Temporal Expectation Modulates Attentional Processing Speed

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In a complex world, temporal expectations help us to guide our attention over time. But the nature of the mechanisms affected by expectations is still debated. Traditionally, reaction time-based measures have been employed to elucidate the workings of temporal expectations and observed effects have generally been ascribed to changes in motoric processes. However, recent studies have suggested that expectations may also affect attention at the perceptual level. We investigated the effects of temporal expectations on two distinct components of visual attention, the threshold of conscious perception and the speed of visual processing, in three experiments using accuracy-based measures that were unconfounded by motor components. Our findings support the claim that temporal expectations can modulate attention perceptually. Specifically, we show that although the temporal threshold of conscious perception is unaffected by temporal expectation, the speed of encoding items into visual short-term memory increases with temporal expectation. Thus, temporal expectations optimize behaviour by increasing not only motor speed, but also perceptual speed.

INTRODUCTION

Temporal expectations play an important role in optimizing perception and behaviour in a complex world by selectively directing attentional resources towards discrete moments in time. However, the exact nature of the attentional processes affected by expectations is still debated. Behavioural effects of temporal expectations have primarily been investigated using reaction time-based cueing paradigms (e.g., Correa, Lupiáñez, Madrid, & Tudela, 2006; Coull, Frith, Buchel, & Nobre, 2000; Coull & Nobre, 1998; Nobre, Correa, & Coull, 2007; also see Niemi & Näätänen, 1981 for a review of early reaction time studies). In these studies cues correctly (valid cues) or incorrectly (invalid cues) predict when in time a target is likely to appear. One well-established motoric effect of temporal cueing is the temporal orienting effect, measured as an increase in the reaction time to invalidly compared to validly cued targets. By analysing accuracy of performance in a more perceptually demanding task (a rapid visual serial presentation (RSVP) paradigm), Correa, Lupiáñez, and Tudela (2005) provided evidence that temporal expectancy may influence not only the speed of motoric processes but also the speed of some of the (higher- or lower-level) cognitive processes used in analyzing a rapidly presented visual stream of letters. Prompted by these findings, we investigated the effect of temporal expectancy on performance of three new versions of a more simple single-letter recognition paradigm, using pure accuracy measures that were unconfounded by the speed of motor processes. We employed computational modelling to determine the impact of temporal expectancy on two different components of attention: the temporal threshold of conscious perception and the speed of encoding items into visual short-term memory, once the perceptual threshold has been passed.

GENERAL METHOD

All three experiments employed a cued single-letter recognition task. The beginning of a trial was marked by the presentation of a central, symbolic cue. After a variable cue-target foreperiod, a target letter from the set [ABDEFGHJKLMNOPRSTVXZ] was briefly presented either above or below the fixation point. Stimuli were presented for varied durations (10, 20, 50, or 80 ms) after which they were terminated by pattern masks. The experimental task was to make an unspeeded report of the identity of the presented target letter. Subjects were instructed to fixate centrally at all times. Two key components of visual attention, the temporal threshold of conscious perception (t_0), and the visual processing speed (v), were estimated by use of Bundesen's (1990) Theory of Visual Attention: The probability (p) of correct report could be approximated as an exponential function of the stimulus duration (t):

$$p = 1 - \exp[-v\,(t - t_0)],$$

where t_0 measured the threshold of conscious perception, and v measured the processing speed at times $t > t_0$ (see Kyllingsbæk, 2006, for a detailed description of the estimation process; also see Bundesen & Habekost, 2008).

EXPERIMENT 1

Method

In Experiment 1, 8 healthy young subjects completed a total of 1,920 trials each. In this experiment the cue was neutral, merely signalling the beginning of a trial. The foreperiod for each trial was chosen from a distribution with six equally likely waiting times: 500 ms, 1,000 ms, 1,500 ms, 2,000 ms, 2,500 ms, and 3,000 ms. We assumed this paradigm would generate a steadily rising temporal expectancy over the time course of a trial, mimicking the increasing conditional probability that the target would appear at the next possible foreperiod given that it had not yet appeared (the "hazard rate").

Results and Discussion

We found that the increase in temporal expectancy during the period from 500 ms to 3,000 ms after the presentation of the cue was accompanied by a similar increase in the processing speed. On average the subjects showed a total increase of 40% in their processing speed over the foreperiod intervals. On the other hand, the threshold of conscious perception did not change over time. With this design, however, we could not determine whether the increase in processing speed reflected changes in temporal expectancy or other effects potentially related to foreperiod length, such as modulations of arousal or sustained attention.

EXPERIMENT 2

Method

In Experiment 2, 8 healthy young subjects completed a total of 4,000 trials each. The cue at the beginning of each trial induced an expectation about the time when the stimulus letter would appear. Waiting times were not fixed but distributed exponentially to produce a non-aging distribution. The cue indicated which of two distributions with different *hazard rates* the waiting time would be drawn from. The hazard rate could be either high (1.33 s^{-1}) or low (0.22 s^{-1}) corresponding to mean waiting times of 750 ms and 4,500 ms, respectively. The shortest possible foreperiod was 5 ms, the longest possible foreperiod was 17 seconds. The high hazard rate condition reflected a higher probability that a target would appear soon, which should induce an increased temporal expectation in the subjects compared to the low hazard rate condition.

Results and Discussion

In this experiment, we again found that cue type did not affect the threshold of conscious perception. However, all subjects showed a highly significant increase (on average 30%) in processing speed on trials with high as compared to low hazard rates. Crucially, this effect was found even though processing speed did not generally decrease over time; thus, the observed pattern was independent of the actual duration of the waiting time, and instead depended entirely on expectation.

EXPERIMENT 3

Method

In Experiment 3, 8 healthy young subjects completed a total of 3,840 trials each. Similar to the previous experiment, the cue at the beginning of each trial induced an expectation about the time when the target letter would appear. In this experiment foreperiods were distributed geometrically using time steps of 500 ms. The cue indicated which of two distributions the waiting time would be drawn from. For one distribution, the probability q that the target would appear at the next possible point in time, given that it had not yet appeared, was high (2/3). For the other distribution, q was low (1/9). The two values of q were chosen to match the mean foreperiods of 750 ms and 4,500 ms used in Experiment 2. In contrast to the previous experiment, we chose discrete waiting times as to have directly comparable foreperiods across the two probability conditions.

Results and Discussion

Experiment 3 almost perfectly reproduced the findings of the previous experiment: Temporal expectancy (high vs. low probability q) did not significantly affect the threshold of conscious perception. However, perceptual processing speed depended strongly on the temporal expectancy induced by the cues: On average the subjects showed a highly significant increase (~30%) in processing speed on trials with a high value of q irrespective of the actual length of the foreperiod.

GENERAL DISCUSSION

We investigated attentional effects of temporal expectation in three waiting time experiments. Analyses were based on Bundesen’s (1990) Theory of Visual Attention, which enabled us to tease apart and estimate two central components of attention: the temporal threshold of conscious perception and the visual speed of processing. In the first experiment different cue-target foreperiods were chosen to induce an increasing expectation from the shortest to the longest possible foreperiod between a cue and a subsequent target. This modulation of expectancy was accompanied by an increase in the speed of visual processing. To rule out the possibility that visual processing was speeded up by the passing of time rather than the increasing expectancy, in Experiment 2 temporal expectations were set at two different levels using foreperiods from two exponential distributions with different hazard rates. Visual processing was faster in the high as compared with the low hazard rate condition, but did not vary as a function of the length of the actual foreperiod. These findings strongly suggest that visual processing speed is modulated by temporal expectations. This hypothesis was further strengthened by the results from the third experiment using geometrically distributed foreperiods. Here, processing speed reflected whether the probability of a target appearing at the next possible point in time was high or low, with high probabilities producing faster processing times. None of the temporal expectation manipulations employed in the three experiments led to changes in the temporal threshold of conscious perception.

Our data extend findings by Correa et al. (2005) suggesting that temporal expectation modulates perceptual sensitivity by pinpointing the component of visual attention that it modulates. Using three novel versions of a simple single-letter recognition paradigm we have provided strong evidence that temporal expectancy influences the speed of purely perceptual encoding (v) without changing the temporal threshold of conscious perception (t_0). Thus, we have shown that speed of visual processing – unconfounded by motor processes or perceptual thresholds – is boosted by knowing when the stimulus is likely to appear.

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