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Short Communication

Selective temporal attention enhances the temporal resolution of visual perception: Evidence from a temporal order judgment task

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ABSTRACT

We investigated whether attending to a particular point in time affects temporal resolution in a task in which participants judged which of two visual stimuli had been presented first. The results showed that temporal resolution can be improved by attending to the relevant moment as indicated by the temporal cue. This novel finding is discussed in terms of the differential effects of spatial and temporal attention on temporal resolution.

Psychophysical and physiological research has provided converging evidence suggesting that spatial attention can enhance the early visual processing of stimuli appearing at cued as opposed to uncued locations (see Reynolds, 2005, for a review). However, given that time is as important as space for representing the dynamic structure of our world (e.g., Fraisse, 1963), it is somewhat surprising that until relatively recently, selective attention research had not explored the ability to intentionally commit attention to specific points in time. Nobre and her colleagues (e.g., Coull and Nobre, 1998) studied people's ability to endogenously orient their attention in the temporal domain using a temporal analogue of Posner's (1978) spatial cuing procedure. Symbolic cues indicated the temporal interval at which the target was most likely to appear (either *early* or *late* in time after the start of a trial). Analogously to the results of spatial cuing studies, participants responded more rapidly to targets appearing at the expected time as compared to unexpected time intervals. In contrast, physiological data on the effects of temporal attention revealed selective activations in left premotor cortex (e.g., Coull and Nobre, 1998) and modulations of late electrophysiological components (Miniussi et al., 1999), suggesting a postperceptual locus for temporal attention effects rather than a genuine perceptual enhancement. Alternatively, however, it could be argued that the detection task used in Nobre et al.'s study may have been insensitive to perceptual modulations, as simple-RT detection tasks demand speeded motor responses, so that the observed activations over motor areas might simply reflect task demands, instead of temporal attention effects (Correa et al., 2004).

In the present study, we explored whether selective attention to time can actually enhance the temporal aspects

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of visual perceptual processing. We combined a temporal cuing procedure with a psychophysical task in which participants had to make temporal order judgments (TOJs) regarding which of two visual stimuli appeared first. The stimulus onset asynchrony (SOA) between the two stimuli was manipulated using the method of constant stimuli and the resulting functions used to compute the just noticeable difference (JND, in milliseconds), which provides an index of the temporal resolution of perception (i.e., small JNDs indicate high temporal resolution). The use of a TOJ task is especially suitable to our two main goals: First, it provides an appropriate index of perceptual processing, since TOJ tasks normally involve accurate unspeeded responses (Klein et al., 1998). Second, the TOJ task provides a direct index of temporal resolution.

Attentional effects on visual temporal resolution have already been studied using a spatial orienting procedure, revealing discrepant results regarding a modulation of JNDs (see Shore and Spence, 2005, for a review). However, the effects of temporal attention on temporal resolution remain to be explored. Hence, the present experiment was designed to study whether temporal attention can modulate perceptual processing by improving the temporal resolution of visual processing. If attending to a particular moment in time really does improve visual temporal resolution, then we should observe smaller JNDs for pairs of stimuli presented at an expected as opposed to an unexpected moment in time.

Forty-six participants, reporting normal or corrected-to-normal vision, took part in the experiment after giving written consent. Eight of the participants were excluded from subsequent data analyses due to their poor temporal resolution (i.e., their JNDs fell outside the range of SOAs tested in the study).

The fixation point consisted of a centrally-presented white cross (0.25° × 0.25° visual angle). The temporal cue consisted of the words "early" or "late", subtending 3.1° and 2.4° horizontally, respectively. Two orange target LEDs (1° in diameter) were attached to the monitor, one on the left side and one on the right side (16° from fixation each). The 'Z' and 'M' keys on the keyboard were used to indicate that the left or right LED flashed first, respectively.

The participants sat resting their chin in a chinrest placed 57 cm from the monitor. They were instructed to use the temporal cue to predict when the target would appear and were encouraged to respond as accurately as possible with no time pressure.

The fixation point appeared for a random duration of 500–1500 ms (see Fig. 1). Next, the cue was presented for 500 ms followed by the fixation point for a further 400 or 1400 ms, depending on the cue–target interval. One of the target LEDs was illuminated, and after a variable SOA of 10, 30, 50 or 110 ms, the other target LED was illuminated on the other side. The two LEDs remained illuminated until the participants made a response. The side of the first target and the SOA factors were counterbalanced and randomly intermixed across trials.

After 16 practice trials, the participants completed four 'early' blocks and four 'late' blocks of 76 trials each, presented in counterbalanced runs (note that the cue served mainly to signal the onset of the temporal interval, as temporal expectancy was fixed during each block of trials). The valid/invalid trial ratio was 3:1. On valid trials, the cue was 'early' (or late) and the first target appeared after 400 (or 1400) ms. On invalid trials, the cue was 'early' (or late) and the first target appeared after 1400 (or 400) ms.

The proportion of correct responses was submitted to a repeated-measures analysis of variance (ANOVA) with the factors of Cue Validity (valid/invalid) and cue–target interval (short/long). The main effect of cue–target interval on accuracy was significant, $F(1,37) = 8.64$; $P < 0.01$, showing better performance at the long interval. More importantly for present purposes, participants responded more accurately for pairs of targets appearing at the valid interval rather than at the invalid interval, leading to a main effect of cue validity, $F(1,37) = 6.76$; $P < 0.01$. This finding reveals that endogenously attending to a particular point in time can improve performance in a temporal discrimination task in which efficient visual processing is demanded, suggesting a perceptual locus

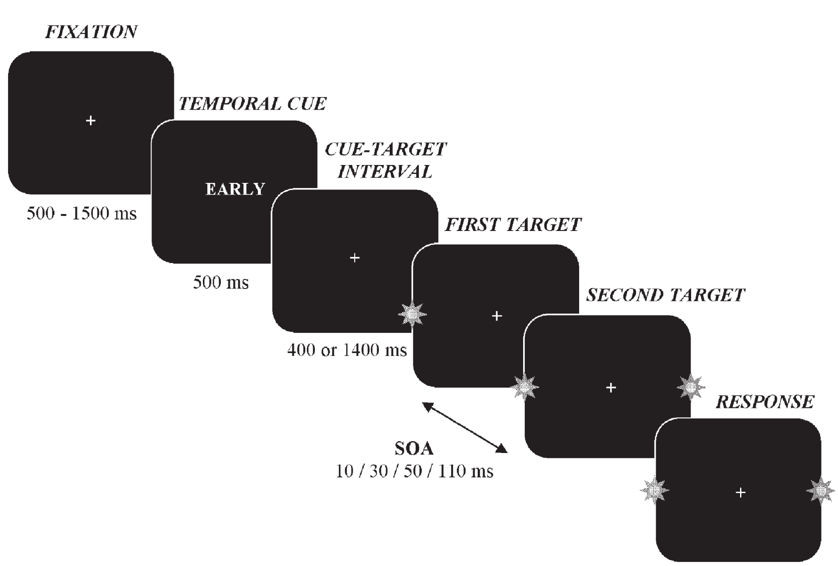

Fig. 1 – The sequence of events in a typical trial.

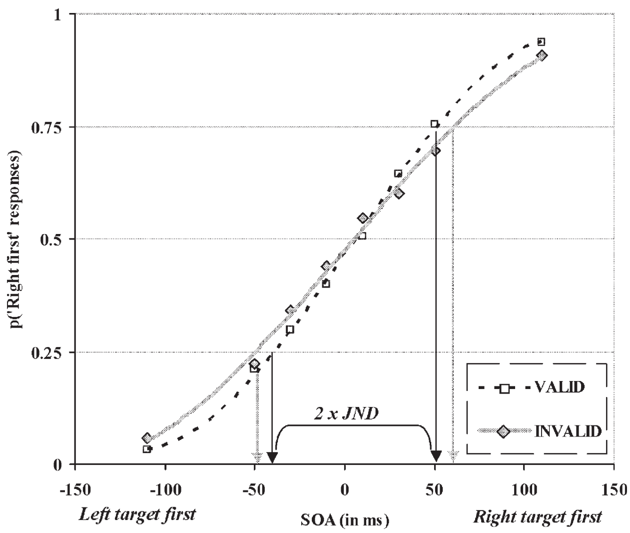

Fig. 2 – The mean proportion of 'right target first' responses as a function of SOA and cue validity (negative SOAs indicate that the left target was presented first). The interval of uncertainty (2 × JND) is shown for valid and invalid conditions. Here, the JND equals half of the interval between the SOA values yielding the 0.75 and 0.25 proportions in the psychometric function.

for such attentional effects. Although the interaction between validity and cue–target interval did not reach significance ($P = 0.13$), we observed no validity effects at the long interval ($F < 1$), which were presumably masked by the reorienting of attention from short to long intervals when the target invalidly appears later than expected (see Nobre, 2001, for a review). This strategy makes sense in that the probability of the target's arrival increases with time, becoming maximal at the long interval. Therefore, the focus for the subsequent JND-analysis was the data from the short interval.

The mean probability of 'right target first' responses is plotted as a function of SOA and cue validity in Fig. 2. In order to compute the JND, the data from each participant were transformed to Z scores, and the Z score distributions were fitted to linear regressions (Finney, 1964) for both the valid and invalid conditions (see Fig. 2). JNDs were computed for each participant using the slopes of such linear trends. Two-tailed paired comparison t tests were performed on the JND data. Crucially, the JND was significantly smaller in the valid condition (41 ms) than in the invalid condition (46 ms), $t(1,37) = 2.2$; $P = 0.03$, suggesting that focusing attention on a specific point in time improves the temporal resolution of visual perception.

To summarise, we combined a temporal cuing procedure with a TOJ task in order to determine whether endogenously orienting attention to a particular point in time can enhance the temporal aspects of perceptual processing. The results, revealing more accurate TOJs at the expected than at the unexpected time interval, support such an enhancement. This finding is in line with previous studies using non-temporal discrimination tasks that have reported temporal attention enhancements in perceptual sensitivity (Correa et al., 2005) and on P1, an ERP component linked to early visual electrophysiological activity (Correa et al., 2006), which contrasts with the conventional view that temporal attention mainly modulates late motor processing (Coull and Nobre, 1998). Critically, the finding of smaller JNDs for attended than for unattended pairs of stimuli shows for the first time that limitations in the temporal resolution of visual perception may be attenuated by attending to the moment in time when the two events occur.

On the other hand, the combination of spatial cuing and temporal resolution tasks has not led to definitive results yet which may guide explanations of the observed temporal attention effects. For instance, Yeshurun and Levy (2003) observed that exogenous spatial attention impaired temporal resolution when participants had to detect a temporal gap, while other studies have reported no such modulation of temporal resolution using TOJ tasks (Spence et al., 2001; Stelmach and Herdman, 1991). This discrepancy may reflect the different processes involved in temporal gap detection and TOJ tasks. Alternatively, however, providing spatial information does not necessarily influence performance when temporal processing, rather than spatial processing, is involved. Importantly, in the present experiment, both TOJ and temporal cuing procedures engaged time as the relevant dimension. Thus, we assumed that by providing temporal information signalling the target onset might enhance performance in temporal resolution tasks, such as TOJ tasks. Indeed, the present results provide support for such an attentional enhancement. Nevertheless, the mechanism by which temporal attention improves temporal resolution remains uncertain. We propose that perceptual processing could be speeded up at the attended time interval, thus increasing the '*refresh rate*' necessary to detect novel stimulus onsets. Further research will hopefully help to elucidate the neural mechanisms by which temporal attention increases temporal resolution in perception.

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