$, and further improved for the SOA30 relative to the SOA20 condition, $t(11) = 5.0$, $p < .001$.

To assess whether participants' ability to detect temporal order might have increased in the course of the experiment, performance was compared between the first two blocks and final two blocks of the One Colour and Two Colour task, respectively. Figure 3 (right panel) shows percentage correct for the first versus second half of these tasks (collapsed across the One and Two Colour tasks), and suggests that if there were any learning effects, they were only present for the longest SOA between the two displays. A repeated-measures ANOVA with the factors SOA condition (SOA10, SOA20, SOA30), and experimental half (first, second) did not produce a reliable effect of experimental half, $F(1,11) < 1$, indicating that there were no reliable learning effects across all three SOAs. However, there was a significant interaction between SOA and experimental half, $F(2,22) = 4.8$, $p = .018$. In the SOA10 and SOA20 conditions, performance did not differ reliably between the first and second half, $t(11) = 1.7$, $p = .363$, and $t(11) < 1$, respectively. When the SOA between the two displays was 30 ms, there was a tendency towards better performance in the second half, which did however not reach Bonferroni-corrected significance, $t(11) = 2.7$, $p = .063$.

4. Discussion

In a series of previous ERP experiments that employed the N2pc component as an electrophysiological marker of attentional target selection (Eimer & Grubert, 2014; Grubert & Eimer, in press), we demonstrated that control processes involved in the allocation of spatial attention to visual targets are remarkably sensitive to the temporal order in which these targets are presented. Even when the SOA between two successive targets was only 10 ms, N2pc components to these targets perfectly mirrored their objective time delay (Figure 2). If this information about the temporal order of visual events is accessible to attentional processes, it might also be accessible for explicit temporal order judgments, in particular if selective attention and conscious awareness are functionally identical. The present behavioural experiment used the same stimulus procedures as our previous N2pc

studies, except that participants now had to report the category of the first of two successively presented target-colour stimuli. To perform this task, they had to be able to detect the temporal order in which these stimuli appeared. Our results show that when these two stimuli were separated by a 10 ms SOA, performance was at chance level (see Figure 3). This demonstrates that participants were not able to temporally discriminate between the first and second target-colour item on these trials. When the SOA was increased to 20 ms and 30 ms, performance gradually improved, with above-chance accuracy already observed for an SOA of 20 ms.

These findings closely resemble previous results by Hirsh and Sherrick (1961), in spite of the fact that these studies used very different stimulation procedures (flashes of light versus coloured letter/digit pairs) and task instructions (localization judgments versus judgments of alphanumeric category). Similar to the current experiment, Hirsh and Sherrick (1961) found that the temporal order of two successive stimuli can be discriminated only when they are separated by an SOA of at least 20 ms. Performance was far from perfect even with a 30 ms SOA in the present experiment, where observers correctly reported the category of the first target-colour item only on approximately two thirds of all trials (see also Hirsh & Sherrick, 1961, for similar observations). These results show that the conscious perception of temporal order requires a temporal interval between two visual stimuli that is longer than the shortest SOA (10 ms) employed in our previous ERP studies (Eimer & Grubert, 2014; Grubert & Eimer, in press). In these two studies, N2pc onset latencies to two target stimuli separated by 10 ms perfectly mirrored the objective onset difference between these two stimuli, demonstrating that temporal order information was available to attentional control processes. In the present experiment, participants were unable to access this information in a task that required the explicit detection of temporal order, which shows that selective attention and conscious awareness differ systematically in their sensitivity to information about the temporal sequence of visual events.

There were no performance differences between the One Colour and Two Colour tasks of the present experiment, thus ruling out the possibility that the detection of temporal order is facilitated when the two critical visual stimuli differ in the selection-relevant visual dimension (colour). In a previous experiment (Grubert & Eimer, in press), the N2pc onset delay between H1 and H2 targets was found to be larger in the Two Colour task than in the One Colour task (Figure 2). If latency differences in the onset of attentional

selection processes for particular objects, as reflected by N2pc components to these objects, could be used as attentional temporal order signals for explicit judgments of temporal precedence, these judgments should have been more accurate in the Two Colour task. The absence of reliable performance differences between the two tasks does not support this hypothesis, and provides further evidence for dissociations between the processing of temporal order information in the attentional system and access to this information during the explicit detection of temporal sequence. There was also no evidence that participants' ability to make above-chance temporal order judgments increased as a result of practice when the SOA between two successive stimuli is very brief (10 or 20 ms). This is important, because our two previous N2pc studies included a large number of trials (six blocks with 64 trials per block for each blocked SOA condition). It could therefore be argued that the sensitivity of attentional control processes to very brief SOAs between successive targets, as reflected by the N2pc onset latency differences to H1 and H2 targets with a 10 ms SOA between the two displays, only emerges in the course of the experiment once the task is highly practised. The absence of any learning effects for SOAs of 10 ms and 20 ms in the present study shows that when SOAs are very short, the quality of temporal order judgments does not improve in the course of the experiment. There was some evidence that practice may facilitate such judgments for longer SOAs, but the improvement observed with an SOA of 30 ms only approached our conservative statistical significance threshold.

Overall, the current behavioural results show a clear dissociation between selective attention and conscious awareness in the detection of the temporal order of visual events. Even though temporal order information is precisely represented in the attentional system (as reflected by N2pc onset latency differences to successive target objects that match their objective temporal separation, as shown by Eimer & Grubert, 2014, and Grubert & Eimer, in press), this information cannot be accessed for explicit temporal order judgments when the SOA between two visual stimuli is shorter than 20 ms. An analogous dissociation between the representation of temporal signals in visual cortex and their inaccessibility to conscious awareness has been found in studies of heterochromatic flicker fusion. When two isoluminant colours alternate at frequencies above 10 Hz, only a single fused colour is perceived. However, neurons in primary visual cortex accurately represent the temporal sequence of alternating colours for frequencies well above the flicker fusion threshold (e.g.,

Gur & Snodderly, 1997), demonstrating that temporal information that is available at the neural level remains inaccessible to conscious visual perception.

This differential sensitivity of attentional processes and awareness to temporal order information demonstrated in the current study is inconsistent with the hypothesis that the mechanisms that implement selective attention and consciousness are functionally identical. If this was the case, temporal information that is represented during the attentional processing of visual stimuli should in principle also be accessible for conscious report. The fact that participants were unable to make above-chance temporal order judgments when the SOA between two successive stimuli was 10 ms provides further evidence that attention and awareness are functionally separable. A number of previous studies have also demonstrated similar dissociations between attention and awareness in different task contexts. For example, visual gratings rendered invisible through lateral masking still produce reliable orientation aftereffects, suggesting that they had been attended (He et al., 2002). Masked stimuli that cannot be consciously detected produce systematic response activation and response inhibition effects (e.g., Eimer & Schlaghecken, 1998), and these effects critically depend on a particular attentional task set (Schlaghecken & Eimer, 2004; see also Naccache, Blandin, & Dehaene, 2002). Many other studies investigating subliminal visuomotor and semantic priming have shown that the processing of stimuli that are inaccessible to awareness are modulated by top-down executive processes (see Kiefer, 2012, for a review), demonstrating that automatic processes triggered by subliminal stimuli can be highly sensitive to attentional control settings.

Together with the current results, such findings suggest that selective attention and conscious awareness may operate at different stages. Attentional processes are responsible for the selective prioritization of potentially task-relevant information at relatively early stages of perceptual processing. This stage of attentional selection is functionally and temporally distinct from a subsequent identification stage which involves the encoding of selected stimuli in working memory and their access to conscious recognition processes (see Eimer, 2014, for further details, and Lamme, 2003, for similar suggestions). In this framework, dissociations between attention and awareness will occur when information that is available to early attentional selection processes is not passed on to later conscious detection and discrimination stages. What the current results show is that even though exact information about the temporal order of visual objects is present during their

attentional selection, this information is no longer represented with the same temporal precision at a subsequent stage that mediates conscious access.

Acknowledgement

References

Ansorge, U., Kiss, M., & Eimer, M. (2009). Goal-driven attentional capture by invisible colors: Evidence from event-related potentials. *Psychonomic Bulletin & Review*, *16*, 648-653.

Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology, 99*, 225-234.

Eimer, M. (2014). The neural basis of attentional control in visual search. *Trends in Cognitive Sciences, 18*, 526-535.

Eimer, M., & Grubert, A. (2014). Spatial attention can be allocated rapidly and in parallel to new visual objects. *Current Biology, 24*, 193-198.

Eimer, M., Kiss, M., & Nicholas, S. (2011). What top-down task sets do for us: An ERP study on the benefits of advance preparation in visual search. *Journal of Experimental Psychology: Human Perception and Performance, 37*, 1758-1766.

Eimer, M., & Schlaghecken, F. (1998). Effects of masked stimuli on motor activation: Behavioral and electrophysiological evidence. *Journal of Experimental Psychology: Human Perception and Performance, 24*, 1737-1747.

Exner, S. (1875). Experimentelle Untersuchung der einfachsten psychischen Processe. *Pflügers Archiv für die gesamte Physiologie des Menschen und der Tiere, 11*, 403-432.

Grubert, A., & Eimer, M. (in press). Rapid parallel attentional target selection in single-colour and multiple-colour visual search. *Journal of Experimental Psychology: Human Perception and Performance*.

Gur, M., & Snodderly, D. (1997). A dissociation between brain activity and perception: chromatically opponent cortical neurons signal chromatic flicker that is not perceived. *Vision Research*, *37*, 377-382.

He, S., Cavanagh, P., & Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature, 383*, 334-337.

Hendrich, E., Strobach, T., Buss, M., Müller, H. J., & Schubert, T. (2012). Temporal-order judgment of visual and auditory stimuli: modulations in situations with and without stimulus discrimination. *Frontiers in Integrative Neuroscience, 6*, 1-9.

Hickey, C., McDonald, J. J., & Theeuwes, J. (2006). Electrophysiological evidence of the capture of visual attention. *Journal of Cognitive Neuroscience, 18*, 604–613.

Hirsh, I. J., & Sherrick, C. E. Jr. (1961). Perceived order in different sense modalities. *Journal of Experimental Psychology: General, 62*, 423-432.

Ishihara, S. (1972). *Tests for color-blindness*. Tokyo: Kanehara Shuppan.

Kiefer, M. (2012). Executive control over unconscious cognition: attentional sensitization of unconscious information processing. *Frontiers in Human Neuroscience*, *6,* 1-12.

Koch, C., & Tsuchiya, N. (2007). Attention and consciousness: two distinct brain processes. *Trends in Cognitive Sciences, 11*, 16-22.

Lamme, V. A. (2003). Why visual attention and awareness are different. *Trends in Cognitive Sciences, 7*, 12-18.

Li, F. F., VanRullen, R., Koch, C., & Perona, P. (2002). Rapid natural scene categorization in the near absence of attention. *Proceedings of the National Academy of Sciences of the United States of America, 99*, 9596-9601.

Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 1000-1014.

Naccache, L., Blandin, E., & Dehaene, S. (2002). Unconscious masked priming depends on temporal attention. *Psychological Science, 13*, 416-424.

O'Regan, J. K., & Noe, A. (2001). A sensorimotor account of vision and visual consciousness. *Behavioral and Brain Sciences, 24*, 939-973.

Posner, M. I. (1994). Attention: the mechanisms of consciousness. *Proceedings of the National Academy of Sciences of the United States of America, 91*, 7398-7403.

Rensink, R. A. (2002). Change detection. *Annual Review of Psychology, 53*, 245-277.

Scharlau, I., & Ansorge, U. (2003). Direct parameter specification of an attention shift: Evidence from perceptual latency priming. *Vision Research*, *43*, 1351-1363.

Schlaghecken, F., & Eimer, M. (2004). Masked prime stimuli can bias "free" choices between response alternatives. *Psychonomic Bulletin & Review, 11*, 463-468.

Simons, D. J. (2000). Current approaches to change blindness. *Visual Cognition, 7*, 1-15.

Woodman, G. F., & Luck, S. J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. *Nature, 400*, 867-869.

Zampini, M., Shore, D. I., & Spence, C. (2003). Audiovisual temporal order judgments. *Experimental Brain Research, 152*, 198-210.

Figure Legends

Figure 1. Stimulus procedures. Schematic illustration of the time course of stimulus events in our previous ERP experiments (Eimer & Grubert, 2014; Grubert & Eimer, in press) and in the current behavioural study. On each trial, two displays with a colour-defined target and a nontarget-colour distractor on opposite sides were presented sequentially. One target/nontarget pair appeared on the horizontal meridian and the other on the vertical meridian. In the One Colour task, all targets had the same colour. In the Two Colour task, there were two possible target colours, and target colour always changed between the first and second display. Each display was presented for 20 ms, and the SOA between the two displays was either 10 ms, 20 ms, or 30 ms. In SOA10 trials, the second display appeared 10 ms after the onset of the first display, so that both displays were simultaneously present for 10 ms. In SOA20 trials, the onset of the second display was synchronous with the offset of the first display. In SOA30 trials, there was a 10 ms gap between the offset of the first and the onset of the second display. The examples shown in this Figure include One Colour trials where both targets are red and Two Colour trials where the two targets are red and green, and all three SOA conditions. In our earlier ERP studies, participants had to judge the alphanumeric category of the two target objects (same/different). In the current study, their task was to report whether the first target-colour item on each trial was a letter or a digit.

Figure 2. Event-related potential results. N2pc results obtained for the One Colour task in the study by Eimer & Grubert (2014) and in the Two Colour task by Grubert and Eimer (in press) in blocks where the SOA between the two displays was 10 ms. Left panel: Grand-average ERP waveforms measured in the 400 ms interval after the onset of the first display at posterior electrodes PO7/PO8 contralateral and ipsilateral to the target in the first display for trials with a horizontal target in the first display (H1 targets) or in the second display (H2 targets), shown separately for the One Colour task (top) and Two Colour task (bottom). Right panel: N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, separately for H1 and H2 targets, in the One Colour task (top) and Two Colour task (bottom). Stars mark the onset of the second display (10 ms after the onset of the first display). Circles mark the points in time when N2pc amplitudes reach the onset criterion value (-1μV). The onset latency difference between N2pc components to H1 and

H2 targets precisely matched the objective time interval between the two target displays (10 ms) in the One Colour task, and was slightly larger (31 ms) in the Two Colour task.

Figure 3. Behavioural results. Performance in the current experiment, where the category (letter or digit) of the first target-colour item had to be reported. The two panels show the percentage of correct responses (relative to a chance level of 50%) for SOAs of 10, 20, or 30 ms between the two displays, in the One Colour and Two Colour tasks (left panel) and in the first two and final two blocks of both tasks (collapsed across the two tasks, right panel). Performance was at chance level for the shortest SOA (10 ms).
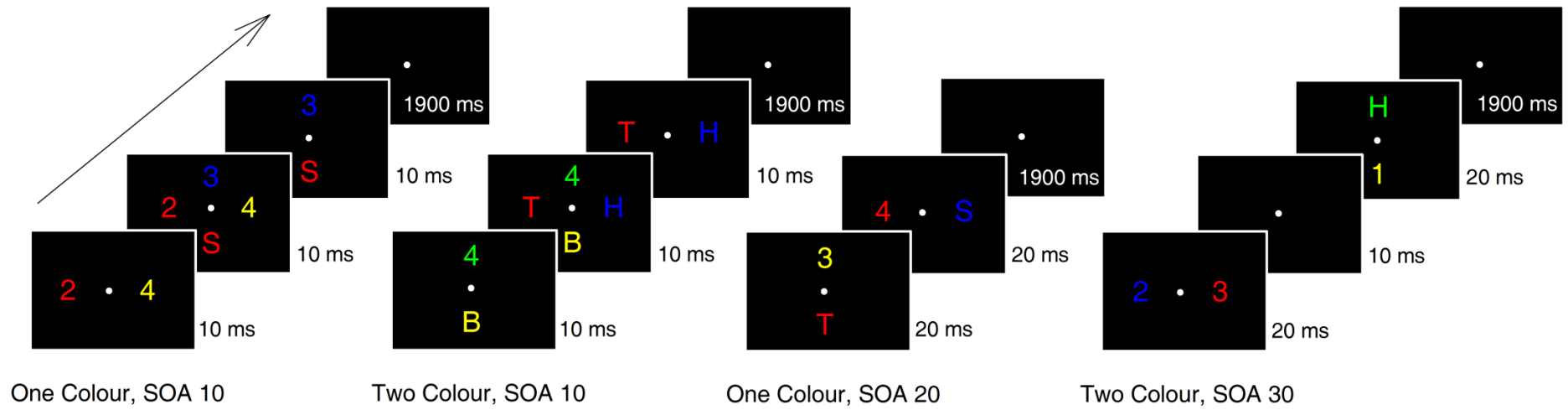
Figure 1.

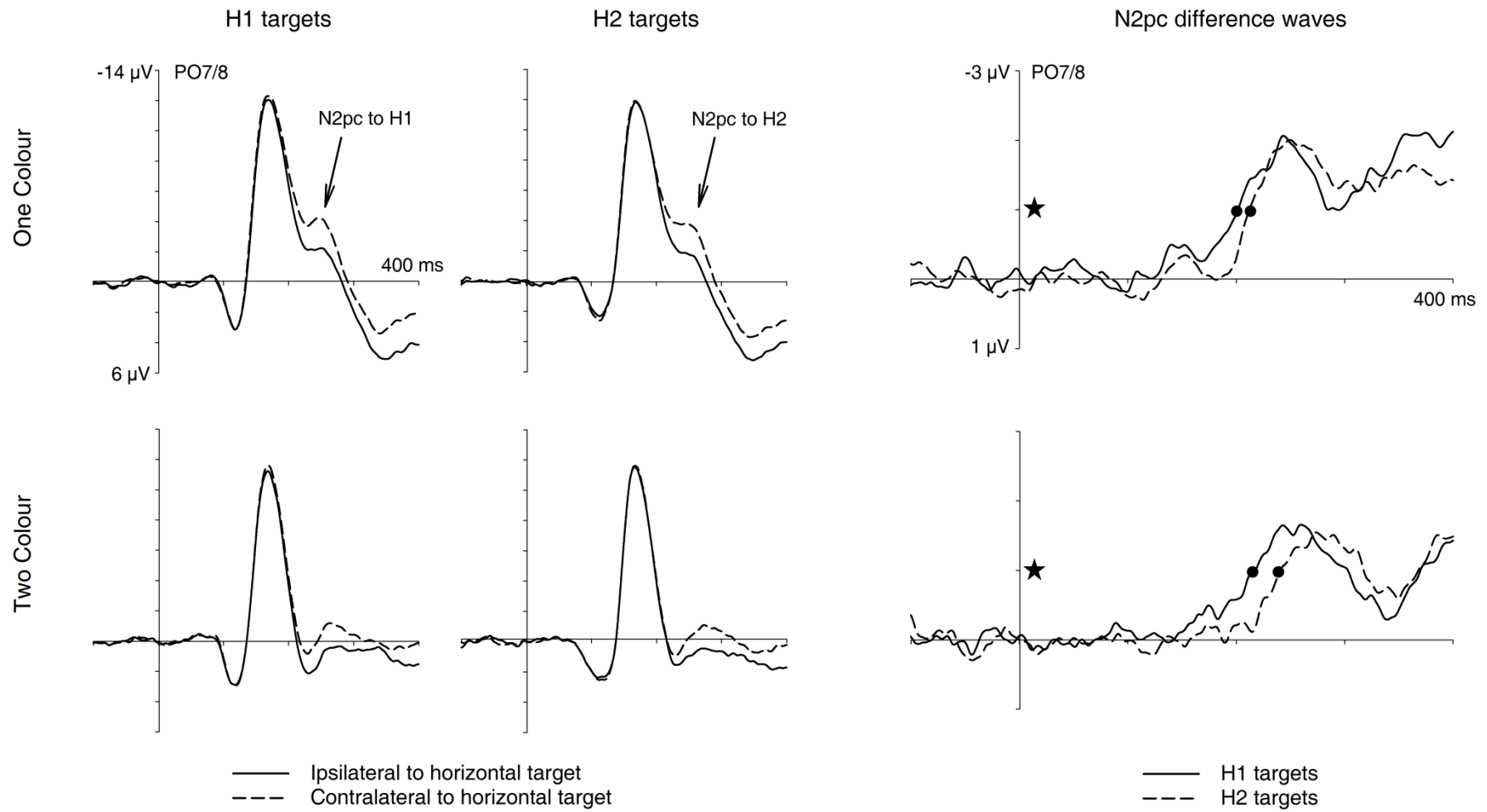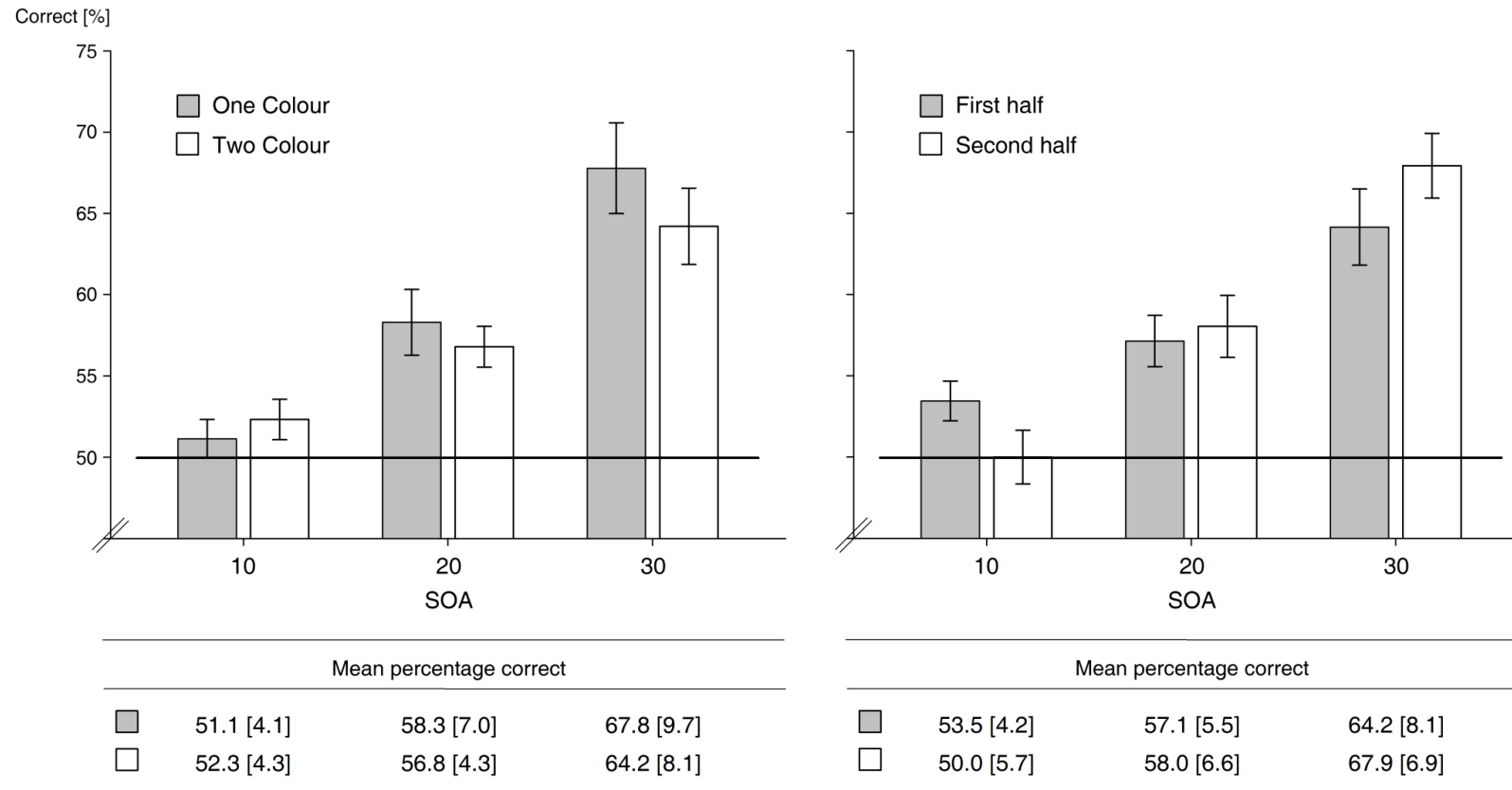One Colour, SOA 10   Two Colour, SOA 10   One Colour, SOA 20   Two Colour, SOA 30

Figure 2.

Figure 3.

Correct [%]

Mean percentage correct				Mean percentage correct		
▣	51.1 [4.1]	58.3 [7.0]	67.8 [9.7]	▣ 53.5 [4.2]	57.1 [5.5]	64.2 [8.1]
▢	52.3 [4.3]	56.8 [4.3]	64.2 [8.1]	▢ 50.0 [5.7]	58.0 [6.6]	67.9 [6.9]

Mean percentage correct for all three SOA conditions separately for the One Colour and the Two Colour task (left panel), and separately for first and second half of the experiment (right panel). Error bars reflect the standard error of the mean. Values in brackets reflect the standard deviation from the mean. The lines in the graphs reflect the 50% chance level.