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# Great Expectations: Temporal Expectation Modulates Perceptual Processing Speed

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In a crowded dynamic world, temporal expectations guide our attention in time. Prior investigations have consistently demonstrated that temporal expectations speed motor behavior. We explore effects of temporal expectation on *perceptual* speed in three nonspeeded, cued recognition paradigms. Different hazard rate functions for the cue-stimulus foreperiod were used to manipulate temporal expectations. By computational modeling we estimated two distinct components of visual attention: the temporal threshold of conscious perception ($t_0$ ms) and the speed of subsequent encoding into visual short-term memory ($v$ items/s). Notably, these components were measured independently of any motor involvement. The threshold $t_0$ was unaffected by temporal expectation, but perceptual processing speed $v$ increased with increasing expectation. By employing constant hazard rates to keep expectation constant over time, we further confirmed that the increase in perceptual speed was independent of the cue-stimulus duration. Thus, our results strongly suggest temporal expectations optimize perceptual performance by speeding information processing.

*Keywords:* temporal attention, temporal prediction, temporal preparation, TVA, hazard function

Beneficial effects of valid temporal expectations on motor responses have been demonstrated repeatedly over the last century (Woodrow, 1914; see Niemi & Näätänen, 1981, for a review of early reaction time studies; see Los, 2010, for a review of more recent studies). Most investigations have used reaction time (RT) based *foreperiod paradigms*, in which the interval (or "foreperiod") between a warning cue and a subsequent target stimulus is manipulated to induce different temporal expectations of target onset. When foreperiods are kept constant within blocks but varied between blocks, performance deteriorates over time such that longer foreperiods result in longer RTs. Conversely, when foreperiods vary from trial to trial within a block, RTs are faster for longer foreperiods (Niemi & Näätänen, 1981).

Studies of the locus of temporal expectation effects have generally pointed to enhancement of motor preparation processes (Mattes & Ulrich, 1997; Miniussi, Wilding, Coull, & Nobre, 1999; Näätänen, 1971; see Nobre, 2010, for an overview), though the possibility of a perceptual influence is recognized (e.g., Nobre, 2001; see also Rolke & Ulrich, 2010). For example, perceptual benefits of temporal expectation have consistently been demonstrated using nonspeeded, accuracy-based responses to rhythmic auditory stimuli (e.g., Barnes & Jones, 2000; Jones, Moynihan, MacKenzie, & Puente, 2002). More recently, using a rapid serial visual presentation (RSVP) paradigm, Correa, Lupiáñez, and Tudela (2005) found that cueing the temporal position (early or late) of a target letter embedded in a stream of distractor letters improved perceptual sensitivity ($d'$) but left perceptual bias unaffected, while Martens and Johnson (2005) found that temporal cueing attenuated the attentional blink. The occurrence of temporal benefits at the perceptual level has been further corroborated by studies of temporal order judgments suggesting that temporal cueing may enhance the temporal resolution of visual perception (Bausenhart, Rolke, & Ulrich, 2008; Correa, Sanabria, Spence, Tudela, & Lupiáñez, 2006).

These perceptual effects might be explained by assuming that cueing the temporal position of a target improves performance by facilitating discrimination between target and distractors. However, Correa et al. (2006) explained their results by hypothesizing that perceptual processing was speeded up at attended time intervals. This is in contrast to a suggestion by Posner and colleagues (Posner & Boies, 1971; Posner, 1978; see also Klein & Kerr, 1974)

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that warning cues do not influence the rate of processing in reaction time tasks. Similarly, Rolke and colleagues (Bausenhart, Rolke, Hackley, & Ulrich, 2006; Bausenhart, Rolke, Seibold, & Ulrich, 2010; Hackley et al., 2009; Rolke, 2008; Rolke & Hofmann, 2007; Seifried, Ulrich, Bausenhart, Rolke, & Osman, 2010) have investigated an "early onset hypothesis," which states that temporal expectations allow subjects to begin processing targets at earlier points in time. These two mechanisms for the way in which temporal expectations could affect the dynamics of perceptual processing—speeding up (Correa, Sanabria, et al., 2006) or earlier onset (Rolke, 2008; Rolke & Hofmann, 2007) of perceptual analysis—would both result in faster and more accurate processing of targets. Bausenhart et al. (2010) have recently tried to disentangle these two accounts by analysis of speed–accuracy trade-off (SAT) functions. They combined a constant foreperiod paradigm with a traditional SAT procedure, where the time available for stimulus processing is manipulated by varying the time between target presentation and response signal. Participants were required to withhold their response to a simple visual discrimination task until an auditory response signal was presented, and thus response latency was defined as the sum of (a) stimulus onset asynchrony between the visual target stimulus and the auditory response signal, and (b) RT to the response signal. Consistent with the early onset hypothesis, results suggested that the longest response latency at which performance was no better than chance increased with the duration of the cue-stimulus foreperiod. However, as noted by Bausenhart et al. (2010), foreperiods were kept constant within blocks, and the apparent evidence for an early onset of the perceptual analysis in the short-foreperiod condition may alternatively be explained by "decreased duration of motor processing rather than a genuine earlier start of perceptual processing" (p. 1031).

In the experiments reported in this article, we aimed to distinguish between the two accounts (speeding up vs. earlier onset) by detailed analyses of pure accuracy measures, unconfounded by the speed of motor processes. By computational modeling based on the Theory of Visual Attention (TVA; Bundesen, 1990), we separated two distinct attentional parameters: parameter $t_0$, the temporal threshold for visual perception, defined as the longest ineffective exposure duration for encoding into visual short term memory; and parameter $v$, the speed of encoding into visual short term memory once the threshold has been exceeded. In our three experiments, we manipulated temporal expectancies by varying the hazard rate for stimulus presentation (i.e., the conditional probability or probability density that the stimulus would be presented at the next possible moment in time, given that it had not yet been presented). The experiments used a nonspeeded, cued, single-letter recognition task. In Experiment 1, we used a classical foreperiod paradigm with six equally likely cue-stimulus foreperiods, such that the probability that the stimulus would appear at the next possible time of presentation increased over the course of a trial. However, with this paradigm the level of temporal expectation is confounded with the actual duration of the foreperiod. In order to disentangle expectancy effects from the effect of foreperiod duration, we modified the paradigm such that in Experiments 2 and 3, foreperiods were drawn from distributions with constant hazard rates (*nonaging* distributions; cf. Luce, 1986; Näätänen, 1971; Thomas, 1967). Foreperiods were either exponentially (Experiment 2) or geometrically (Experiment 3) distributed, with the hazard rate for stimulus presentation (i.e., the temporal expectation) being either high or low.

## General Method

All three experiments employed a cued single-letter recognition task (see Figure 1). The beginning of a trial was marked by the presentation of a brief central, symbolic cue. After a variable cue-target foreperiod, a randomly chosen target letter from the set [ABDEFGHJKLMNOPRSTVXZ] was briefly presented 5 degrees of visual angle above (probability .5) 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. Participants were instructed to fixate centrally at all times, and their task was to make a nonspeeded report of the identity of the letter if they were "fairly certain" of having seen it (i.e., to use all available information but refrain from pure guessing). Participants were informed of the accuracy of their reports (the probability that a reported letter was correct discounting trials in which no report was made) after each block (60–100 trials) and were encouraged to keep their reports within a specified accuracy range of 80–90% correct. Stimulus letters were written in the font Ariel (broad) with a letter point size of 68 corresponding to 2.7 by 2.3 degrees of visual angle. The masks were made from letter fragments and measured 100 by 100 pixels to completely cover the letters. Stimulus displays were presented on a 19" CRT monitor at 100 Hz using the E-prime 2 software with participants seated approximately 65 cm from the monitor in a semidarkened room.

From the performance on the single-letter recognition task, two key components of visual attention were estimated by use of TVA: the temporal threshold for conscious perception, $t_0$, and the perceptual processing speed, $v$. The probability $p$ of correct report could be approximated as an exponential function of the stimulus duration $t$:

$$p = 1 - e^{-v(t-t_o)}, \tag{1}$$

where $t_0$ measured the temporal threshold in seconds, and $v$ measured the perceptual processing speed in letters per second at times $t > t_0$ (Bundesen, 1990). The relationship between the two parameters can be visualized by plotting the probability of correct report as a function of exposure duration (see the upper panel of Figure 2). The lower panel of Figure 2 shows the observed performance of a single, representative participant in Experiment 2, for two levels of expectancy, fitted by Equation 1 with the values of the parameters obtained by a TVA-based maximum likelihood method (Dyrholm, Kyllingsbæk, Espeseth, & Bundesen, in press; Kyllingsbæk, 2006). The maximum likelihood fits were remarkably good, accounting for almost all variation in the participants' observed mean scores. Goodness-of-fit measures averaged across participants for the different experimental conditions in all three experiments are summarized in Tables 1 and 2.

## Experiment 1

### Method

**Participants.** Twelve healthy young women ($M_{\text{age}}$ = 23 years, *SD* = 3 years) participated. They all reported normal or corrected-to-normal visual acuity, and four were left-handed (Old-

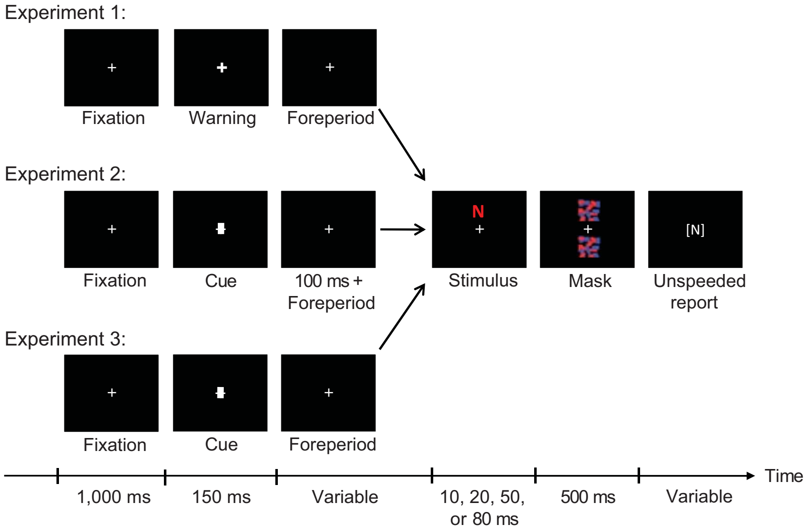

*Figure 1.* Time course of a single trial in Experiments 1–3. In Experiment 1 the initial fixation cross was followed by a warning (brief brightening of the fixation cross) signaling the beginning of the foreperiod before the imperative letter stimulus. In Experiments 2 and 3 the fixation cross was replaced by a cue signaling one of two temporal expectancy conditions. High expectancy was indicated by a brightening of the vertical line (as shown), while low expectancy was indicated by a brightening of the horizontal line. In all experiments, the letter stimulus could be presented either above (as shown) or below the fixation cross for 10, 20, 50 or 80 ms after which the possible stimulus positions were masked. Note that the foreperiod distributions used were unique for each of the three experiments.

field, 1971). Each participant completed four hours of testing and received $80. Participants for all three experiments were students recruited from the University of Copenhagen, Denmark.

**Procedure.** In Experiment 1 the cue preceding the letter to be recognized was a neutral warning signal, merely marking the beginning of a trial. The foreperiod (the interval between cue offset and stimulus onset) for each trial was chosen randomly from a uniform 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. As all foreperiods were intermixed, this procedure was equivalent to the variable foreperiod paradigms widely used in RT based investigations of temporal preparation (Los, 2010; Näätänen, 1970; Niemi & Näätänen, 1981). We assumed this paradigm would generate a steadily rising temporal expectancy over the time course of a trial, mimicking the increasing conditional probability, the *hazard rate*, that the target would appear at the next possible foreperiod given that it had not yet appeared (see Figure 3, conditional probability curve). Every participant completed a total of 1,920 trials, 320 trials for each of the six foreperiods.

## Results

The effect of temporal expectation on components of attention was investigated in separate one-way ANOVAs with Foreperiod (six levels) as a within-subject factor. We found that the theoretical increase in temporal expectancy throughout the duration of a trial was accompanied by an empirical increase in processing speed, $v$ (see Figure 3), $F(5, 55) = 6.713$, $p < .001$, $\eta_p^2 = .38$. This finding was supported by a significant linear trend, $F(1, 11) = 76.968$, $p < .001$, $\eta_p^2 = .88$. One-tailed dependent $t$ tests revealed significant differences between the shortest (500 ms) and four longest foreperiods: 1,500 ms, $t(11) = -1.87$, $p = .04$, $d = -.41$; 2,000 ms, $t(11) = -1.92$, $p = .04$, $d = -.32$; 2,500 ms, $t(11) = -4.90$, $p < .001$, $d = -.70$; and 3,000 ms, $t(11) = -4.53$, $p < .001$, $d = -.93$.[1] On average the subjects showed a total increase of 35% in their processing speed over the foreperiod intervals. However, the threshold of conscious perception $t_0$ did not change with foreperiod duration, $F(5, 55) = .93$, $p = .47$, $\eta_p^2 = .08$, nor did the error proneness of the subjects, $F(5, 55) = .17$, $p = .97$, $\eta_p^2 = .02$. Table 1 summarizes the results with respect to threshold and error rate (the probability that a reported letter was incorrect).

## Discussion

In Experiment 1, we manipulated temporal expectations by allowing the hazard rate of stimulus presentation to increase monotonically throughout the course of a trial. We found strong effects associated with this manipulation, confirming that hazard rates can be used to improve perceptual processing, and extending prior RT based investigations of hazard rates to the perceptual domain. By using TVA to separate out discrete components of attention, we found that as the hazard rate increased during the course of a trial, the perceptual threshold ($t_0$) remained constant but the subsequent speed of perceptual processing ($v$) increased in line with increasing hazard rate (see Figure 3). Unfortunately, the cause of the increase in perceptual processing speed was uncertain because the hazard rate and, therefore, the level of temporal expectation, was con-

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[1] Effect measures for $t$ tests are stated as Cohen's $d$. Where appropriate, the $d$-value is corrected for correlations between samples (see Dunlap, Cortina, Vaslow, & Burke, 1996).

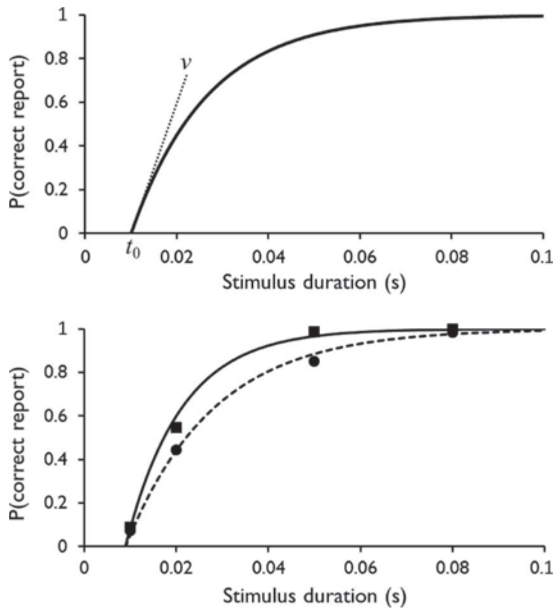

*Figure 2.* Probability of correct report as a function of stimulus duration. Upper panel: The solid curve shows predictions by Equation 1. The temporal threshold $t_0$ is the longest ineffective exposure duration. The slope of the curve at $t_0$ (the rate of increase of the curve) equals the perceptual processing speed $v$. Lower panel: Performance at two levels of temporal expectancy (■ = high, ● = low) for a representative participant in Experiment 2. The curves show the TVA-based fits to the observations (solid curve = high expectancy, dashed curve = low expectancy).

founded with foreperiod duration. In order to confirm that the increase in speed reflected increased temporal expectation, as opposed to other effects of increasing foreperiod duration such as changes in general arousal or sustained attention, we modified the paradigm such that in Experiments 2 and 3, the foreperiods were drawn from distributions with constant hazard rates (nonaging distributions).

## Experiment 2

### Method

**Participants.** Eight healthy young women ($M_{\text{age}} = 23.3$ years, $SD = 2.7$ years) participated. They all reported normal or corrected-to-normal visual acuity and two were left-handed. Each participant completed eight hours of testing and received $160.

**Procedure.** Each trial began with a 1,000 ms fixation screen followed by a cue signaling one of two possible expectancy conditions: High expectancy was represented by a brightening of the vertical line of the fixation cross, while low expectancy was represented by a brightening of the horizontal line (see Figure 1). After the cue and a 100 ms fixation screen, the foreperiod was initiated. Specifically, the cue indicated which of two exponential distributions, each with a distinct hazard rate, the foreperiod would be drawn from. The hazard rate was either high (1.33 $\text{s}^{-1}$) or low (0.22 $\text{s}^{-1}$) corresponding to mean foreperiod durations of 750 ms and 4,500 ms, respectively (see Figure 4). The shortest foreperiod was 10 milliseconds; the longest foreperiod was 17 seconds. We employed a blocked design, where each session of 400 trials was divided into four equally long blocks alternating between the two expectancy conditions. Participants completed a full session as practice and then 10 experimental sessions yielding a total of 4,000 experimental trials, 2,000 trials in each of the two conditions. A written description of the condition was shown on the computer screen at the beginning of each block, and participants were instructed to actively use the cue as a reminder of which condition they were doing in the block in question.

### Results

The manipulation of temporal expectancy using foreperiods from two different nonaging distributions was associated with a strong variation in the speed of perceptual processing. The result was a marked increase in processing speed on trials with high as compared with low hazard rates (mean difference = 15 items/s, 95% CI [6.78, 22.89]). Thus, the difference between the two expectancy conditions was highly significant, $t(7) = 4.35$, $p = .003$, $d = 1.17$. In contrast, neither the perceptual threshold, $t_0$, nor the error rate of the participants were influenced by the hazard rate manipulation, $t(7) = 1.10$, $p = .31$, $d = .32$, and $t(7) = -.91$, $p = .40$, $d = -.20$, respectively.

In principle the difference in processing speed between the two expectancy conditions might be due to the fact that the actual foreperiod durations differed between the two conditions rather than being due to a difference in expectations. To evaluate the effect of foreperiod duration, trials from each expectancy condition were grouped into three bins based on the length of their foreperiods: 0–750 ms, 750–1,500 ms, and ≥ 1,500 ms, respectively, with the last interval including all trials with foreperiods exceeding 1,500 ms. This particular division was chosen to optimize the reliability of the estimated attentional parameters by ensuring that a sufficient number of trials from both conditions were represented in each interval. The upper panels of Figure 5 show the resulting estimates for $v$ and $t_0$, respectively, for each of the foreperiod intervals in the two expectancy conditions, and Table 2 (Experiment 2) shows the corresponding error rates.

The effect of foreperiod duration was tested in repeated measures ANOVAs with Temporal expectancy (high vs. low) and Foreperiod interval (0–750 ms, 750–1,500 ms, or ≥1,500 ms) as

Table 1

*Mean Estimated Temporal Threshold, Error Rate, and Goodness of Fits Across Foreperiods in Experiment 1*

| | $t_0$ | | Error rate | | Var% | RMSD |
|---|---|---|---|---|---|---|
| Foreperiod | *M* | *SE* | *M* | *SE* | *M* | *M* |
| 500 ms | 12.3 | 1.4 | .13 | .04 | 98.0 | .049 |
| 1,000 ms | 13.6 | 1.3 | .13 | .04 | 98.8 | .036 |
| 1,500 ms | 13.4 | 1.4 | .13 | .04 | 98.8 | .038 |
| 2,000 ms | 12.9 | 1.3 | .13 | .03 | 98.5 | .043 |
| 2,500 ms | 13.7 | 1.3 | .13 | .04 | 98.8 | .035 |
| 3,000 ms | 14.1 | 1.2 | .13 | .03 | 99.5 | .026 |

*Note.* Threshold of conscious perception, $t_0$, is measured in milliseconds. Var%: Percentage of variance in the observed individual mean scores accounted for by the maximum likelihood fits. RMSD: Square root of the mean squared deviation between observed and theoretical mean scores.

Table 2
*Mean Error Rate and Goodness of Fits Across Expectancy Conditions and Foreperiods in Experiments 2 and 3*

| | High expectancy | | | Low expectancy | | |
|---|---|---|---|---|---|---|
| Foreperiod | Error rate (*SE*) | Var% | RMSD | Error rate (*SE*) | Var% | RMSD |
| Experiment 2 | | | | | | |
| 0–750 ms | .11 (.02) | 98.9 | .041 | .10 (.02) | 98.9 | .038 |
| 750–1,500 ms | .10 (.02) | 99.0 | .038 | .10 (.01) | 98.3 | .052 |
| ≥1,500 ms | .11 (.02) | 98.4 | .050 | .12 (.02) | 97.9 | .060 |
| Experiment 3 | | | | | | |
| 500 ms | .14 (.02) | 97.6 | .050 | .14 (.02) | 94.8 | .080 |
| 1,000 ms | .15 (.02) | 97.9 | .057 | .13 (.02) | 97.7 | .055 |
| 1,500 ms | .13 (.03) | 96.4 | .072 | .18 (.03) | 98.7 | .051 |
| ≥2,000 ms | .16 (.03) | 99.0 | .026 | .17 (.03) | 98.1 | .048 |

*Note.* Var%: Mean percentage of variance in the observed individual mean scores accounted for by the maximum likelihood fits. RMSD: Square root of the mean squared deviation between observed and theoretical mean scores across subjects.

within-subject factors. The effect of the expectancy manipulation on processing speed was corroborated by a significant main effect of Temporal expectancy, $F(1, 7) = 10.17$, $p = .015$, $\eta_p^2 = .60$. There was no general decline in processing speed over time, $F(2, 14) = 2.02$, $p = .17$, $\eta_p^2 = .22$, nor any modulation of the temporal expectancy effect by the passing of time, $F(2, 14) = 1.09$, $p = .36$, $\eta_p^2 = .14$. Thus, the observed variation in processing speed was independent of the duration of the foreperiod and instead depended entirely on expectation (see Figure 5, upper left panel). Furthermore, the effect of expectancy was highly specific, as neither $t_0$ nor the error rate were affected, both $F$s $< 1$, both $\eta_p^2$s $< .01$. Similarly, foreperiod duration affected neither $t_0$, $F(2, 14) = 1.22$, $p = .32$, $\eta_p^2 = .15$, nor the error rate, $F(2, 14) = 1.46$, $p = .27$, $\eta_p^2 = .17$.

## Discussion

The results confirm that perceptual processing speed $v$, but not threshold $t_0$, is influenced by temporal expectations induced by the hazard rate of occurrence of an imperative stimulus. We used nonaging distributions to produce two distinct hazard rates that differed in their level of expectation, though each rate remained constant across time. Processing speeds perfectly reflected these distributions, being faster for high versus low hazard rates but remaining constant over time. The beneficial effects of temporal expectation on processing speed were thus independent of foreperiod duration. Nevertheless, by employing continuous foreperiod distributions, trials had to be grouped into broad bins when evaluating the possible effect of foreperiod duration. Therefore, to evaluate the effect of foreperiod more precisely and to further corroborate our findings, we investigated performance with geometrically distributed foreperiods.

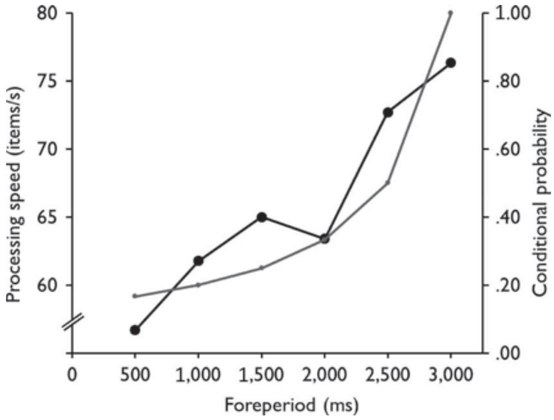

*Figure 3.* Increasing mean perceptual processing speed, $v$, measured in items/s (black dots and line), and theoretical expectancy (dark gray line) represented by the conditional probability of a target appearing at the next foreperiod given that it had not yet appeared, across the six possible foreperiods of Experiment 1.

## Experiment 3

## Method

**Participants.** Eight healthy young women ($M_{\text{age}} = 22.13$ years, $SD = 2.17$ years) participated. They all reported normal or

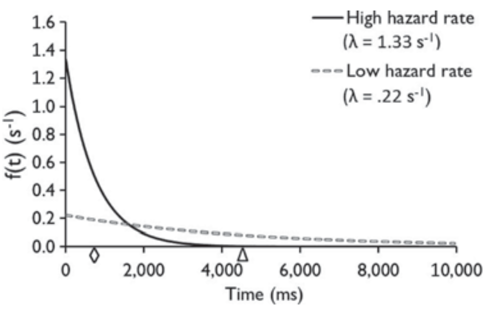

*Figure 4.* Probability density functions for the two exponential distributions, with different hazard rates (λ), from which the foreperiods in Experiment 2 were drawn. In the high expectancy condition, foreperiods were drawn from the distribution with a high hazard rate resulting in a mean foreperiod of 750 ms, marked by ◇. In the low expectancy condition, foreperiods were drawn from the distribution with a low hazard rate resulting in a mean foreperiod of 4,500 ms, marked by Δ.

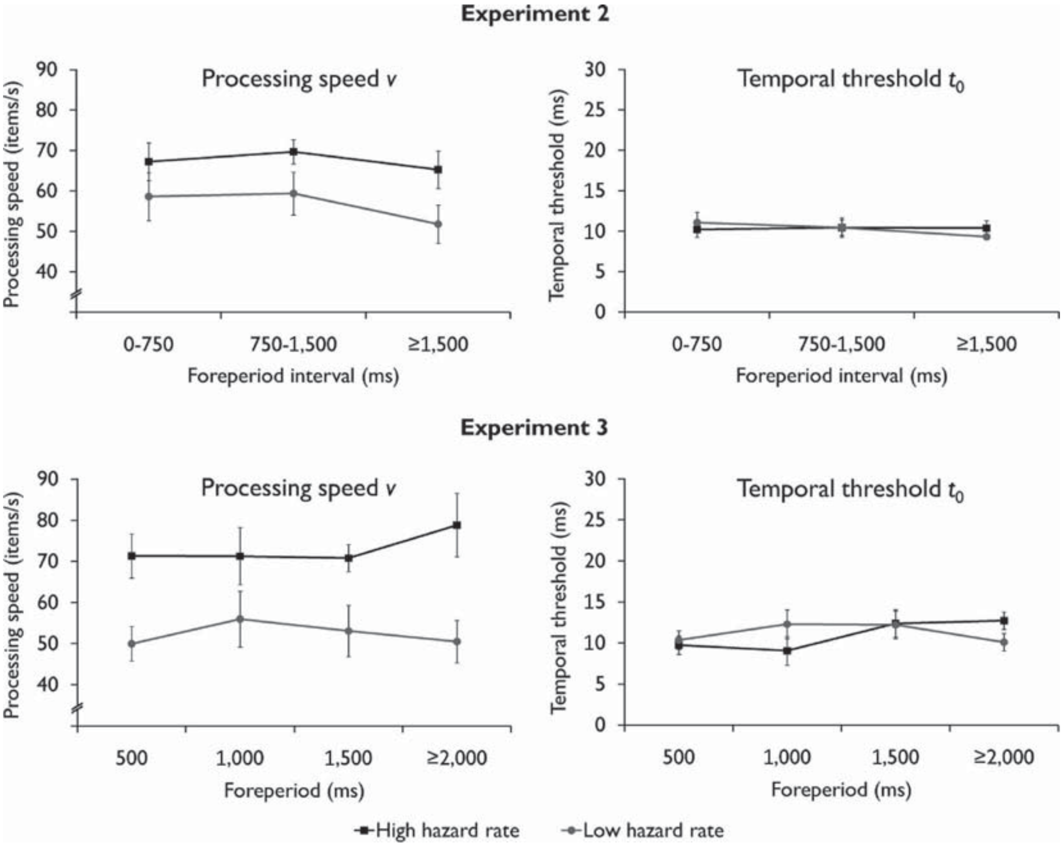

*Figure 5.* Mean perceptual processing speed and mean temporal threshold as functions of temporal expectancy condition (high vs. low hazard rate) and foreperiod interval or foreperiod in Experiments 2 and 3. Error bars show standard errors of the mean.

corrected-to-normal visual acuity and three were left-handed. Each participant completed eight hours of testing and received $160.

**Procedure.** Similar to Experiment 2, the cue at the beginning of each trial induced a particular level of temporal expectation about the target letter appearance. In Experiment 3, however, foreperiods were distributed geometrically using time-steps of 500 ms, resulting in *discrete* nonaging distributions. 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). These values were chosen to match the mean foreperiods of 750 ms and 4,500 ms used in Experiment 2. Accordingly we hypothesized that this manipulation of expectancy should yield a difference in processing speed comparable to the one observed in Experiment 2. The shortest possible foreperiod was 500 milliseconds; the longest possible foreperiod was 15.5 seconds. The participants completed a total of 3,840 trials each in eight sessions. One session comprised 480 trials divided into six blocks of 80 trials, and as in Experiment 2, the expectancy conditions alternated between blocks.

## Results and Discussion

Experiment 3 replicated our previous findings. Perceptual processing speed ($v$) increased with temporal expectancy, leading to significantly faster processing in the high expectancy condition (mean difference = 17 items/s, CI [7.70, 27.72]) compared with the low expectancy condition, $t(7) = 4.18$, $p = .004$, $d = 1.12$. In contrast, temporal expectancy did not significantly affect the temporal threshold ($t_0$), $t(7) = -1.20$, $p = .27$, $d = -.42$, nor the error rate, $t(7) = -1.52$, $p = .17$, $d = -.30$.

To examine the effects of foreperiod duration, attentional parameters were estimated separately for the two expectancy conditions at three discrete foreperiods (500 ms, 1,000 ms, and 1,500 ms) and for foreperiods $\geq$ 2,000 ms. The lower panels of Figure 5 show the resulting parameter estimates, and Table 2 (Experiment 3) shows the corresponding error rates.

To test for potential effects induced by foreperiod duration, we conducted repeated measures ANOVAs with Temporal expectancy (high vs. low) and Foreperiod (500 ms, 1,000 ms, 1,500 ms, or $\geq$ 2,000 ms) as within-subject factors. For all foreperiods, perceptual processing was faster in the high expectancy condition resulting in a highly significant main effect of Temporal expectancy, $F(1, 7) = 26.89$, $p = .001$, $\eta_p^2 = .79$ (see Figure 5, lower left panel). Processing speed was unaffected by the actual duration of the foreperiod, $F(3, 21) = .52$, $p = .67$, $\eta_p^2 = .07$, and there was no interaction between the level of temporal expectancy and the length of the foreperiod, $F(3, 21) = 1.03$, $p = .40$, $\eta_p^2 = .13$. The null effects of expectation on both the perceptual threshold ($t_0$) and the error rate found in Experiment 2 were also replicated, $F$s $< 1$, both $\eta_p^2$s $< .10$. However, though foreperiod duration did not affect $t_0$, $F(3, 21) = 1.22$, $p = .32$, $\eta_p^2 = .15$, the participants made slightly more errors at the longer foreperiods, $F(3, 21) = 4.88$, $p = .01$, $\eta_p^2 = .41$.

# General Discussion

## Summary

We investigated the effects of temporal expectation on the dynamics of perceptual processing in three cued recognition experiments. To eliminate potentially confounding effects on motor preparation, performance was nonspeeded. By use of analyses based on TVA (Bundesen, 1990), we separated out two central discrete components of attention: the temporal threshold of conscious perception ($t_0$) and the visual speed of processing ($v$). In Experiment 1, a variable foreperiod manipulation was used to induce an increasingly strong expectation from the shortest to the longest possible foreperiod between a cue and a subsequent stimulus. Increases in perceptual speed closely followed the increasing hazard rate and, by association, the theoretical evolution of temporal expectation over the duration of the foreperiod (see Figure 3). However, this did not allow us to conclude definitively that the increase in perceptual processing speed was due to increased expectation, as the hazard rate and, therefore, the level of temporal expectation, was confounded with the duration of the foreperiod. In order to disentangle these effects, we modified the paradigm in Experiments 2 and 3, such that foreperiods were drawn from distributions with constant hazard rates (nonaging distributions) thereby rendering temporal expectations correspondingly constant across time. Foreperiods were either exponentially (Experiment 2) or geometrically (Experiment 3) distributed, but in both experiments temporal expectations were set at two different levels using foreperiods from distributions with two different, time-invariant hazard rates. Both experiments showed that visual processing speed was faster in the high as compared with the low expectancy condition and, crucially, was independent of foreperiod duration. Notably, none of the expectancy manipulations we employed led to changes in the temporal threshold of conscious perception.

## Relation to Previous Studies

Previous authors have hypothesized that the benefits of temporal expectancies on visual processing depend on modulation of either the temporal onset (Rolke, 2008; Rolke & Hofmann, 2007) or speed of ensuing stimulus processing (Correa, Sanabria, et al., 2006). Modeling nonspeeded performance (cf. Bausenhart et al., 2010) by use of TVA, we found strong evidence that temporal expectation enhances information processing by increasing the speed of perceptual processing rather than allowing information processing to begin sooner. Thus, our findings provide empirical evidence for the hypothesis proposed by Correa, Sanabria, Spence, Tudela, & Lupiáñez, et al. (2006), at least for performance in the nonspeeded cued single-letter recognition paradigm we have developed. In contrast, the results of our experiments do not support accounts stating that temporal expectancy leaves the rate of perceptual processing unaffected (e.g., Posner, 1978; Posner & Boies, 1971; Rolke, 2008; Rolke & Hofmann, 2007). More generally, our findings provide more direct evidence than has hitherto been available that the temporal characteristics of perceptual processing depend on temporal expectation.

## Perspectives

In TVA, the speed of encoding the categorization that stimulus $x$ is a letter of type $i$ into visual short-term memory is given by

$$v(x, i) = \eta(x, i)\beta_i,$$

where $\eta(x, i)$ is the strength of the sensory evidence that $x$ is a letter of type $i$, and $\beta_i$ is the perceptual decision bias associated with letter type $i$. In a letter recognition task, letter categorizations are desired, so the perceptual bias parameters associated with letter types should be high. Now, we propose that temporal expectations affect perception by changing perceptual biases (values of $\beta$ parameters). Specifically, a strong expectation that a stimulus letter will appear at the next moment should yield an increase in the $\beta$ values of letter types, which should speed the recognition of the stimulus letter if it appears when it is highly expected.

In the neural interpretation of TVA known as NTVA (Bundesen, Habekost, & Kyllingsbæk, 2005), the encoding speed ($v$ value) of a categorization depends on both the number of cortical neurons representing the categorization and the firing rates of those neurons. The bias parameter $\beta_i$ is conceptualized as a scale factor that multiplies activations (firing rates) of all cortical neurons coding for feature $i$ (e.g., a particular letter type). Multiplicative scaling of rates of firing by change in perceptual biases ($\beta$ values) may be the neural mechanism by which temporal expectations corresponding to particular hazard rates influence information processing. The hypothesis fits with electrophysiological studies in monkeys demonstrating that neural firing in feature-specific cortical regions varies in ways that appear to reflect the monkeys' temporal expectations indexed by the hazard function of stimulus presentation (Ghose & Maunsell, 2002; Janssen & Shadlen, 2005; Riehle, Grün, Diesmann, & Aertsen, 1997).

Electrophysiological (EEG) studies in humans examining event related potentials (ERPs) elicited by temporal cueing have offered mixed evidence for modulation of early ERP components, thought to be related to perceptual processing, while later components, related to decision and response stages of information processing (e.g., N2 and P300), are consistently influenced by temporal attention (e.g., Correa et al., 2005; Griffin, Miniussi, & Nobre, 2002; Miniussi, Wilding, Coull, & Nobre, 1999). Modulation of early (perceptual) ERP components by temporal cueing has been shown only in specific circumstances, for example in the auditory, rather than visual, modality (Lange, Krämer, & Röder, 2006; Lange, Rösler, & Röder, 2003; Rimmele, Jolsvai, & Sussman, 2011), when temporal and spatial cueing are combined (Doherty, Rao, Mesulam, & Nobre, 2005), or when perceptual task difficulty is increased (Correa, Lupiáñez, Madrid, & Tudela, 2006). In addition, the few EEG studies that have used conditional probability to manipulate temporal expectancy (e.g., Correa & Nobre, 2008; Los & Heslenfeld, 2005; Müller-Gethmann, Ulrich, & Rinkenauer, 2003; Trillenberg, Verleger, Wascher, Wauschkuhn, & Wessel, 2000) used RT paradigms, which measured the effects of temporal expectancy on speed of motor responding rather than perceptual accuracy.

In a world presenting us with an abundance of visual information spatial attention helps us select the most important spatial information. Similarly, temporal expectations guide our attention over time in a dynamic world. We have proposed that temporal expectations are directly linked to the efficiency of information processing at the perceptual level. Using temporal information to speed up perceptual processing is a highly efficient way of optimizing behavior by enhancing information processing when it is temporally relevant and preventing errors at crucial times. To obtain converging evidence for the proposed TVA-based interpretation of the results presented in this article, we are currently investigating how speeding of perceptual processing may be realized in the human brain by applying the TVA-based designs of Experiments 2 and 3 in an EEG setup.

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