Pre-target oculomotor inhibition reflects temporal orienting rather than certainty

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Abstract

A series of recent studies suggested that eye movements are linked to temporal predictability. In these studies, temporal predictability was manipulated by setting the interval between a cue and a target (*foreperiod*) to be either fixed or random, in separate blocks. Findings showed that shortly prior to target onset, oculomotor behavior was reduced in the fixed relative to the random condition. This effect was interpreted as reflecting the formation of temporal expectation. However, it is still unknown whether the effect is driven by target-specific temporal orienting (*orienting hypothesis*), or whether it is a result of a more general and context-dependent state of certainty that participants may experience during blocks with a high predictability rate (*certainty hypothesis*).

In the following study we examined this question by dissociating certainty and orienting. In each trial, a temporal cue (fixation color change) was followed by a slightly tilted grating-patch, on which participants made tilt-discrimination decision. The distribution of the foreperiods was varied between blocks to be either fully fixed (100% of trials with the same foreperiod), mostly fixed (80% of trials with one foreperiod and 20% with another) or random (five foreperiods in equal probabilities). The two hypotheses led to different prediction models which were tested against the experimental data.

Results were highly consistent with the orienting hypothesis and inconsistent with the certainty hypothesis, supporting the link between oculomotor inhibition and temporal orienting and its validity as a marker for target-specific expectations in future studies.

Keywords: Temporal expectation; eye movements; saccades; microsaccades; temporal attention

Introduction

Temporal expectation is a prediction regarding the timing of events based on previously-experienced temporal regularities (Nobre & van Ede, 2017). Recent studies showed that the oculomotor system is tightly linked to temporal attention and expectation: oculomotor activity (saccades, ocular drift, and blinks) is inhibited for a few hundred milliseconds prior to the appearance of a predictable, relative to an unpredictable, stimulus (Abeles et al., 2020; Amit et al., 2019; Badde et al., 2020; Dankner et al., 2017; Denison et al., 2019). This oculomotor inhibition phenomenon can be used as a sensitive marker for temporal expectation and, as such, has several advantages over traditional behavioral and electrophysiological markers (Amit et al., 2019). Oculomotor inhibition prior to a predictable target was found to occur with various types of temporal structures: with rhythmic expectations, when stimuli were predictable because they are part of a rhythmic stream of stimulation (Dankner et al., 2017), and with associative expectations, when targets are rendered predictable by a precedent informative temporal cue in a visual (Amit et al., 2019), auditory (Abeles et al., 2020) or tactile (Badde et al., 2020) task. Oculomotor inhibition was also hypothesized to be modulated by conditional expectations – expectations that gradually increase as time progresses and an expected event has not yet occurred (Amit et al., 2019). The oculomotor inhibiton phenomenon is thought to depend on sustained attention as it was reduced in people who were diagnosed with attention deficit and hyperactivity disorder (ADHD) and in participants who showed high inter-trial variability in reaction times, a measurement indicative of sustained attention abilities (Dankner et al., 2017).

In the previous studies on oculomotor inhibition, temporal expectation was manipulated by modulating the foreperiod - the time period between a predicting event (e.g. the onset of a temporal cue or the previous stimulus in a stream) and target onset. The foreperiod was manipulated in two conditions: (a) in the fixed condition, the forepriod was identical for all

trials, rendering the target predictable and (b) in the random condition, it varied between a few options, rendering the target less predictable. The findings showed that pre-stimulus oculomotor activity was consistently more inhibited when the foreperiod was fixed relative to when it varied, reflecting the formation of expectations for an upcoming stimulus.

Despite the high reliability of the oculomotor inhibition effect and its modulation by target predictability, the characterization of the mechanism underlying this effect is still unknown. Specifically, is still unknown whether the oculomotor inhibition effect reflects temporal orienting of attention for specific targets, or a general state of elevated certainty in the fixed relative to the random blocks. Repeated encounters with predictable targets in fixed blocks may have elevated the participants' general feeling of certainty in those blocks. It could be hypothesized that in states of high certainty, the oculomotor system inhibits activity, either because it is prone to be less explorative or due to lower task engagement.

In the present study we contrasted these two hypotheses by examining whether the oculomotor inhibition effect reflects temporal orienting or certainty. In each trial, participants (N=20) were presented with a temporal cue that was followed, after a foreperiod interval, with a target – a tilted grating patch - on which they performed a tilt-discrimination task. Temporal orienting and certainty were manipulated by varying the foreperiod distribution between blocks in three different ways: (1) in *full-certainty blocks*, the same foreperiod (1 or 2 s) was used in all trials; (2) in *high-certainty blocks*, one foreperiod (1 or 2 s) was used in most (80%) of the trials and another foreperiod (2 or 1 s, respectively) was used in the rest of the trials; (3) lastly, in *low-certainty block*, five different foreperiods (1, 1.5, 2, 2.5, 3 s) occurred in equal probabilities. These three block types resulted in four trials conditions: (1) *full-certainty trials*: trials of the full-certainty-1s and the full-certainty-2s blocks; (2) *high-certainty-frequent trials*: 1s foreperiod trials of the high-certainty-1s blocks and 2s foreperiod trials of the high-certainty-2s blocks; (3) *high-certainty-rare trials*: 2s foreperiod trials of the high-certainty-1s blocks and

1s foreperiod trials of the high-certainty-2s blocks; (4) *low-certainty trials*: trials of the low-certainty blocks.

By examining the pre-target saccade-rate (SR) in 1 s and 2 s foreperiods, we tested two alternative predictions as depicted in **Figure 1**. The *certainty hypothesis* (**Figure 1A**), predicts that the pre-target SR would be determined solely by the foreperiod distribution within the block, regardless of the identity of specific trials. According to this hypothesis, it should be lowest (i.e. strongest oculomotor inhibition) in the full certainty trials, higher in the high certainty trials (both rare and frequent) and highest in the low certainty trials. Importantly, this hypothesis predicts no significant difference between high-certainty-frequent and high-certainty-rare trials as they both feature the same high level of certainty. Since certainty does not vary by foreperiod, the certainty hypothesis also predicts no difference in the pattern of results between trials with 1 s and 2 s foreperiods. In contrast, the *temporal orienting hypothesis* (**Figure 1B**) predicts that the pre-target SR would be determined exclusively by the probability of a target to occur at a specific timing, regardless of its context within the block. According to this hypothesis, predictions differ for trials with a foreperiod of 1 s and trials with a foreperiod of 2 s. For trials with a 1 s foreperiod, target-probability is determined solely by the frequency of this foreperiod within a given block (20%, 80% or 100%). Accordingly, the hypothesis predicts that pre-target SR should be lowest (i.e. strongest inhibition) in full-certainty trials (in which the target occurs after 1 s in all trials), higher in high-certainty-frequent trials (in which the target occurs after 1 s in 80% of the trials) and highest in high-certainty-rare and the low-certainty trials (in which the target occurs after 1s in 20% of the trials). Importantly, for 1s foreperiod trials the hypothesis predicts no significant difference between high-certainty-rare and low-certainty trials, as the probability for a 1 s foreperiod in both conditions is 20%. For trials with a 2 s foreperiod, on the other hand, temporal orienting is not only determined by

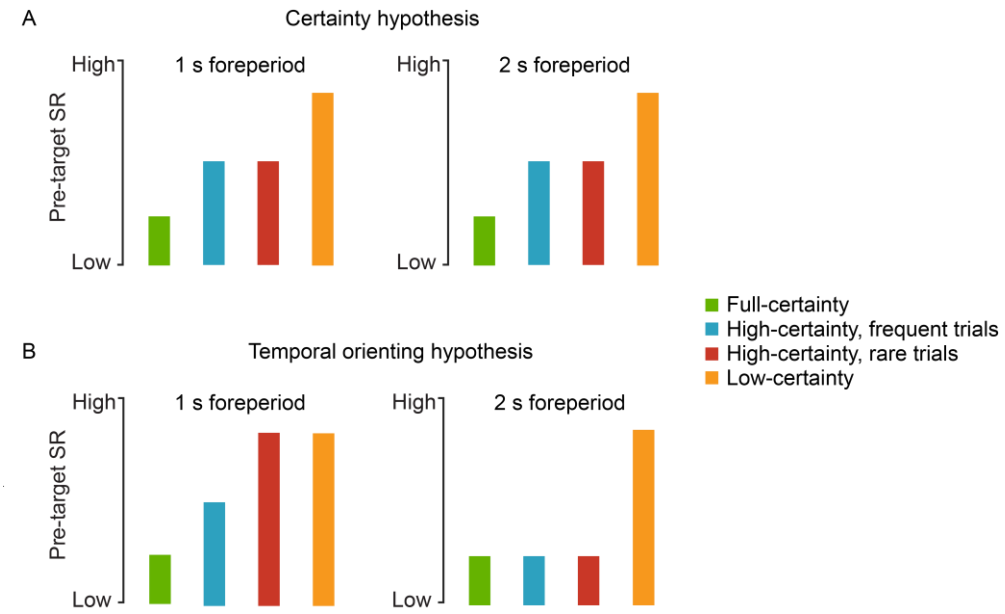

Figure 1. *Hypotheses*. Theoretical predictions of the *certainty* (A) and the *temporal orienting* (B) *hypotheses* for pre-target saccade-rates (SR) in trials of 1 s (left) and 2 s (right) foreperiod, of the four conditions.

foreperiod frequency but also by the conditional probability – how likely a target is to occur at a certain time given that it has not occurred up until that point (the hazard-rate function). Considering that the pre-target SR is measured slightly before 2 s post cue, at this time range the probability of target occurrence is full in three out of the four trial-types. Naturally, probability for target occurrence is full in full-certainty trials in which the targets occur at 2 s in all of the trials; but it is also full in the high-certainty trials, where there are only trials with foreperiods of 1 s or 2 s, and therefore once one second has elapsed and no target has yet appeared, the target will certainly occur at exactly 2 s post cue. In contrast, in low-certainty blocks, where there are five optional foreperiods, slightly before 2 s there is only a 33% chance for the target to occur at 2 s. The temporal orienting hypothesis predicts pre-target SR would reflect these conditional probabilities, i.e. be high for the low-certainty blocks and low for the other three block types. Notably, the hypothesis predicts no significant difference between the full-certainty, high-certainty-rare and high-certainty-frequent trials as in all three conditions the target is fully predictable at 2 s, given that it has not occurred at 1 s.

Results of the present study confirm the predictions of the temporal orienting hypothesis and are inconsistent with the certainty hypothesis. These findings provide conclusive evidence that oculomotor inhibition reflects temporal orienting for specific targets rather than a general sense of certainty, and further validate the use of oculomotor inhibition as a marker of target-specific temporal expectation.

Method

Participants

Twenty students of Tel-Aviv University participated in this experiment (11 female, one left-handed, Mean age 22.6, standard deviation (SD) age 3.5). The sample size was determined based on a similar previous study which used the same number of participants (Amit et al., 2019). To ensure that that this sample size leads to adequate power in this study despite having a lower number of trials per condition (80 here compared to 100 in the previous study), we performed a power simulation (using Superpower package; Caldwell & Lakens, 2019) based on truncated data of the previous study using only the 80 first trials of each condition. Simulation results indicated that with 20 participants and 80 trials there is a high probability for finding predictability effects (fixed vs. random) with 1 s ($1-\beta > .99$, Cohen's d_z= 1.902) and 2 s ($1-\beta > .99$, Cohen's d_z = 1.275) foreperiods. Participants reported normal or corrected-to-normal vision with no history of neurological disorders. Participants volunteered or received payment or course credits for their participation. The experiment was approved by the ethical committees of Tel-Aviv University and the School of Psychological Sciences at Tel-Aviv University. All participants signed an informed consent prior to their participation.

Stimuli

Fixation-target was a cross (black or blue, 0.4° × 0.4°), and target was a Gabor grating patch (2° diameter, 30% contrast, spatial frequency of 5 cycles/degree) slightly tilted clockwise

(CW) or counter-clockwise (CCW) from vertical, with tilt degree determined individually via 3-up 1-down staircase procedure (mean 1.02°, SD 0.41°, range 0.5-1.8°). All stimuli were displayed at screen-center on a mid-gray background.

Procedure

Participants sat in a dimly lit room at a distance of 100 cm from the monitor (24" LCD ASUS VG248QE, 1,920 × 1,080 pixels resolution, 120 Hz refresh rate, mid-gray luminance of 110 cd/m^2) using head- and chin-rest. The experiment was generated and controlled using MATLAB R2015a (Mathworks, USA) with Psychophysics Toolbox v3 (Brainard, 1997). Trial procedure was similar to a previously reported experiment (Amit et al., 2019), and is depicted in **Figure 2**. A central black fixation cross was presented between trials for a jittered inter-trial interval of 700-1200 ms. At trial onset, the fixation cross changed color from black to blue. This color change acted as a cue which marked the onset of the foreperiod interval. After the foreperiod had elapsed, the target (tilted Gabor patch) was briefly (33 ms) presented and followed by a blank screen. Participants were asked to report the orientation of the Gabor patch (CW/CCW) by pressing one of two keys. When a response was detected or 3 s with no response had elapsed, the fixation changed color again to provide feedback on task performance (green or red for correct and incorrect answers, respectively). A lack of response was considered as an incorrect response.

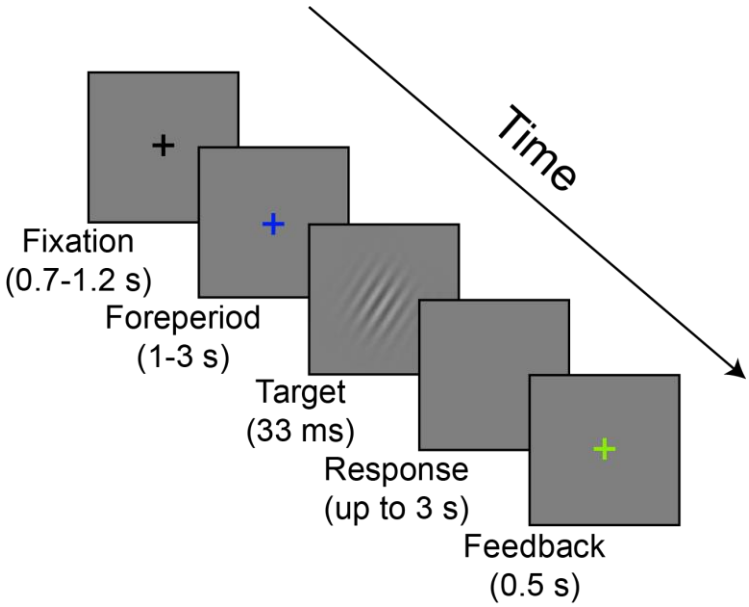

Figure 2. *Trial progression*. Exemplary trial with a correct response. In incorrect response trials or in trials where no response was given within 3 s, the feedback was colored red. The foreperiod prior to target onset is determined according to condition, as depicted in Table 1. Stimuli are shown for illustration purposes only and are not to scale.

		Foreperiod [s]				
		1	***1.5***	***2***	***2.5***	***3***
Condition	***Full-certainty-1s***	100%	0%	0%	0%	0%
	Full-certainty-2s	0%	0%	100%	0%	0%
	High-certainty-1s	80%	0%	20%	0%	0%
	High-certainty-2s	20%	0%	80%	0%	0%
	Low-certainty	20%	20%	20%	20%	20%

Table 1. *Foreperiod distribution across conditions*. Percentage of trials of each foreperiod, within a block.

There were five different block types with 80 trials in each block. These block types differed by the distribution of their foreperiod durations, which determined the level of certainty: (1) Full-certainty-1s: a 1s foreperiod was used in all trials; (2) Full-certainty-2s: a 2 s foreperiod was used in all trials; (3) High-certainty-1s: a 1 s foreperiod was used in 80% of the trials and a 2 s foreperiod was used in the rest of the trials; (4) High-certainty-2s: a 2 s foreperiod was used in 80% of the trials and a 1 s foreperiod was used in the rest of the trials. (5) Low-certainty: The foreperiods were uniformly distributed between 1 s to 3 s in 0.5 s increments within each block. Foreperiod distribution for each condition is summarized in

Table 1. Participants were not informed of the differences between blocks, such that any learning that occurred was incidental.

Participants completed one block of Full-certainty-1s, one block of Full-certainty-2s and five blocks of each of the other block-types. The study consisted of two separate sessions, one with 10 blocks and the other with 7 blocks. All blocks of the same type were performed serially in order to support the learning of the specific foreperiod distribution of that block-type, but the order of the block types within a session was randomized between participants. A short break was given every other block as well as upon the participants' request. A practice session consisting of 12 trials with a fixed foreperiod of 2 s was administered at the beginning each experimental session. In the first session, a staircase procedure was performed on the Gabor tilt (with fixed foreperiods of 2 s) to determine individual thresholds, yielding accuracy rates of approximately 79%. This threshold tilt was then applied to the rest of the experimental blocks of both sessions. The starting tilt of the staircase procedure was set to 15° and step-size changed logarithmically. The staircase procedure was terminated after four consecutive reversals, or after reaching 100 trials.

Eye tracking

Binocular eye movements were monitored using EyeLink 1000 Plus infrared video-oculographic desktop mounted system (SR Research Ltd., Oakville, ON, Canada), which has a spatial resolution lower than 0.01° and 0.25–0.5° average accuracy when using a chin-rest, according to the manufacturer. Eye-gaze position was recorded continuously in each block at a sampling rate of 1000 Hz. A nine-point calibration was performed at the beginning of the experiment as well as when necessary.

Gaze analysis was done using MATLAB R2018b. The raw gaze data was low-pass filtered at 60 Hz (as in Amit et al., 2019), and segmented between -300 ms relative to cue onset

and 300 ms relative to target onset. Blinks were detected based on the built-in algorithm provided by EyeLink, employing an additional criterion requiring binocular change in pupil size that exceeded 2.5 standard deviations from segment's mean pupil-size for 3 or more consecutive samples (Hershman et al., 2018).

Saccades were detected using a published algorithm (Engbert & Kliegl, 2003; Engbert & Mergenthaler, 2006), such that saccade onset was defined as the point in which the absolute standardized eye velocity exceeded the segment's median eye velocity by six or more standard deviations, for a minimum of six consecutive samples. Only binocular saccades were included in the analysis. A 50 ms interval between saccade offset and next the saccade onset was imposed to prevent detection of "overshoots" (Amit et al., 2017). Intervals with blinks and 200 ms before the onset of blinks and after their offsets, were excluded from the saccades analysis. Analysis included saccades of all sizes, although most saccades were miniscule (<1°) due to the instruction to maintain fixation. Correlation between saccade amplitude and peak velocity (main sequence, Zuber, Stark, & Cook, 1965) was high ($r > 0.9$) for all participants.

For each participant and condition, saccade-rate (SR) per second was calculated by averaging the number of saccade onsets per sample across all samples (not including samples that were excluded due to blinks), and multiplying these values by the sampling rate (1000 Hz). Following previous studies (Amit et al., 2019; Dankner et al., 2017), statistical analysis was performed on the *mean pre-target SR* measurement: average saccade rate at -100 to 0 ms relative to target onset.

Statistical analysis

There were four trials conditions: (1) *full-certainty*; (2) *high-certainty-frequent;* (3) *high-certainty-rare*; and (4) *low-certainty*. Mean pre-target SR was analyzed using a two-way repeated measures ANOVA, with Condition (full-certainty, high-certainty-frequent, high-

certainty-rare and low-certainty) and Foreperiod (1 and 2 s) as independent variables. This ANOVA was followed by simple effect analysis on the two foreperiods, using planned contrasts with False-Discovery-Rate (FDR) adjusted p-value (Benjamini & Hochberg, 1995). Sphericity was tested using Mauchly's test, and corrected *p*-values are reported for significant violations ($p < .05$) along with epsilon (ϵ) value, with correction method determined according to epsilon (Greenhouse-Geisser for $\epsilon < .7$; Huynh-Feldt for $\epsilon > .7$). Pearson correlations, where reported, were calculated individually for each participant and then transformed using Fisher Z-transformation. Mean correlations were calculated as the inverse Fisher transform of the averaged individual z-scores (Trillenberg et al., 2000). Within-subject standardized effect-sizes (Cohen's *d* or η_p^2, according to analysis) are reported for each significant ($p < .05$) result along with the 95% confidence interval (CI).

Support for null effects is provided by reporting the Bayes factor (BF) for non-significant results ($p > .05$) along with approximate percentage error of the estimates. BFs were calculated using a default (standard) Cauchy prior for the alternative hypothesis (Rouder et al., 2009). For convenience, BFs are reported with the null hypothesis in the nominator (BF_{01}), where the reported value indicates how many times the results are more likely under the null hypothesis, compared to the alternative hypothesis. Analyses were conducted using R-studio v1.1.463 (R Core Team, 2018) in R v3.5.2, with afex package (Singmann et al., 2020) used to perform analysis of variance, with emmeans (Lenth, 2020) and sjstats (Lüdecke, 2020) packages used to calculate effect sizes, and with psych package (Revelle, 2019) used for Fisher transformations. BF was calculated using the BayesFactor package (Morey & Rouder, 2018).

Data availability

The dataset used for power analysis, the dataset generated by this study, and an R-

markdown file that reproduces all the reported statistical analyses, tables and bar graphs within the paper, are uploaded to the Open Science Foundation repository and are available at: https://osf.io/xyfsq/

Results

Behavior

Accuracy rates and reactions times are reported in **Tables 2** and **3**, respectively. Since there were no specific hypotheses regarding these measures, no statistical tests were performed on them.

Trial condition	***Foreperiod [s]***				
	1	***1.5***	***2***	***2.5***	***3***
Full-certainty	79.30 (9.99)	*NA*	81.32 (8.89)	*NA*	*NA*
High-certainty-frequent	81.71 (9.84)	*NA*	82.03 (10.26)	*NA*	*NA*
High-certainty-rare	79.66 (10.45)	*NA*	83.71 (10.34)	*NA*	*NA*
Low-certainty	82.36 (10.42)	83.03 (9.97)	84.19 (8.53)	84.12 (10.81)	84.24 (10.57)

Table 2. Mean accuracy [%], averaged on the data of 20 participants separately for each condition and foreperiod. Standard deviations [%] are reported in parentheses. Trial conditions with no corresponding foreperiod marked as non-applicable (NA).

Trial condition	***Foreperiod [s]***				
	1	***1.5***	***2***	***2.5***	***3***
Full-certainty	648 (168)	*NA*	657 (149)	*NA*	*NA*
High-certainty-frequent	665 (174)	*NA*	651 (126)	*NA*	*NA*
High-certainty-rare	681 (148)	*NA*	664 (165)	*NA*	*NA*
Low-certainty	661 (112)	634 (100)	640 (110)	626 (89)	640 (96)

Table 3. Mean reaction times for correct trials [ms], averaged on the data of 20 participants separately for each condition and foreperiod. Standard deviations [ms] are reported in parentheses. Trial conditions with no corresponding foreperiod marked as non-applicable (NA).

Saccade-rate

To test the prediction of the temporal orienting and the certainty hypotheses, we performed a two-way repeated measures ANOVA on the pre-target SR, with factors Condition (full-certainty, high-certainty-frequent, high-certainty-rare and low-certainty) and Foreperiod (1 s, 2 s). This analysis revealed a significant interaction between Condition and Foreperiod ($F(3, 57) = 6.27$, $p < .001$, $\eta_p^2 = .248$, 95% CI = [.053 .39]), consistent with the temporal orienting hypothesis (**Figure 1B**). Main effects were not tested as there were no predictions regarding them and the interaction rendered them meaningless.

Next, to interpret the interaction and test the predictions of the temporal orienting and the certainty hypotheses, we analyzed the two foreperiods separately.

Analysis of 1 s foreperiod trials

We performed a one-way repeated-measures ANOVA on the pre-target SR of the 1 s foreperiod trials, with Condition as an independent variable. Consistent with both hypotheses, this analysis revealed a significant difference in mean pre-target SR across conditions ($F(3, 57) = 13.36$, $p < .001$, $\eta_p^2 = .413$, 95% CI = [.193 .54], **Figure 3A**). A planned contrast revealed a significant predictability effect: lower pre-target SR for blocks with a fixed foreperiod (full-

certainty) relative to varying foreperiods (low-certainty) ($t(57) = 5.442$, FDR-adjusted $p < .001$, Cohen's $d = 1.721$, 95% CI = [1.006, 2.436]). This effect, also consistent with both hypotheses, replicates our findings of a previous study (Amit et al., 2019).

Next, we performed two independent planned contrasts to test the predictions of the hypotheses: (a) high-certainty-rare vs. high-certainty-frequent; and (b) high-certainty-rare vs. low-certainty. The certainty hypothesis predicts that pre-target SR would be lower for high certainty relative to low certainty trials, but that it would be unaffected by foreperiod frequency. Therefore, it predicts that pre-target SR would: (a) not differ significantly between the high-certainty-rare and the high-certainty-frequent conditions; and (b) be lower for the high-certainty-rare relative to the low-certainty condition (**Figure 1A**). In contrast, the temporal orienting hypothesis predicts that target frequency would determine the pre-target SR and that certainty would have no effect. Therefore, it predicts that pre-target SR would: (a) be lower for the high-certainty-frequent relative to the high-certainty-rare condition; and (b) not differ significantly between the high-certainty-rare and the low-certainty conditions (as in both conditions frequency is 20%) (**Figure 1B**).

Results showed that: (a) pre-target SR was lower for the high-certainty-frequent relative to the high-certainty-rare condition ($t(57) = 3.015$, FDR-adjusted $p = .006$, Cohen's $d = 0.953$, 95% CI = [0.291 1.620]); and (b) there was no evidence for difference between the high-certainty-rare and low-certainty conditions ($t(57) = 0.383$, FDR-adjusted $p = .703$, $BF_{01} = 4.13 \pm .02\%$). This is consistent with the prediction of the temporal orienting hypothesis and inconsistent with the certainty hypothesis.

Analysis of 2 s foreperiod trials

We performed a one-way repeated-measures ANOVA on the pre-target SR of the 2 s foreperiod trials, with Condition as an independent variable. Consistent with both hypotheses,

this analysis revealed a significant difference in mean pre-target SR across conditions ($F(3, 57) = 3.798$, $p = .0149$, $\eta_p^2 = .167$, 95% CI = [.007 .306], **Figure 3B**). Using a planned contrast we found a significant predictability effect: lower pre-target SR for blocks with fixed foreperiods (full-certainty) relative to varying foreperiods (low-certainty) ($t(57) = 2.876$, FDR-adjusted $p = 0.011$, Cohen's $d = 0.909$, 95% CI = [0.244 1.580]). This effect is only partially consistent with our previous study, where we found a predictability trend for trials of 2 s foreperiod, but this trend has not reached significance (Amit et al., 2019). Interestingly, however, when reanalyzing the 2 s foreperiod trials from the previous study and matching the number of trials to the present study by including only the first 80 trials (as was done for the power analysis procedure, see Methods), the predictability effect was found to be significant also in the previous study.

To examine the alternative predictions for trials with a 2 s foreperiod, we contrasted the full-certainty condition against the two high-certainty conditions combined. The certainty hypothesis predicts that pre-target SR would be affected by certainty within a block rather than by the conditional probabilities. Therefore, it predicts lower pre-target SR for 2 s foreperiod trials in the full-certainty condition relative to the combined high-certainty condition (**Figure 1A**). In contrast, the temporal orienting hypothesis predicts that pre-target SR would be affected solely by the probability of the target to occur at a specific time, rather than by the general sense of certainty. Since the conditional probability for a target to occur at 2 s post cue reaches a maximum shortly prior to 2 s in both full-certainty and the two high-certainty conditions, this hypothesis predicts no difference in pre-target SR between these conditions. (**Figure 1B**)

Results supported the temporal orienting hypothesis by showing no evidence for a significant difference in mean pre-target SR between the full-certainty and the combined two high-certainty conditions ($t(57) = 0.541$, FDR-adjusted $p = .591$, $BF_{01} = 3.89 \pm .02\%$). As in

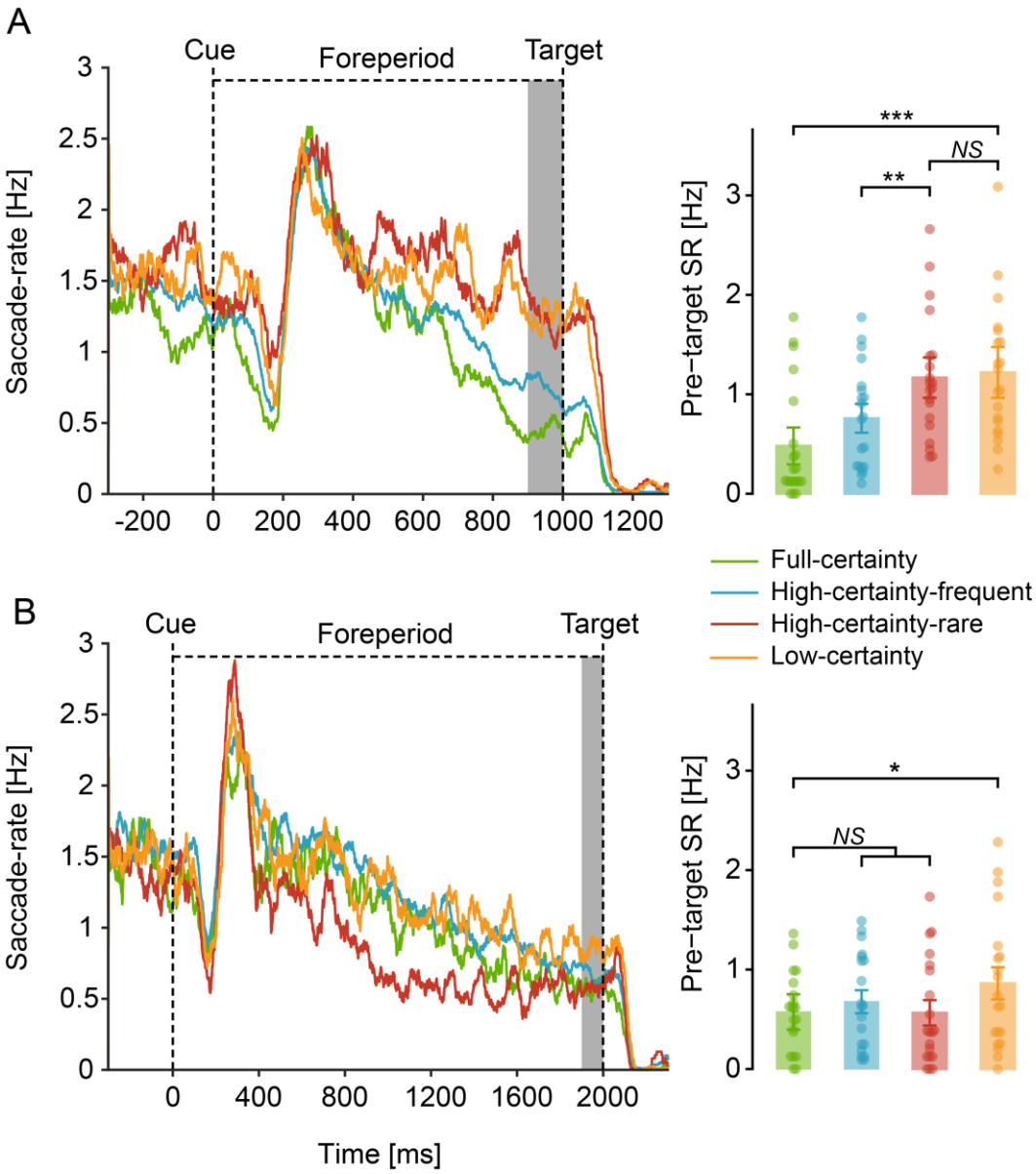

Figure 3. *Saccade-rate results*. Saccade-rate (SR) traces (left) relative to cue onset in 1 s (A) and 2 s (B) foreperiod trials, averaged across participants (N=20). SR traces were smoothed using 50 ms running window for display purposes. Mean pre-target SR was averaged across -100 to 0 ms relative to target onset (shaded region) and analyzed (right). Individual mean pre-target SR represented as dots for each condition. Error bars designate ±1 within-subject standard error from the mean (Cousineau & O'Brien, 2014). FDR-corrected *p*-values are reported for the planned contrasts conducted. * $p < .05$; ** $p < .01$; *** $p < .001$; *NS* not significant.

the 1 s foreperiod results, these results are consistent with the prediction of the temporal orienting hypothesis and inconsistent with the certainty hypothesis.

Foreperiod effects: the involvement of conditional probabilities

Behavioral studies showed that when foreperiods vary within blocks, trials with longer foreperiods were associated with faster responses (Grabenhorst et al., 2019; Näätänen, 1970; Niemi & Näätänen, 1981). This behavioral *foreperiod effect* is thought to reflect changes in expectations due to the gradual increase in the conditional probabilities – the probabilities that a target would occur at a certain time given that it has not yet occurred (Näätänen, 1970). Conditional probabilities follow a specific function called the 'hazard-rate' and therefore it is expected that neural and behavioral effects that are related to conditional probabilities would follow the same function. In a previous study, we found an oculomotor foreperiod effect – in blocks with varying foreperiod durations, longer foreperiods were associated with less pre-target SR, i.e. stronger oculomotor inhibition (Amit et al., 2019). However, the interpretation of this effect remained inconclusive, as the change rate of the oculomotor inhibition effect across time was linear and did not closely follow a 'hazard rate' function. These results were replicated in the present findings. A one-way repeated measures ANOVA on the pre-target SR of low-certainty trials with foreperiod duration (1s/1.5s/2s/2.5s/3s) as the independent measure, revealed a significant difference between foreperiods ($F(4, 76) = 4.445$, $p = .003$, $\eta_p^2 = .19$, 95% CI = [.028 .306]); **Figure 4**). Polynomial contrasts revealed a significant negative linear trend ($t(76) = -3.810$, $p < .001$, Cohen's $d = -2.69$, 95% CI = [-1.2 -4.19]) with no additional significant polynomials ($p = .08 - .94$).

To assess the involvement of conditional probabilities in determining the pre-target SR, we calculated two Pearson correlations for each participant and condition: (a) between the pre-target SR (mean across trials) and the hazard-rate probability weights (0.2, 0.25, 0.33, 0.5, 1); and (b) between the pre-target SR and linear weights (0.2, 0.4, 0.6, 0.8, 1). This analysis revealed that the pre-target SR significantly correlated with both a hazard-rate trend (mean r_{hazard} across participants = -.28, $t(19) = -2.38$, $p = .028$) and a linear trend (mean r_{linear}

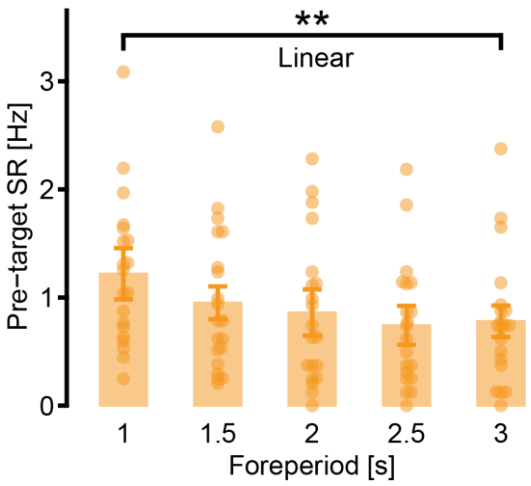

Figure 4. *Low-certainty trials results*. Mean pre-target saccade-rate (SR) averaged across -100 to 0 ms relative to target onset for each foreperiod, averaged across participants (N=20). Individual mean pre-target SR represented as dots for each foreperiod. Error bars designate ±1 within-subject standard error from the mean (Cousineau & O'Brien, 2014). *p*-value indicated for polynomial contrasts. ** $p < .01$

across participants = -.43, difference from zero: $t(19) = -3.12$, $p = .006$), but the correlation was stronger for the linear trend ($t(19) = -2.50, p = .022$).

Discussion

This study examined two competing explanations for the pre-target oculomotor inhibition effect. Under the temporal orienting hypothesis, pre-target oculomotor inhibition depends on the probability that the target would occur at a specific time. In contrast, under the certainty hypothesis, oculomotor inhibition depends on the participant's state of certainty, which is determined by the consistency of target timings within a given context (i.e. a block). Results from the current study consistently support the predictions made by the temporal orienting hypothesis, and not those made by the certainty hypothesis.

The oculomotor inhibition effect as a measurement of predictability

In a series of previous studies it has been suggested that pre-target oculomotor inhibition could be an informative measurement for assessing target predictability (Abeles et al., 2020; Amit et al., 2019; Badde et al., 2020; Dankner et al., 2017; Denison et al., 2019). These findings were interpreted as reflecting a link between pre-target oculomotor inhibition

and three different types of temporal structures (Nobre & van Ede, 2017): those due to the association between cue and target (associative regularity), those due to rhythmic stimulations (rhythmic regularity), and those due to conditional probabilities (hazard rate). Moreover, the pre-target oculomotor inhibition effect was found to be a more sensitive and a more reliable index for predictability than other common behavioral and electrophysical measurements (Amit et al., 2019).

The present study is an important step in strengthening this conclusion. The present findings provide a replication for the previously-reported effects. As in previous studies, we found that: (a) slightly prior to target onset, saccade rate is lower (i.e. more strongly inhibited) for predictable relative to unpredictable targets; and (b) that for unpredictable targets, longer foreperiods are associated with lower pre-target saccade rates. The first finding supports the link between pre-target oculomotor inhibition and associative and rhythmic regularities, and the second finding supports the link to the hazard rate (discussed in the following section). In addition to providing replication, this study sheds new light on the interpretation of the present and previous findings by showing that the oculomotor inhibition effect does not reflect the mere cognitive state of the participant, but can be directly linked to target probability.

Using between-blocks vs. within-block design to study temporal expectation

Temporal expectation can be studied using a between-blocks or within-block design. In a between-blocks design (e.g. Amit et al., 2019; Breska & Deouell, 2016, 2017; Breska & Ivry, 2018; Niemi & Näätänen, 1981), expectation is manipulated by comparing blocks with different foreperiod distributions; often fixed and random distributions. In a within-block design (e.g. Coull et al., 2000, 2013, 2016; Davranche et al., 2011; Rohenkohl et al., 2014), expectation regarding target onset is manipulated by pairing symbolic cues with various target timings and by comparing trials with informative, uninformative and invalid cues.

Both between-blocks and within-block designs are valid and common approaches for studying temporal expectation, with each having its own advantages and disadvantages. Within-block designs eliminate most of the context-dependent effects and effects that slowly develop between blocks, such as fatigue and training. However, unlike between-block designs, the formation of expectations in within-block designs depends on a high-level identification of the semantic identities of multiple cues. Such high-level cue identification requires either explicit instructions or very long sessions to allow enough time to establish implicit learning of this complex information. In contrast, between-blocks designs, such as the one used in the current study, allow temporal regularities to be implicitly and quickly learned with no need for explicit instructions regarding the meaning of the cues.

Isolating the effects of temporal orienting from those of certainty, requires including either blocks (in a between-blocks design) or trials (in a within-block design) that manipulate these two factors separately. In a between-block design, this would require modifying the amount of predictable trials per block as was done in this study and previous ones (e.g. Breska & Deouell, 2016, 2017). In a within-block design this would mean adding invalid trials, i.e. rare trials where the cue does not predict target onset (as in Coull et al., 2000; Rohenkohl et al., 2014). Importantly, while switching to a within-block design with invalid trials could have been a relatively straight-forward way to dissociate temporal orienting and certainty, doing so would have defeated the main goal of previous studies on oculomotor inhibition – to examine how oculomotor behavior reflects *implicit* learning of temporal regularities. By using a between-block design with a varied level of certainty, we demonstrated in this study how temporal orienting and certainty can be manipulated in a between-block design without compromising the implicit nature of the task. This approach could be advantageous for future studies in this field.

Hazard-rate expectations and the pre-target oculomotor inhibition effect

Findings of our previous study (Amit et al., 2019), provided inconclusive evidence regarding the link between pre-target oculomotor inhibition and "hazard-rate" expectations – expectations that are based on conditional probabilities. On one hand, our findings in the previous study, replicated here as well, showed that when the foreperiod varies within a block, oculomotor inhibition gradually increase as time progresses (i.e. pre-target saccade rate was lower for a longer foreperiod). On the other hand, in both the previous and current study, this effect fitted with a linear trend better than with the exponential hazard-rate modulation, which was expected to reflect changes in conditional probabilities as time progressed. This poor fit with the hazard-rate function is consistent with previous findings on RTs using a similar design (Niemi & Näätänen, 1981). This non-exponential fit was interpreted to reflect increases in uncertainty in trials with longer foreperiods, which may have counteracted increases in conditional expectations. Additionally, as we have noted in our previous study, these findings are based on correlations across only five data points (the five foreperiods that were used). With only five data points, the distinction between the linear model and the hazard rate model is only minor and, therefore, any difference between them is difficult to interpret.

In the present study we took a second step towards examining the link between the pre-target oculomotor inhibition and hazard-rate probabilities. The findings showed no significant difference in pre-target SR among 2 s foreperiod trials of the full-certainty block and both types of high-certainty blocks, along with mild Bayesian support for the null result. As the three conditions differed in the prior probability (i.e., trial proportion) of a target appearing after the 2 s foreperiod, but all shared the same conditional probability, these results support the hypothesis that pre-target oculomotor inhibition is modulated by the conditional probabilities for target occurrence.

While these results may contribute to the evidence supporting the hazard-rate influence on oculomotor inhibition over time, it should be noted that they are also consistent with some studies that challenged the reliance of the perceptual system on the hazard-rate function for temporal expectation. The computation of the hazard-function over non-discrete time is relatively complex and numerically unstable (Luce, 1986; Rice & Rosenblatt, 1976). A recent study found that the reciprocal of the probability density function (i.e., 1/PDF), which is simpler to compute than the hazard-rate function, provided a better fit to RT results in three separate sensory modalities (Grabenhorst et al., 2019). Others have argued that the hazard-rate hypothesis fails to account for some of the known phenomena of temporal expectation (Los et al., 2014). It was further suggested that the commonly observed behavioral foreperiod effects can be explained by the degraded accumulation of memory traces from previous trials experienced by the participant, rather than by conditional probabilities (Los et al., 2014, 2017). Given the similarity between RT effects and the oculomotor inhibition effect observed here and in other studies (Amit et al., 2019), we acknowledge that these alternative accounts may also explain the pattern of results that we have observed without incurring the hazard-rate function. Importantly, this possibility does not affect the validity of the oculomotor inhibition as a marker of target-specific temporal expectation. Rather, converging evidence from this marker along with other markers may help resolve the open questions regarding the hazard-rate function.

Conclusions

This study shows that oculomotor inhibition reflects temporal orienting of attention. These findings support the feasibility of using pre-target oculomotor inhibition as a biomarker to study target-specific temporal expectation.

Bibliography

Abeles, D., Amit, R., Tal-Perry, N., Carrasco, M., & Yuval-Greenberg, S. (2020). Oculomotor inhibition precedes temporally expected auditory targets. *Nature Communications*. https://www.biorxiv.org/content/10.1101/2020.04.28.065839v1. https://doi.org/https://doi.org/10.1101/2020.04.28.065839

Amit, R., Abeles, D., Bar-Gad, I., & Yuval-Greenberg, S. (2017). Temporal dynamics of saccades explained by a self-paced process. *Scientific Reports*, *7*(1), 1–15. https://doi.org/10.1038/s41598-017-00881-7

Amit, R., Abeles, D., Carrasco, M., & Yuval-Greenberg, S. (2019). Oculomotor inhibition reflects temporal expectations. *NeuroImage*, *184*(March 2018), 279–292. https://doi.org/10.1016/j.neuroimage.2018.09.026

Badde, S., Myers, C. F., Yuval-Greenberg, S., & Carrasco, M. (2020). Oculomotor freezing reflects tactile temporal expectation and aids tactile perception. *Nature Communications*. bioRxiv 2020.04.27.064899 (2020). https://doi.org/doi:10.1101/2020.04.27.064899

Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate : A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Societ*, *57*(1), 289–300. https://www.jstor.org/stable/2346101

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*, 433–436. https://doi.org/10.1163/156856897x00357

Breska, A., & Deouell, L. Y. (2016). When Synchronizing to Rhythms Is Not a Good Thing : Modulations of Preparatory and Post-Target Neural Activity When Shifting Attention Away from On-Beat Times of a Distracting Rhythm. *Journal of Neuroscience*, *36*(27), 7154–7166. https://doi.org/10.1523/JNEUROSCI.4619-15.2016

Breska, A., & Deouell, L. Y. (2017). Neural mechanisms of rhythm-based temporal prediction: Delta phase-locking reflects temporal predictability but not rhythmic entrainment. *PLOS Biology*, *15*(2), e2001665. https://doi.org/10.1371/journal.pbio.2001665

Breska, A., & Ivry, R. B. (2018). Double dissociation of single-interval and rhythmic temporal prediction in cerebellar degeneration and Parkinson's disease. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(48), 12283–12288. https://doi.org/10.1073/pnas.1810596115

Caldwell, A., & Lakens, D. (2019). *Power Analysis with Superpower*. https://arcaldwell49.github.io/SuperpowerBook

Coull, J. T., Cotti, J., & Vidal, F. (2016). Differential roles for parietal and frontal cortices in fixed versus evolving temporal expectations: Dissociating prior from posterior temporal probabilities with fMRI. *NeuroImage*, *141*, 40–51. https://doi.org/10.1016/J.NEUROIMAGE.2016.07.036

Coull, J. T., Davranche, K., Nazarian, B., & Vidal, F. (2013). Functional anatomy of timing differs for production versus prediction of time intervals. *Neuropsychologia*, *51*(2), 309–319. https://doi.org/10.1016/j.neuropsychologia.2012.08.017

Coull, J. T., Frith, C. D., Büchel, C., & Nobre, A. C. (2000). Orienting attention in time: Behavioural and neuroanatomical distinction between exogenous and endogenous shifts. *Neuropsychologia*, *38*(6), 808–819. https://doi.org/10.1016/S0028-3932(99)00132-3

Cousineau, D., & O'Brien, F. (2014). Error bars in within-subject designs: a comment on Baguley (2012). *Behavior Research Methods*, *46*(4), 1149–1151. https://doi.org/10.3758/s13428-013-0441-z

Dankner, Y., Shalev, L., Carrasco, M., & Yuval-Greenberg, S. (2017). Prestimulus Inhibition of Saccades in Adults With and Without Attention-Deficit / Hyperactivity Disorder as an Index of Temporal Expectations. *Psychological Science*, *28*(7), 835–850. https://doi.org/10.1177/0956797617694863

Davranche, K., Nazarian, B., Vidal, F., & Coull, J. T. (2011). Orienting Attention in Time Activates Left Intraparietal Sulcus for Both Perceptual and Motor Task Goals. *Journal of Cognitive Neuroscience*, *23*(11), 3318–3330. https://doi.org/10.1162/jocn_a_00030

Denison, R. N., Yuval-Greenberg, S., & Carrasco, M. (2019). Directing voluntary temporal attention increases fixational stability. *Journal of Neuroscience*, *39*(2), 353–363. https://doi.org/10.1523/JNEUROSCI.1926-18.2018

Engbert, R., & Kliegl, R. (2003). Microsaccades uncover the orientation of covert attention. *Vision Research*, *43*(9), 1035–1045. https://doi.org/10.1016/s0042-6989(03)00084-1

Engbert, R., & Mergenthaler, K. (2006). Microsaccades are triggered by low retinal image slip. *Proceedings of the National Academy of Sciences of the USA*, *103*(18), 3–8. https://doi.org/10.1073/pnas.0509557103

Grabenhorst, M., Georgios, M., Maloney, L. T., & Poeppel, D. (2019). The Anticipation of Events in Time. *Nature Communications*, *10*, 5802. https://doi.org/10.1038/s41467-019-13849-0

Hershman, R., Henik, A., & Cohen, N. (2018). A novel blink detection method based on pupillometry noise. *Behavior Research Methods*, *50*(1), 107–114. https://doi.org/10.3758/s13428-017-1008-1

Lenth, R. (2020). *emmeans: Estimated Marginal Means, aka Least-Squares Means*. https://cran.r-project.org/package=emmeans

Los, S. A., Kruijne, W., & Meeter, M. (2014). Outlines of a multiple trace theory of temporal preparation. *Frontiers in Psychology*, *5*(September), 1–13. https://doi.org/10.3389/fpsyg.2014.01058

Los, S. A., Kruijne, W., & Meeter, M. (2017). Hazard versus history: Temporal preparation is driven by past experience. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(1), 78–88. https://doi.org/10.1037/xhp0000279

Luce, R. D. (1986). *Response Times: Their Role in Inferring Elementary Mental Organization*. Oxford University Press.

Lüdecke, D. (2020). *sjstats: Statistical Functions for Regression Models (Version 0.17.9)*. https://doi.org/10.5281/zenodo.1284472

Morey, R. D., & Rouder, J. N. (2018). *BayesFactor: Computation of Bayes Factors for Common Designs*. https://cran.r-project.org/package=BayesFactor

Näätänen, R. (1970). The diminishing time-uncertainty with the lapse of time after the warning signal in reaction-time experiments with varying fore-periods. *Acta Psychologica*, *34*, 399–419. https://doi.org/10.1016/0001-6918(70)90035-1

Niemi, P., & Näätänen, R. (1981). Foreperiod and Simple Reaction Time. *Psychological Bullettin*, *89*(1), 133–162. https://doi.org/10.1037/0033-2909.89.1.133

Nobre, A. C., & van Ede, F. (2017). Anticipated moments: temporal structure in attention. *Nature Reviews Neuroscience*, *19*(1), 34–48. https://doi.org/10.1038/nrn.2017.141

R Core Team. (2018). *R: A Language and Environment for Statistical Computing*. https://www.r-project.org/

Revelle, W. (2019). *psych: Procedures for Psychological, Psychometric, and Personality Research*. https://cran.r-project.org/package=psych

Rice, J., & Rosenblatt, M. (1976). Estimation of the Log Survivor Function and Hazard Function. *Sankhyā: The Indian Journal of Statistics*, *38*(1), 60–78.

Rohenkohl, G., Gould, I. C., Pessoa, J., & Nobre, A. C. (2014). Combining spatial and temporal expectations to improve visual perception. *Journal of Vision*, *14*(8), 1–13. https://doi.org/10.1167/14.4.8.doi

Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian t tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin and Review*, *16*(2), 225–237. https://doi.org/10.3758/PBR.16.2.225

Singmann, H., Bolker, B., Westfall, J., Aust, F., & Ben-Shachar, M. S. (2020). *afex: Analysis of Factorial Experiments*. https://cran.r-project.org/package=afex

Trillenberg, P., Verleger, R., Wascher, E., Wauschkuhn, B., & Wessel, K. (2000). CNV and temporal uncertainty with “ageing” and “non-ageing” S1-S2 intervals. *Clinical Neurophysiology*, *111*(7), 1216–1226. https://doi.org/10.1016/S1388-2457(00)00274-1

Zuber, B. L., Stark, L., & Cook, G. (1965). Microsaccades and the velocity-amplitude relationship for saccadic eye movements. *Science*, *150*(702), 1459–1460. https://doi.org/10.1126/science.150.3702.1459