

Only Time Will Tell the Future: Anticipatory Saccades Reveal the Temporal Dynamics of Time-Based Location and Task Expectancy

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Humans form associations between time intervals and subsequent events and thus develop time-based expectancies that enable time-based action preparation. For instance, when each of two foreperiods (short vs. long) is frequently paired with one specific task (e.g., number magnitude judgment vs. number parity judgment) and infrequently with the alternative task, participants are faster to respond to frequent rather than infrequent foreperiod–task combinations. Here, we investigated the time course of time-based task expectancy by measuring eye movements toward a left and right target location. Foreperiods predicted target locations with 100% validity and tasks with 90% validity. In 2 experiments, without having any explicit knowledge about the foreperiod–location or foreperiod–task contingencies, participants first moved their eyes to the location associated with the short foreperiod and then looked toward the location of the long foreperiod (if no stimulus had been presented after the short foreperiod had passed). That is, they proactively moved their eyes to optimize perception in line with the specific time and location they expected an event to occur at. Importantly, these eye movements reflected not only time-based location expectations, but also time-based task expectations. We discuss new insights in time-based expectancy and its temporal dynamics obtained from anticipatory eye movements and highlight spontaneous eye movements as a window into cognitive processes that cannot be assessed via behavioral response measures.

Public Significance Statement

Previous research has demonstrated that humans learn regularities between waiting periods and subsequent events (e.g., short waiting period → Task 1; long waiting period → Task 2). We respond faster and commit fewer errors when the event (e.g., task) that typically occurs after a waiting period of a certain duration occurs rather than when a different, unexpected event occurs. This shows that humans expect future events on the basis of time, specifically on the basis of preceding waiting periods. Here, we demonstrate that such expectations also lead to corresponding eye movements that reveal which events we expect at what time. These eye movements reflect how we prepare for upcoming events on the basis of time.

Keywords: time-based expectancy, task switching, anticipatory saccades, action control, eye tracking

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Effective action control would be difficult if stimuli occurred at random. Luckily, certain stimuli often occur together (i.e., allowing for classical conditioning; e.g., Le Pelley, 2004; Pavlov, 1927; Rescorla & Wagner, 1972), most often in certain situational contexts or at certain locations (e.g., Brockmole & Henderson, 2006; Doricchi, Macci, Silvetti, & Macaluso, 2010; Draschkow & Vö, 2017; Hoffmann & Kunde, 1999; Vö & Wolfe, 2013a), or in

predictable stimulus and/or response sequences (e.g., Hoffmann & Koch, 1997; Nissen & Bullemer, 1987; Soetens, Melis, & Notebaert, 2004; Trempler et al., 2017). Such contingencies allow us to predict the occurrence of future stimuli or required actions and to derive expectations that guide our everyday actions.

Interestingly, we cannot only predict upcoming stimuli or required actions on the basis of sensory stimulation, but also based

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on temporal contingencies. For instance, when our interaction partners take rather long to reply to a question, we can expect that they either cannot answer the question or have to give a negative reply. In contrast, when somebody immediately answers our question, we expect a positive or a correct answer (e.g., Roberts & Francis, 2013; Roberts, Margutti, & Takano, 2011). Here, we examined how such time-based expectancies and time-based shifts in expectancies are reflected in anticipatory eye movements.

Temporal Expectancy and Time-Based Expectancy

Temporal expectations can be observed when using foreperiods of variable length that precede the appearance of a target (see, e.g., Niemi & Näätänen, 1981, for a review). Participants respond faster after long rather than short foreperiods, adapting to the increasing probability of target appearance once the short foreperiod has elapsed (e.g., Bertelson & Tisseyre, 1968; Näätänen, 1970, 1971; but see Langner, Steinborn, Eickhoff, & Huestegge, 2018; Los, Kruijne, & Meeter, 2017; Los & Van den Heuvel, 2001; Steinborn & Langner, 2012; Steinborn, Rolke, Bratzke, & Ulrich, 2010, for alternative explanations).

Importantly, we cannot only expect when an event will occur, but also which event will occur on the basis of time. The time-event correlation paradigm by Wagener and Hoffmann (2010) reveals such effects of time-based predictability (i.e., foreperiod durations predicting upcoming events). Responding to one of two tones in a two-choice reaction task, participants were faster and committed fewer errors when target tones appeared after foreperiods that had frequently rather than infrequently preceded them (see also e.g., Thomaschke, Hoffmann, Haering, & Kiesel, 2016). That is, participants were able to prepare for the upcoming target on the basis of time. Similarly, foreperiods can predict stimulus locations (Rieth & Huber, 2013) and responses (Thomaschke & Dreisbach, 2013; Thomaschke & Haering, 2014; Thomaschke, Kiesel, & Hoffmann, 2011, for a review of time-based predictability see Thomaschke & Dreisbach, 2015).

Such time-based predictability effects are explained by assuming that participants develop time-based expectancies regarding the upcoming event (Thomaschke & Dreisbach, 2015; Wagener & Hoffmann, 2010; Wendt & Kiesel, 2011). These time-based expectancies develop as participants form associations between the duration of foreperiods and the events (i.e., stimuli, responses, or other features of a current task) following them (e.g., Los, Kruijne, & Meeter, 2014; Thomaschke & Dreisbach, 2013, 2015; Thomaschke et al., 2011). Interestingly, time-based expectancy can also be assessed for events that are not directly associated with a sensory stimulation like word valence (Roberts et al., 2011; Thomaschke, Bogon, & Dreisbach, 2018), linguistic complexity (Watanabe, Hirose, Den, & Minematsu, 2008), or conflict likelihood in a flanker task (Wendt & Kiesel, 2011; see Thomaschke & Dreisbach, 2015, for a review).

Most relevant in the present context are studies investigating time-based expectancy for tasks (Aufschnaiter, Kiesel, Dreisbach, et al., 2018; Aufschnaiter, Kiesel, & Thomaschke, 2018). In a recent task switching study (Aufschnaiter, Kiesel, Dreisbach, et al., 2018; for an overview of task switching, see, e.g., Kiesel et al., 2010; Koch, Poljac, Müller, & Kiesel, 2018; Monsell, 2003), participants performed magnitude and parity judgments on number targets. Crucially, one task frequently had to be performed after a

short foreperiod and infrequently after a long foreperiod and vice versa for the other task. For time-task contingencies ranging from 90% to 70%, participants responded faster to targets in trials with frequent as compared to infrequent foreperiod–task combinations, showing that they had developed time-based task expectancies.

Once time-based expectancies have developed, it is assumed that participants' expectations change during the time course of the foreperiod (e.g., Aufschnaiter et al., 2018; Thomaschke & Dreisbach, 2015; see Thomaschke, Wagener, Kiesel, & Hoffmann, 2011; Volberg & Thomaschke, 2017). For instance, during the short foreperiod, participants expect a low tone. Once the duration of the short foreperiod has passed, participants shift their expectations on the basis of time and expect a high tone.

Expectancy and Anticipatory Eye Movements

Eye movements represent a more direct way of assessing human expectations. First, saccades toward targets are initiated faster when a preceding warning signal temporally predicts the target (Pratt, Bekkering, & Leung, 2000; Ross & Ross, 1980, 1981; Reuter-Lorenz, Oonk, Barnes, & Hughes, 1995). This benefit of oculomotor readiness seems to result from preparing for the possible target locations (Dorris & Munoz, 1998; Kingstone & Klein, 1993; Paré & Munoz, 1996; Rolfs & Vitu, 2007). Second, when changes in a scene are predictable, observers viewing natural dynamic scenes exhibit anticipatory saccades toward the locations at which these changes will occur (Vig, Dorr, Martinetz, & Barth, 2011). Similar eye movements have been shown in everyday action sequences like driving (Land & Lee, 1994), walking (Patla & Vickers, 1997), playing cricket (Land & McLeod, 2000), preparing tea (Land, Mennie, & Rusted, 1999), or making sandwiches (Hayhoe, 2000; for an overview, see also Land, 2006, 2009) and have been linked to action control (e.g., Land & Hayhoe, 2001).

Anticipatory saccades are also used to monitor action consequences. When participants' saccades would turn a neutral face into a smiling/frowning face, saccades toward this still neutral face landed closer to the mouth/eye brow region (Herwig & Horstmann, 2011), which is most indicative of a smile/frown (Nusseck, Cunningham, Wallraven, & Bühlhoff, 2008). That is, based on their expectations, participants adapted their saccade landing position to monitor whether the expected facial expressions occurred following their saccades. Similarly, in a study in which participants' left/right key presses produced irrelevant visual effects after a delay, Pfeuffer, Kiesel, and Huestegge (2016) found anticipatory saccades toward the predictable future location of these visual effects. In line with ideomotor theories of action control (e.g., Elsner & Hommel, 2001; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Kunde, 2001; for a review see Shin, Proctor, & Capaldi, 2010), Pfeuffer et al. (2016) suggested that participants formed bidirectional associations between their right/left actions and the effects these responses caused in their environment (i.e., stimuli appearing on the right/left side). They argued that these anticipatory saccades are executed to monitor whether our expectations are met. Based on the summarized findings, we hypothesized that similar anticipatory saccades should also occur when participants can predict the occurrence of events on the basis of time.

Time-Based Expectancy and Anticipatory Saccades

Interestingly, studies in the context of ideomotor action control indicated that participants cannot only associate their actions with an effect's location (e.g., Kunde, 2001; Pfeuffer et al., 2016) or identity (e.g., Koch & Kunde, 2002), but also with temporal features of the effect (delay: e.g., Dignath, Pfister, Eder, Kiesel, & Kunde, 2014; duration: e.g., Kiesel & Hoffmann, 2004; Kunde, 2003; Pfister, Pfeuffer, & Kunde, 2014).

These findings corroborate research on time-based expectancy, suggesting that humans form associations between the duration of foreperiods and, for instance, the stimuli or responses following them (Los et al., 2014; Thomaschke & Dreisbach, 2013, 2015; Thomaschke et al., 2011).

So far, assessments of time-based expectancy only provided indirect evidence for time-based expectancy (and shifts thereof) via overall faster and less error prone responses for frequent (i.e., predictable) rather than infrequent (i.e., unpredictable) foreperiod-event mappings. A notable exception is a study by Volberg and Thomaschke (2017), who demonstrated that participants' time-based response expectancies (and shifts thereof after the short foreperiod) were associated with corresponding deflections in the lateralized readiness potential. Yet, this method is restricted to time-based response expectancy and cannot be used for other types of time-based expectancy (e.g., expectancy for stimuli).

We conjecture that it is possible to assess the temporal dynamics of time-based expectancy by using eye tracking building on the previously reported research on anticipatory saccades.¹ By relying on eye tracking's temporal and spatial resolution, we wanted to gain insights into the time course of time-based expectancy and time-based shifts in participants' expectations during long foreperiods.

To test whether time-based expectancies were reflected in anticipatory saccades, we combined the time-event correlation paradigm (e.g., Aufschnaiter, Kiesel, Dreisbach, et al., 2018; Thomaschke et al., 2011; Thomaschke & Dreisbach, 2013; Wagener & Hoffmann, 2010) with the eye tracking paradigm developed by Pfeuffer et al. (2016).

Observing saccades that are first directed toward the location at which an event will occur after a short foreperiod and then, when the short foreperiod has passed, shift toward the location at which an event will occur after a long foreperiod would, for the first time, provide direct evidence for the time course of time-based location expectancy. This would, first, provide direct support for the notion of shifts in time-based location expectancies. Second, it would establish anticipatory eye movements as a novel method for assessing time-based location expectancy also in its time course. More fine-grained temporal analyses could provide further insights into the mechanisms underlying shifts in time-based location expectancies occurring once the short foreperiod has passed.

Yet, this method would be restricted to assessments of one specific type of time-based expectancy, time-based location expectancy. To determine whether anticipations of additional, nonspatial features of an event predicted by temporal contingencies might also be reflected in such anticipatory saccades, we therefore also manipulated the events occurring at the target locations predicted by temporal contingencies. If anticipatory saccades also reflected nonspatial aspects of time-based expectancies, this would enable a wider use of anticipatory saccades in assessments of

various types of time-based expectancy. Specifically, here we focused on manipulations of time-based task expectancy.

The Present Experiments

On each trial, participants had to classify a number according to one of two tasks, magnitude or parity judgment, by pressing a left or right key. The color of the target number indicated which task participants were to perform. Crucially, the appearance of a target number was preceded by either a short (500 ms) or long (1,500 ms) foreperiod (see Figure 1 for the trial structure of Experiment 1). Unbeknownst to participants, foreperiod duration predicted whether the target would appear on the left or right side of the screen with 100% validity. We assessed time-based location expectancy by examining whether participants first directed their gaze toward the location at which the target would appear after the short foreperiod and subsequently looked in the opposite direction when the short foreperiod had passed without target appearance.

Importantly, we also manipulated the contingency between foreperiod and task. After a short foreperiod the magnitude task had to be performed in 90% of the trials and the parity task had to be performed in 10% of the trials or vice versa. The reverse was the case for the long foreperiod.

Apart from replicating time-based task expectancy effects in manual responses (e.g., Aufschnaiter, Kiesel, Dreisbach, et al., 2018), we expected participants to perform anticipatory saccades during the foreperiod. Before the duration of the short foreperiod had passed, we expected participants to perform more saccades toward the location at which a target would appear after the short foreperiod (i.e., expectancy-congruent saccades) rather than in the opposite direction (i.e., expectancy-incongruent saccades). After the short foreperiod had passed, we expected participants to, conversely, more often direct their gaze in the direction in which the target would be expected based on the duration of the long foreperiod.

Importantly, the procedure of Experiment 1 would not yet allow us to tell whether participants also developed time-based task expectancies that were reflected in their anticipatory saccades. As each foreperiod was consistently paired with one subsequent task location, location-based task expectancies could alternatively account for the predicted pattern of results. For a first assessment of time-based task expectancy, we therefore shifted foreperiod–task contingencies after half of the trials to determine whether time-based task expectancies were also reflected in anticipatory saccades. Experiment 2 subsequently assessed the influence of time-based task expectancies on anticipatory saccades in more detail.

Experiment 1

In Experiment 1, we wanted to gain first insights into whether participants developed not only time-based location expectancy, but also time-based task expectancy. To assess whether changes in

¹ Note that temporal expectancies (i.e., expectancies that include only expectations for the timing of an event, but not the identity of the event) were already shown to improve early perceptual processes like visual attention (e.g., Correa, Lupiáñez, Madrid, & Tudela, 2006; Correa, Lupiáñez, & Tudela, 2005; Rolke & Hofmann, 2007; Vangkilde, Coull, & Bundesen, 2012).

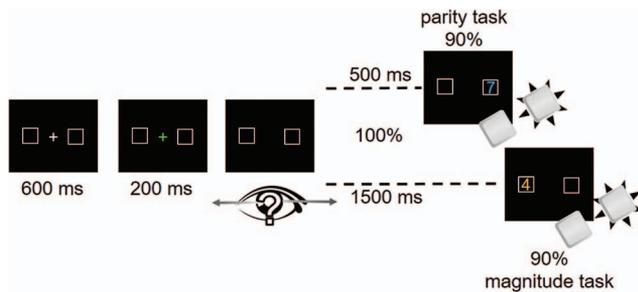


Figure 1. Trial structure of Experiment 1. After the offset of a warning signal (fixation cross turning green) a short or long foreperiod (500 ms vs. 1,500 ms) started. After one foreperiod, the target appeared in the right target location marker, after the other foreperiod it appeared in the left target location marker (100% validity of the foreperiod–location mapping). One foreperiod was frequently (90%) associated with the parity task and infrequently (10%) with the magnitude task, whereas the reverse was true for the other foreperiod (90% validity of the foreperiod–task mapping). See the online article for the color version of this figure.

time-based task predictability affected anticipatory saccades, we therefore reversed the foreperiod–task mapping after half of the experiment while keeping the foreperiod–location mapping constant. Note, however, that with this rather crude manipulation, we would expect an effect of time-based task expectancy in participants’ saccades only if adapting time-based task expectancies took a considerable number of relearning instances.

Method

Participants. A prior sample size estimations on the basis of the mean effect size ($\eta_p^2 = .25$) reported in [Aufschnaiter, Kiesel, Dreisbach, et al. \(2018\)](#) suggested that 27 participants were necessary to find a significant effect ($\alpha < .05$) with 80% power (GPower; [Erdfelder, Faul, & Buchner, 1996](#)). For reasons of counterbalancing, 32 participants (11 male, none left-handed, mean age = 24.3 years, $SD = 2.9$) participated after providing written informed consent. All participants had normal or corrected-to-normal vision. Participants received course credit or 10€ as compensation. Three additional participants were replaced as they did not complete the experiment and one additional participant was replaced due to technical issues during eye tracking leading to signal loss.

Stimuli and apparatus. Participants sat 60 cm from a 24" LCD screen (1,920 pixels \times 1,080 pixels, 144 Hz) in a dark, sound attenuated laboratory room. Their head rested in a chin rest and the index fingers of their left and right hand rested on two external keys placed in front of them to the left and right (key distance: 13.5 cm). The screen background was black throughout the experiment which was run via EPrime (Version 2.0.10.3.5.6, Psychological Software Tools Inc., Sharpsburg, PA).

An EyeLink 1000 Plus Desktop Mount (SR Research Ltd., Ontario, Canada) tracked participants’ eyes. Corneal reflection and pupil diameter were measured via an infrared camera and eye movements (dominant eye) were sampled at 1,000 Hz with a spatial resolution of 0.01° visual angle. Calibration and validation were performed before the beginning of each block.

Design and procedure. Throughout each trial, two target location markers (square with a white frame, 1.8°, 12.6° to the left

and right of the screen center) were consistently present (except when error feedback was displayed). A white fixation cross (0.8°) appeared in the center of the screen for 600 ms (see [Figure 1](#) for the trial structure of Experiment 1). Subsequently the fixation cross turned green and remained on screen for another 200 ms. This color change was merely used as a warning signal to serve as a temporal anchor and starting point for participants’ time estimation. Then a foreperiod of either 500 ms or 1,500 ms followed before a target (0.8°) was presented in the center of the left or right target location marker (i.e., 12.6° to the left or right of the screen center) and remained visible until participants responded with a left or right key press. Each foreperiod consistently led to the presentation of the target in the center of one of the two target location markers. That is, after a short foreperiod (500 ms) the target always appeared on the right and after a long foreperiod (1,500 ms) the target always appeared on the left or vice versa. The numbers 1 to 9, except 5, were used as targets and displayed either in blue or yellow depending on whether participants were to classify the target number as smaller or larger than five (magnitude task) or as odd or even (parity task). Crucially one of the foreperiods (500 ms vs. 1,500 ms) was followed by the magnitude task in 90% of the trials and by the parity task in 10% of the trials, whereas the opposite was true for the other foreperiod. Thus, there were frequent and infrequent foreperiod/location–task combinations. Color–task mappings, foreperiod–location mappings, foreperiod–task mappings, and the order of foreperiod–task mappings were counterbalanced across participants. Moreover, task identity could repeat (task repetition) or switch (task switch) on two subsequent trials. Correct responses started the subsequent trial. Whenever participants responded incorrectly, an error message (“Fehler!” [“error!”]) was displayed in red in the center of the screen for 1,500 ms before the next trial ensued. The order of tasks, targets, and foreperiods was random with both tasks and foreperiods appearing equally often in each block. Furthermore, each target appeared equally often for each of the two tasks per block.

Participants completed one practice block of 48 trials and two times five blocks of 80 trials of the experiment proper. During the practice block, targets appeared in the center of the screen following a blank screen of 500 ms. The two task location markers, the fixation cross, and the foreperiods were only introduced once the experiment proper started. Whenever participants committed an error in the practice block, following the error feedback an instruction reminder informing participants about the category–response mappings of the two tasks was displayed for 8000 ms. Between the first and second half of the experiment proper (i.e., after five blocks), the foreperiod–task mapping reversed. However, each foreperiod was still frequently (90%) followed by the same task and the target still appeared at the same location after the short/long foreperiod. After each block, participants had the chance to take a self-paced break.

Instructions emphasized speed and accuracy equally strongly. Importantly, participants did not receive any instructions regarding their eye movements. Thus, we can assume that all observed eye movements occurred spontaneously and uninstructedly.

Results

Manual responses. We first assessed participants’ manual responses and replicated the time-based task expectancy effect

found in prior studies (e.g., Aufschnaiter, Kiesel, Dreisbach, et al., 2018; Aufschnaiter, Kiesel, & Thomaschke, 2018). An overview over participants' manual responses can be found in Figure 2. Detailed analyses of manual responses can be found in the online supplemental materials, as the results of manual responses were not the main focus of the present study.

Anticipatory saccades. Saccades were detected according to a combined velocity (30°/s), motion (0.1°), and acceleration (8,000°/s²) threshold. For the analyses of anticipatory saccades we examined only saccades that occurred between fixation offset and

target onset (i.e., during the foreperiod). During the foreperiod, participants could anticipate the upcoming target location and task based on the time that had passed since the fixation cross had disappeared. Note that the left and right target location marker were visible during the foreperiod. To be included in our analyses, saccades had to fulfill two criteria. They had to extend at least 1° in horizontal direction (i.e., the maximum inaccuracy accepted during tracking validation; 12,691 saccades in total were excluded due to this amplitude criterion). Furthermore, we only included saccades of trials in which the first saccade started around fixation (± 100 pixels/2.6°; 14,975 saccades in total excluded) to ensure that participants had perceived the offset of the fixation cross and could accurately judge the time that had passed since its disappearance. 21,211 remaining saccades (occurring in 40.8% of the trials) were included in our analyses.

Relative saccade frequency. First, we assessed the relative frequency of saccades in the direction of the later target and in the opposite direction during the short (500 ms) and long (1,500 ms) foreperiod (see Figures 3A for the time course of relative saccade frequencies and Figure 4A for the time course of participants' eye positions relative to the target, i.e., the saccadic gain over time).

To analyze participants' relative saccade frequencies per foreperiod (500 ms vs. 1,500 ms), we first classified saccades as matching versus mismatching the ultimate target position (e.g., saccade toward the right and target ultimately appears on the right after the foreperiod = match) and assessed the frequencies of matching and mismatching saccades. Thus, in trials with a short foreperiod (500 ms), we would expect participants to perform more matching than mismatching saccades if their time-based expectancy was reflected in their eye movements. In trials with a long foreperiod (1,500 ms), as the ultimate target location is coded as matching, time-based expectancy would be evidenced by more mismatching than matching saccades during the first interval part of the foreperiod (0–500 ms) and more matching than mismatching saccades during the second interval part of the foreperiod (501–1,500 ms). Based on the frequency of matching and mismatching saccades, we then computed participants' relative saccade frequencies (relative saccade frequency = $N_{\text{matching}} / [N_{\text{matching}} + N_{\text{mismatching}}]$).

If participants did not develop any time-based expectancies, they should look about equally often in the direction matching and mismatching the ultimate target position. Thus, relative saccade frequencies that do not differ from 50% indicate that participants have not developed time-based expectancies. Conversely, relative saccade frequencies differing from 50% would indicate that participants developed time-based expectancy at least for the target location. For the 500-ms foreperiod and for the second interval part (501–1,500 ms) of the 1,500 ms foreperiod, relative saccade frequencies above 50% would indicate effective time-based expectancy (i.e., more saccades toward the ultimate target position than in the opposite direction). For the first interval part (0–500 ms) of the 1,500 ms foreperiod, relative saccade frequencies below 50% would indicate effective time-based expectancy. One possible consequence of this way of coding saccades has to be noted. When assessing the long (1,500 ms) foreperiod overall without differentiating between the two interval parts, the frequencies of matching and mismatching saccades might cancel out leading to a relative saccade frequency of around 50%. We therefore assessed the first

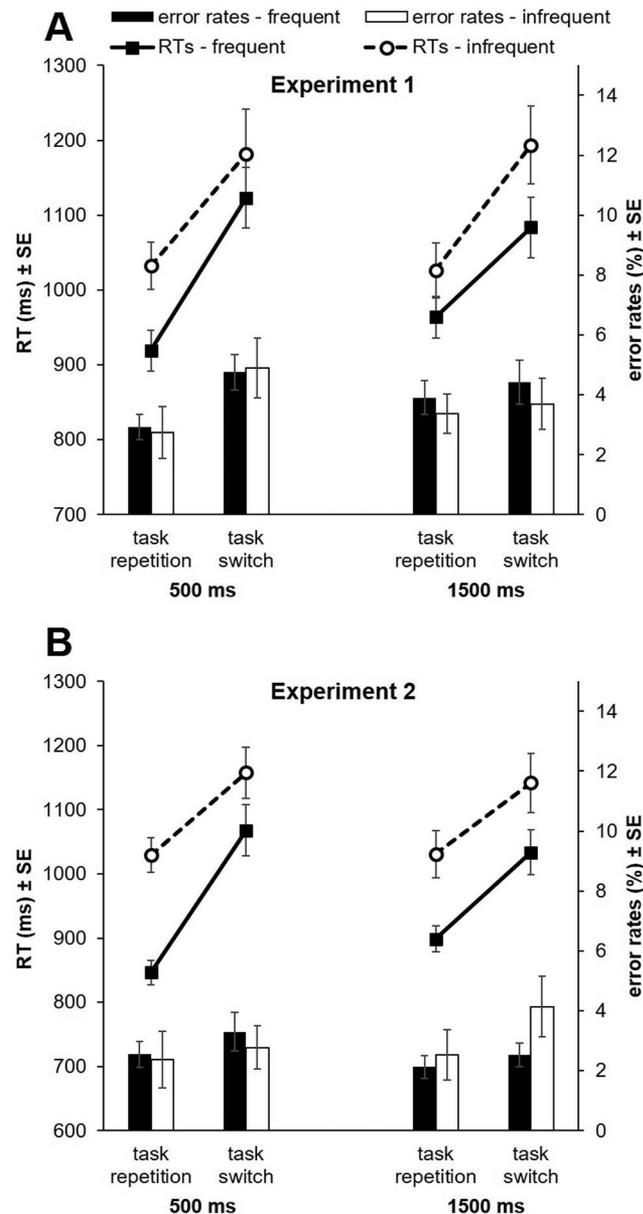


Figure 2. Reaction time (RT) and error rate results of (A) Experiment 1 and (B) Experiment 2. RTs (lines) and error rates (bars) are displayed separately for the factors frequency (frequent vs. infrequent), task sequence (repetition vs. switch), and foreperiod (500 ms vs. 1,500 ms). Error bars indicate the standard error of the mean (SE).

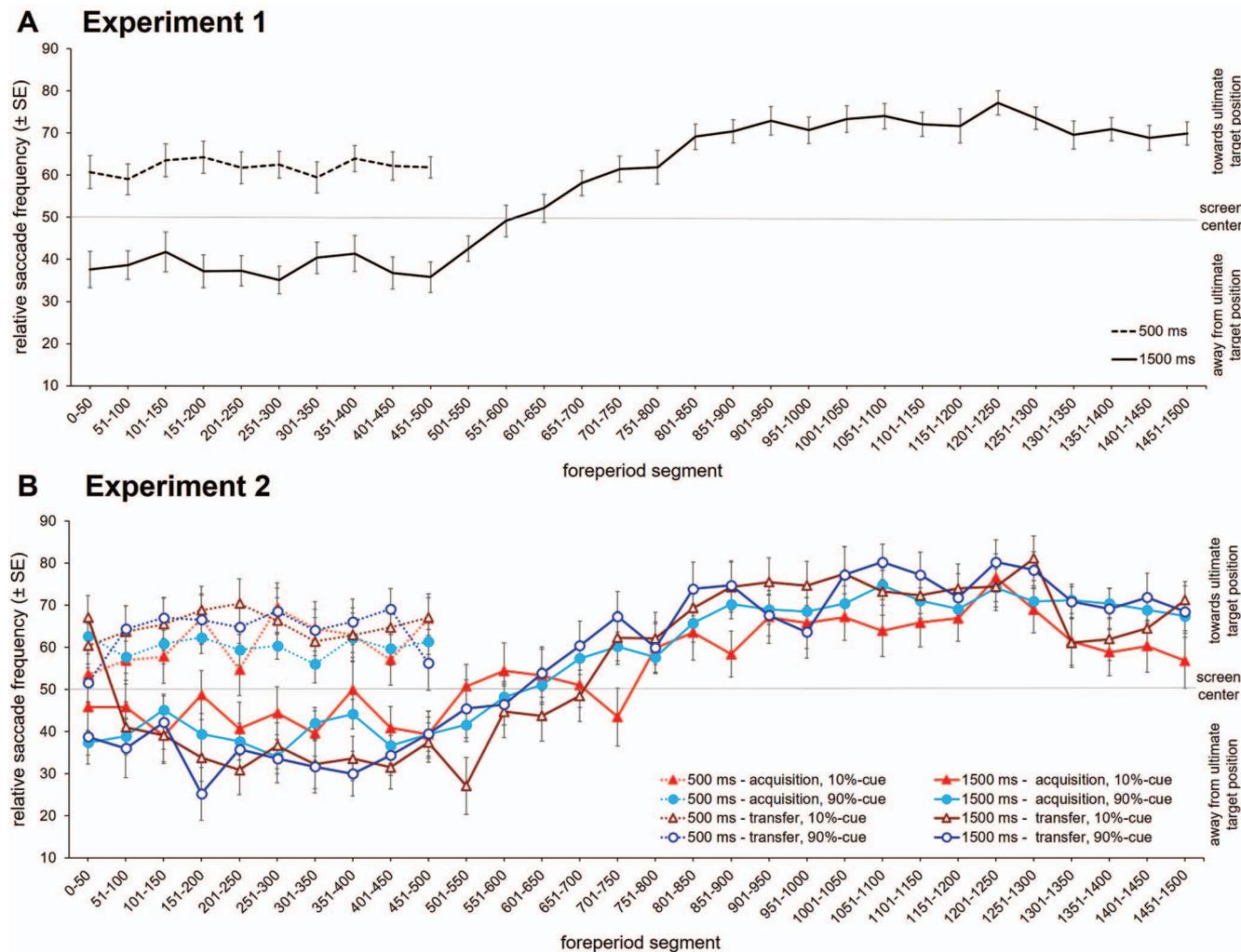


Figure 3. Relative saccade frequencies ($N_{\text{matching}}/N_{\text{matching}} + N_{\text{mismatching}}$) in (A) Experiment 1 and (B) Experiment 2 depicted in 50 ms latency bins for the two foreperiods (500 ms, dotted lines, vs. 1,500 ms, solid lines) and (B) depicted separately for the acquisition and transfer blocks as well as for the 10% and 90% frequency cue. Error bars indicate the standard error of the mean (SE). See the online article for the color version of this figure.

(0–500 ms) and second interval part (501–1,500 ms) of the 1,500-ms foreperiod separately.

First, we computed one sample t tests to compare participants' relative saccade frequencies in the short (500 ms; mean $N_{\text{saccades matching}} = 119.2$, mean $N_{\text{saccades mismatching}} = 57.6$) foreperiod against 50%. In trials with a short 500-ms foreperiod ($M = 66.3\%$) relative saccade frequencies were significantly higher than 50%, $t(31) = 8.05$, $p < .001$, $d = 1.42$. We then assessed participants' saccades in trials with a long 1,500-ms foreperiod separately for the first (0–500 ms; mean $N_{\text{saccades matching}} = 57.1$, mean $N_{\text{saccades mismatching}} = 120.9$) and second interval part (501–1,500 ms; mean $N_{\text{saccades matching}} = 198.3$, mean $N_{\text{saccades mismatching}} = 115.4$) of the 1,500 ms foreperiod. Both in the first ($M = 32.63\%$), $t(31) = -7.67$, $p < .001$, $d = 1.36$, and second interval part ($M = 62.0\%$), $t(31) = 9.27$, $p < .001$, $d = 1.64$, participants' relative saccade frequencies significantly differed from 50%. In the first interval part, relative saccade frequencies were

significantly lower than 50%, in the second interval part, relative saccade frequencies were significantly higher than 50%. Thus, as hypothesized, both during the short foreperiod and during the two interval parts of the long foreperiod, participants looked more often in the direction in which they could anticipate the target to appear on the basis of the current time.

Furthermore, at present, little is known about how fast time-based task expectancies develop and are relearned. If one assumed that relearning after a shift in foreperiod–task contingencies takes a substantial number of trials and if anticipatory saccades reflected not only time-based location expectancy but also time-based task expectancy, we should observe a reduction in saccades toward temporally predictable target locations after the reversal of location–task contingencies as compared to before.

To assess the influence of the task location reversal after Block 5 on participants' saccades, we also computed a paired t test on the

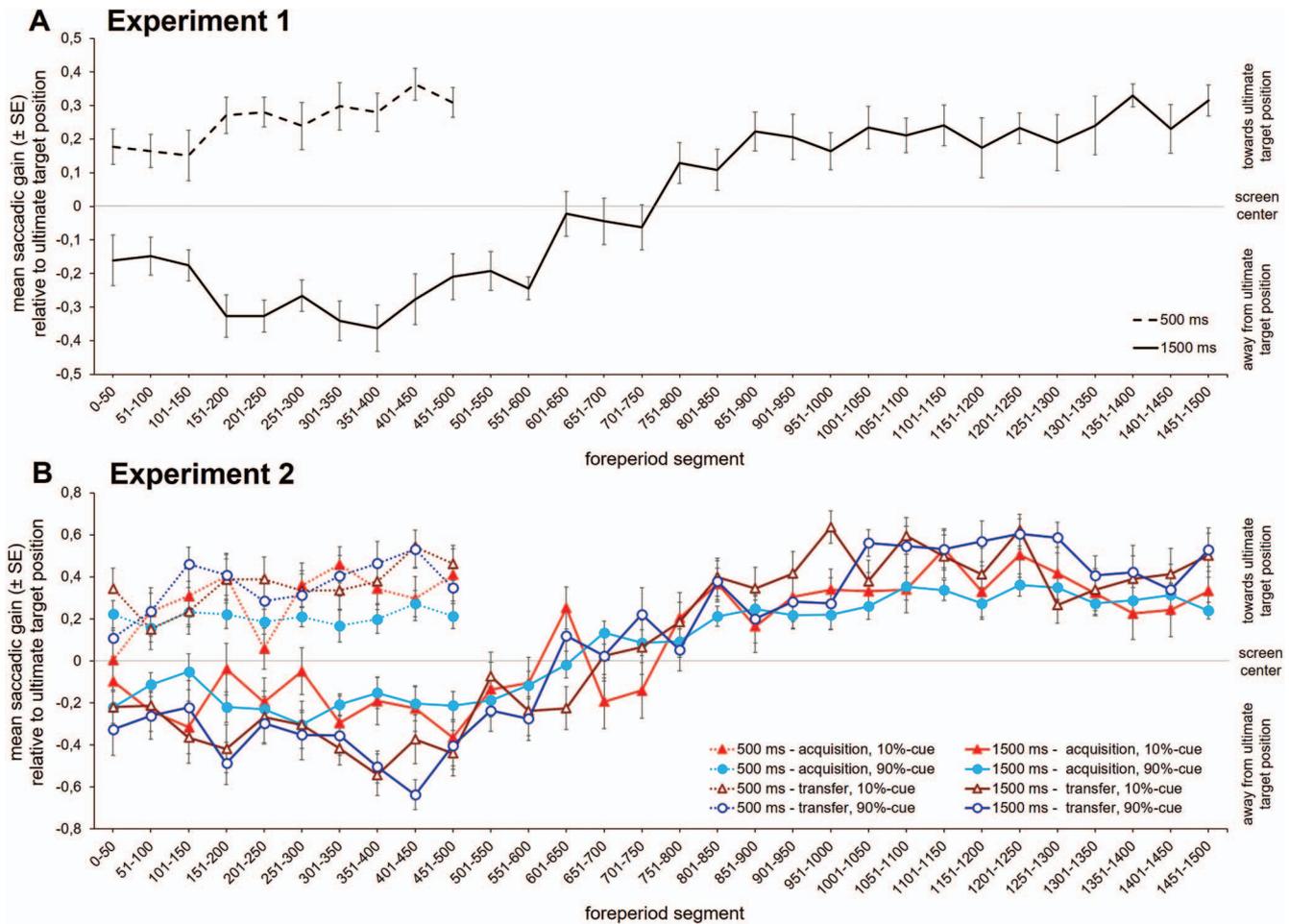


Figure 4. Mean saccadic gain over time relative to the ultimate target position (0 = center of the screen/position of the fixation at trial start, 1 = ultimate target position, -1 = position opposite to the ultimate target position) in (A) Experiment 1 and (B) Experiment 2. Mean saccadic gain is depicted in 50 ms latency bins for the two foreperiods (500 ms, dotted lines, vs. 1,500 ms, solid lines) and (B) depicted separately for the acquisition and transfer blocks as well as for the 10% and 90% frequency cue. Error bars indicate the standard error of the mean (*SE*). See the online article for the color version of this figure.

data of the 500-ms foreperiod comparing the last 40 trials before and the first 40 trials after task location reversal. One participant had to be excluded from this analysis, because he or she had not performed any saccades that fulfilled the criteria during these trials. Relative saccade frequencies did not differ significantly between the trials before and after task location reversal for the 500-ms foreperiod, $t(30) = 0.18$, $p = .862$, $d = 0.03$. A 2×2 repeated measures analysis of variance (ANOVA) conducted on the two interval parts of the 1,500-ms foreperiod (0–500 ms vs. 501–1,500 ms) and task location reversal showed a significant main effect of interval part, $F(1, 30) = 23.90$, $p < .001$, $\eta_p^2 = .44$. None of the other effects reached significance, $F_s < 1$. Participants' relative saccade frequencies did not suggest any differences between trials before and after a reversal in foreperiod–task contingencies.

Saccade latency. To descriptively assess how fast shifts in time-based expectancy were reflected in participants' eye movements during the first and second interval part, we also analyzed

the mean latency of participants' first expectancy-congruent saccade (i.e., the first saccade in the direction in which the target is to be expected given the current time relative to fixation offset). For saccades in the second interval part (501–1,500 ms) of the 1,500-ms foreperiod, saccade latencies were determined relative to the end of the first interval part (0–500 ms; i.e., by subtracting 500 ms).

A paired t test comparing mean saccade latencies during the first and second interval part showed that participants' first expectancy-congruent saccade occurred significantly earlier in the first ($M = 239$ ms) as compared to the second interval part ($M = 470$ ms), $t(31) = 15.45$, $p < .001$, $d = 2.73$.

To descriptively estimate the time at which participants' time-based expectancies shifted in the 1,500 ms foreperiod, we computed the mean latency of the last saccade during the first 500 ms of the foreperiod per participant and the mean latency of the first saccade during the second interval part (501–1,500 ms) in the 1,500-ms foreperiod (latency assessed relative to fixation offset).

This assessment suggested that participants' expectancy shifted between 500 ms and 800 ms (more precise estimations are difficult as saccade latencies also depend on, for instance, when the previous saccade ended).

Correlations. Time-based expectancy effects in manual reaction times (RTs) and error rates (see [online supplemental materials](#)) in the present experiment can be attributed to time-based task expectancy. Locations remained temporally predictable throughout the experiment and thus should not yield an additional influence on time-based expectancy effects in manual responses. Therefore, correlations between participants' individual time-based task expectancy effects in manual responses and their relative saccade frequencies could serve as another indicator that anticipatory saccades also reflect time-based task expectancies.

Thus, we correlated the time-based task expectancy effect in RTs and error rates before and after task location reversal with the relative saccade frequencies before and after task location reversal. Relative saccade frequencies and manual time-based expectancy effects correlated neither before nor after task location reversal, error rates before task location reversal: $r \leq .26, p \geq .146$; others: $r \leq .06, p \geq .759$. There was no indication for correlations between time-based task expectancy effects in manual responses and participants' relative saccade frequencies.

Postexperiment questions. Finally, prior studies on time-based task expectancy (e.g., [Aufschnaiter, Kiesel, Dreisbach, et al., 2018](#); [Aufschnaiter et al., 2018](#)) indicated that time-based task expectancy effects emerged although participants did not gain explicit knowledge about foreperiod–task contingencies. As, in the present study, foreperiod–location mappings were completely predictable, we asked participants about any regularities they might have observed in the experiment to assess whether they had gained explicit knowledge of the foreperiod–event manipulations.

Asked for task regularities, only two participants mentioned any regularities that involved different time intervals, but none had realized that there were frequent and infrequent foreperiod–task combinations. Two participants reported having observed that they made eye movements to one side and, if no target had appeared, switched to the other side and one person indicated that they felt their eye movements slowing down after the task location reversal. None of the other participants mentioned regularities relevant to the task context. When asked whether they had noticed different time intervals in the experiment, 14 participants said yes, but only three indicated that there were two or more time intervals. No participant answered that there were exactly two time intervals.

Discussion

Experiment 1 used an adapted version of the time–event correlation paradigm ([Aufschnaiter, Kiesel, Dreisbach, et al., 2018](#); [Aufschnaiter et al., 2018](#)) to investigate whether time-based (location and/or task) expectancy was reflected in anticipatory saccades. Foreperiods predicted target locations with 100% validity and tasks with 90% validity.

First, we replicated the findings of [Aufschnaiter, Kiesel, Dreisbach, et al. \(2018\)](#); see also [Aufschnaiter et al., 2018](#)). Participants responded faster in trials with frequent foreperiod–task combinations rather than infrequent foreperiod–task combinations (see [online supplemental materials](#) for details). These findings indicate that participants formed associations between foreperiods

and tasks and thus developed time-based task expectancies that affected their performance.

Most importantly, if participants' expectations regarding target location (and task) were not reflected in their eye movements, we would expect them to perform eye movements at random during the foreperiod. Thus, there should not be any differences in the relative frequency of saccades in the direction in which a target is to be expected and the opposite direction. However, we observed that participants first looked toward the location at which they expected the target to appear after the short foreperiod. In trials with long foreperiods, after the short foreperiod had passed, their gaze shifted and they more often performed saccades in the direction in which a target would appear after the long foreperiod. These saccades crossed the horizontal midpoint of the screen and extended about as far on the opposite side of the screen as the saccades during the short foreperiod. Thus, they cannot be accounted for by merely assuming increasing probabilities of return saccades. These findings clearly indicate that participants developed time-based location expectancies that were reflected in anticipatory saccades toward expected target locations. Thus, we validated that the present eye tracking paradigm can be used to assess the temporal dynamics of (at least) time-based location expectancy.

In Experiment 1, we reversed foreperiod–task contingencies after half of the blocks. Our reasoning was that, if the relearning of foreperiod–task associations took a substantial number of trials, we should observe differences in anticipatory saccades between trials before and after the reversal of foreperiod–task contingencies. This was not the case. There are two possible explanations for this pattern of results. Either relearning of foreperiod–task associations occurs within a few trials, so that we could not observe any effect on anticipatory saccades or anticipatory saccades only reflect time-based location but not task expectancy. Thus, we conducted Experiment 2 as another test for the influence of time-based task expectancy on anticipatory saccades that was not based on the assumption that a substantial number of relearning instances were necessary to adapt foreperiod–task associations after a shift in contingencies. In Experiment 2, in a first part of the experiment (acquisition phase²), we used frequency cues to allow participants to anticipate whether a frequent/infrequent foreperiod–task combination would follow the foreperiod. In a second part of the experiment (transfer phase), these frequency cues were no longer indicative of the frequency of the foreperiod–task combination.

Experiment 2

Experiment 2 adapted the paradigm used in Experiment 1 to investigate whether participants developed not only time-based location expectancy, but also time-based task expectancy. To do so, we built on prior research regarding expectancy violations.

² The term *acquisition phase* is commonly used to contrast learning trials from later test trials. Note, however, that, in Experiment 2, the acquisition phase itself was also of interest and therefore examined in detail. It was followed by a transfer phase during which frequency cue mappings acquired in the acquisition phase switched on some trials. The acquisition phase of Experiment 2 was thus used both to replicate and extend Experiment 1 and to provide an acquisition context for the frequency cue mappings to be tested in the subsequent transfer phase.

Humans typically respond slower to unexpected as compared to expected events not only in studies on time-based expectancy, but also in various other contexts (e.g., unexpected action consequences: e.g., Band, van Steenbergen, Ridderinkhof, Falkenstein, & Hommel, 2009; oddball sounds: e.g., Parmentier, Elsley, Andrés, & Barceló, 2011; posterror slowing: e.g., Rabbitt, 1966; Ullsperger & Danielmeier, 2016). Importantly, responses to violations of (location) expectancies have also been assessed in eye tracking (e.g., Vö and Wolfe, 2013b).

We assumed that violations of participants' time-based task expectancy would also affect their anticipatory saccades. Thus, we hypothesized that, if participants' anticipatory saccades were (partly) guided by time-based task expectancy (and not only time-based location expectancy), their anticipatory saccades should be influenced by violations thereof. That is, the overall frequency of anticipatory saccades toward and away from target locations expected on the basis of time should be affected by whether participants anticipated that a frequent or infrequent (expectancy violation) foreperiod–task combination would follow.

To address whether this was the case, in Experiment 2, we introduced a frequency cue that predicted whether the frequent or infrequent task would appear after the respective foreperiod. The fixation cross was replaced with one of two frequency cues that, unbeknownst to the participants, predicted with 100% validity whether the task frequently or infrequently following the current foreperiod would have to be performed at the end of the foreperiod (i.e., whether a frequent/infrequent foreperiod–task combination would follow). Thus, participants could learn the cue–frequency contingencies, develop corresponding expectancies regarding the frequency of the upcoming foreperiod–task combination on the basis of the frequency cues, and predict the upcoming task on the basis of the frequency cue and the current foreperiod. In a subsequent transfer phase, the frequency cues were randomly paired with frequent and infrequent foreperiod–task combinations. Thus, participants were not able to predict the upcoming task anymore and any expectations they might have formed during the acquisition phase were violated in a proportion of the trials.

To investigate whether participants' anticipatory saccades were affected by time-based task expectancy, we examined, first, whether participants eye movements differed in the acquisition phase depending on whether a frequent or infrequent foreperiod–task combination was predicted by the frequency cue. We expected that preparing for the infrequent task (i.e., going against ones foreperiod–task associations) should be more difficult than preparing for the frequent task. This difficulty in preparing for the infrequent task should also affect participants' anticipatory saccades if they reflected time-based task expectancy in addition to time-based location expectancy. This in turn should show in a difference in relative saccade frequencies between trials in which the frequency cue indicates frequent rather than infrequent foreperiod–task combinations. Second, we assessed whether this effect would diminish/vanish in the transfer phase.

Method

Participants. Thirty-two different participants (eight male, four left-handed, M age = 22.5 years, $SD = 2.9$) took part after providing written informed consent. All participants had normal or corrected-to-normal vision. Again, participants either received

course credit or 10€ as compensation. Two additional participants did not complete the experiment, one additional participant committed too many errors (error rate >20%), and two additional participants were excluded due to technical issues during eye tracking.

Stimuli and apparatus. The setting of Experiment 2 was equivalent to Experiment 1.

Design and procedure. The trial structure of Experiment 2 was similar to Experiment 1 with some crucial exceptions (see Figure 5). The white and green fixation cross were replaced by one of two frequency cues, a white/green triangle or square, and the experiment consisted of two phases, an acquisition and a transfer phase.

Note that, nevertheless, the contingencies of Experiment 1 were preserved in Experiment 2: Foreperiods validly predicted target locations (100%). One foreperiod was frequently (90%) associated with the parity task and infrequently (10%) with the magnitude task, whereas the reverse was true for the other foreperiod (90% validity of the foreperiod–task mapping) throughout the entire experiment.

After a practice block of 48 trials, participants completed eight blocks of 80 trials in the acquisition phase and, subsequently, three blocks of 80 trials in the transfer phase of the experiment.

Unbeknownst to the participants, in the acquisition phase, the frequency cues validly (100%) predicted whether the task frequently or infrequently combined with the following foreperiod would occur (i.e., whether a frequent/infrequent foreperiod–location–task–combination would follow; e.g., triangle = frequent foreperiod–location–task combination, square = infrequent foreperiod–location–task combination). That is, participants could predict the task they would have to perform on the basis of the frequency cue and the foreperiod. This manipulation also implicated that one of the two frequency cues appeared more frequently than the other (10% vs. 90% of trials in the acquisition phase). Each frequency cue preceded short/long foreperiods in 50% of the trials it was presented on (90% vs. 10% of trials in the acquisition phase, respectively).

In the following transfer phase, the two frequency cues appeared equally often before each foreperiod–location–task combination and overall (50% of trials per frequency cue) and were not predictive of whether the task frequently or infrequently combined with the following foreperiod would have to be performed any more (see Figure 5 for a graphical illustration of the frequency cue manipulation).

Results

Manual responses. Again, we first assessed participants' manual responses and replicated the time-based task expectancy effect found in prior studies (e.g., Aufschnaiter, Kiesel, Dreisbach, et al., 2018; Aufschnaiter, Kiesel, & Thomaschke, 2018). An overview over participants' manual responses can be found in the [online supplemental materials](#) (see also Figure 2B).

Anticipatory saccades. Saccades were detected and treated as in Experiment 1; 13,210 saccades were excluded as they did not meet the amplitude criterion and 11,535 saccades were excluded as the first saccade of the trial after fixation offset did not start around fixation. A total of 26,385 saccades (occurring in 51.9% of the trials) were included in the analyses.

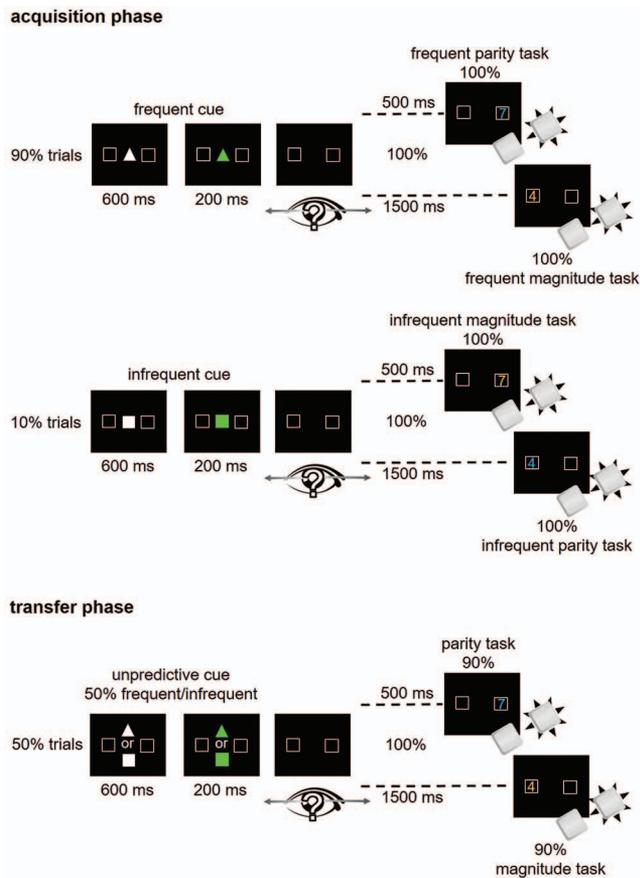


Figure 5. Trial and experiment structure of Experiment 2. A frequency cue (triangle vs. square; switching from white to green for the last 200 ms of its presentation) was followed by a short or long foreperiod (500 ms vs. 1,500 ms). Throughout the entire experiment, after one foreperiod, the target appeared in the right target location marker, after the other foreperiod it appeared in the left target location marker (100% validity of the foreperiod–location mapping). One foreperiod was frequently (90%) associated with the parity task and infrequently (10%) with the magnitude task, whereas the reverse was true for the other foreperiod (90% validity of the foreperiod–task mapping) throughout the entire experiment. In the acquisition phase, frequency cues predicted to 100% whether a frequent or infrequent foreperiod–location–task combination would follow. Each frequency cue preceded short/long foreperiods in 50% of the trials it was presented on, but the infrequent cue appeared only on 10% of the trials of the acquisition phase, whereas the frequent cue appeared on 90% of the trials of the acquisition phase. In the transfer phase, frequency cues were not predictive of frequent/infrequent foreperiod–location–task combinations anymore and appeared equally often overall (50% of trials in the transfer phase) as well as per foreperiod–location–task combination. See the online article for the color version of this figure.

Relative saccade frequency. Based on the findings of Experiment 1, we expected to observe relative saccade frequencies above 50% for the short (500 ms) foreperiod during both the acquisition and the transfer phase. For the long (1,500 ms) foreperiod, we again expected a shift from relative saccade frequencies below 50% (0–500 ms) to above 50% (501–1,500 ms) during both phases of the experiment (see Figures 3B and 4B for the time

course of participants relative saccade frequencies and eye positions).

In the acquisition phase, participants' relative saccade frequencies were significantly higher than 50% in the 500-ms foreperiod ($M = 60.2\%$; mean $N_{\text{saccades matching}} = 109.1$, mean $N_{\text{saccades mismatching}} = 66.3$), $t(31) = 4.25$, $p < .001$, $d = 0.75$. For the 1,500 ms foreperiod, relative saccade frequencies significantly differed from 50% both during the first (lower than 50%; $M = 38.8\%$; mean $N_{\text{saccades matching}} = 64.5$, mean $N_{\text{saccades mismatching}} = 108.8$), $t(31) = -4.28$, $p < .001$, $d = 0.76$, and second interval part (higher than 50%; $M = 64.7\%$; mean $N_{\text{saccades matching}} = 182.6$, mean $N_{\text{saccades mismatching}} = 95.1$), $t(31) = 9.07$, $p < .001$, $d = 1.60$, of the 1,500 ms foreperiod.

In the transfer phase, relative saccade frequencies were higher than 50% for the 500-ms foreperiod ($M = 65.2\%$; mean $N_{\text{saccades matching}} = 40.9$, mean $N_{\text{saccades mismatching}} = 18.6$), $t(31) = 3.93$, $p < .001$, $d = 0.69$. Again, relative saccade frequencies significantly differed from 50% both during the first (lower than 50%; $M = 32.4\%$; mean $N_{\text{saccades matching}} = 18.1$, mean $N_{\text{saccades mismatching}} = 40.7$), $t(31) = -4.83$, $p < .001$, $d = 0.85$, and second interval part (higher than 50%; $M = 73.9\%$; mean $N_{\text{saccades matching}} = 63.4$, mean $N_{\text{saccades mismatching}} = 22.7$), $t(31) = 9.96$, $p < .001$, $d = 1.76$, of the 1,500 ms foreperiod.

As expected, during both the acquisition and transfer phase of Experiment 2, participants looked more often in the direction in which the target could be expected on the basis of time rather than in the opposite direction.

Extending on the findings of Experiment 1, if the time-based task expectancies participants had formed affected their eye movements, we expected that anticipatory saccades should differ between trials in which participants anticipated a frequent versus infrequent foreperiod–task combination on the basis of the frequency cue. Importantly, in the acquisition phase, by indicating whether a frequent or infrequent foreperiod–task combination would follow, the frequency cue indirectly also indicated which task to expect based on the current time and allowed participants to prepare for this task. In terms of task preparation, it is relevant whether the to-be-performed task repeats from the previous trial or switches (e.g., task repetition: trial $N-1$ – parity, trial N – parity; task switch: trial $N-1$ – parity, trial N – magnitude). Task switches are commonly associated with costs relative to task repetitions (e.g., for a review see Kiesel et al., 2010). Manual responses showed this effect as well as a time-based task expectancy effects, indicating that participants had prepared for the upcoming task of a trial on the basis of time. As task preparation is affected by the sequence of tasks across trials (task repetition vs. task switch), a reflection of time-based task expectancies in participants' eye movements could therefore also be evident in differences between conditions in which a task repetition versus a task switch is predicted. That is, preparing for and anticipating a task switch should be harder than preparing for and anticipating a task repetition. This might, for instance, lead to fewer saccades toward the later target location in task switch as compared to task repetition trials.

To assess the influence of the cue that predicted the frequency of the current foreperiod–task combination (and thus in combination with the temporal progression of the current foreperiod also predicted whether the task would repeat or switch), we conducted additional $2 \times 2 \times 2$ repeated measures ANOVAs on the relative

saccade frequencies during the acquisition and transfer phase (see Figure 6). A first analysis assessed the influence of the within-subject factors foreperiod (500 ms vs. 1,500 ms), frequency cueing (frequent vs. infrequent), and task-sequence cueing (task repetition vs. task switch). Then, a second analysis on trials with long foreperiods assessed the influence of the within-subject factors interval part (0–500 ms vs. 501–1,500 ms), frequency cueing, and task-sequence cueing.³

In the overall analysis of the acquisition phase (see Figure 6A), we found a main effect of foreperiod, $F(1, 31) = 4.56, p < .041, \eta_p^2 = .13$, with higher relative saccade frequencies for the short as compared to the long foreperiod. Furthermore, there was a significant three-way interaction between foreperiod, frequency cueing, and task sequence cueing, $F(1, 31) = 16.74, p < .001, \eta_p^2 = .35$. Subsequent 2×2 repeated measures ANOVAs conducted separately for the two foreperiods revealed that frequency cueing and task sequence cueing significantly interacted during the 500 ms foreperiod, $F(1, 31) = 13.48, p = .001, \eta_p^2 = .30$, as well as during the 1,500-ms foreperiod, $F(1, 31) = 11.97, p = .002, \eta_p^2 = .28$. However, interaction patterns differed. In trials with a 500 ms foreperiod, in task repetition trials, relative saccade frequencies were higher for predicted frequent as compared to infrequent foreperiod–task combinations, whereas in task switch trials, relative saccade frequencies were higher for predicted infrequent as compared to frequent foreperiod–task combinations (as predicted by the frequency cue). The reverse was the case for trials with a 1,500 ms foreperiod. All other effects failed to reach significance, $F_s \leq 2.51, p_s \geq .123, \eta_p^2 \leq .08$.

The analysis of the data of the acquisition phase in the long foreperiod condition (see Figure 6B) showed a significant main effect of interval part, $F(1, 31) = 44.87, p < .001, \eta_p^2 = .59$, with higher relative saccade frequencies during the second interval part as compared to the first. Furthermore, frequency cueing and task sequence cueing significantly interacted, $F(1, 31) = 23.83, p < .001, \eta_p^2 = .44$. Paired t tests examining this interaction showed that differences in relative saccade frequencies between frequent and infrequent foreperiod–task combinations indicated by the cue were significant both when the frequency cue indicated a task repetition, $t(31) = -2.74, p = .010, d = 0.48$, and when it indicated a task switch, $t(31) = 3.29, p = .003, d = 0.58$. The direction of the effect, however, differed. When a task repetition was indicated, participants' relative saccade frequencies were higher for infrequent as compared to frequent foreperiod–task combinations. When a task switch was indicated, participants' relative saccade frequencies were higher for frequent as compared to infrequent foreperiod–task combinations. All other effects failed to reach significance, $F_s \leq 2.66, p_s \geq .113, \eta_p^2 \leq .08$.

As explained previously, because of the coding we used (i.e., match vs. mismatch with the ultimate target location), a null effect of this three-way interaction between interval part, frequency cueing, and task sequence cueing suggests opposing interaction patterns regarding the relative frequency of expectancy-congruent saccades between the first and second interval part. Thus, we also computed the corresponding Bayes factor (BF_{01}) using JASP (Version 0.8.0.0, Love et al., 2015; see Rouder, Morey, Verhagen, Swagman, & Wagenmakers, 2017; Rouder, Speckman, Sun, Morey, & Iverson, 2009, for information on Bayesian statistics) to assess the evidence in favor of the null hypothesis. The Bayes factor suggested that, for the three-way interaction, the null hy-

pothesis was 3.92 times more likely than the alternative hypothesis given the data ($BF_{01} = 3.92$). According to Jarosz and Wiley (2014), Bayes factors between 3 and 10 constitute substantial evidence for the null hypothesis.

Summarizing the results of relative saccade frequencies in the acquisition phase, we did not observe the main effects of frequency cueing and/or task sequence cueing we had expected. Instead, we observed a complex interaction pattern between these factors. Though unexpected, this pattern could only have emerged if participants' eye movements were influenced by their time-based task expectancies.

In the transfer phase in which the prior frequency cues occurred at random and were no longer predictive, we expected that the influence of the frequency cues on participants' eye movement should be reduced or even absent.

In the overall analysis of the transfer phase (see Figure 6C), we found a main effect of foreperiod, $F(1, 31) = 7.48, p = .010, \eta_p^2 = .19$. Relative saccade frequencies were significantly higher during the 500-ms foreperiod as compared to the 1,500-ms foreperiod. The three-way interaction between foreperiod, frequency cueing, and task sequence cueing showed a nonsignificant trend, $F(1, 31) = 3.18, p = .085, \eta_p^2 = .09$. All other effects failed to reach significance, $F_s \leq 2.22, p_s \geq .147, \eta_p^2 \leq .07$.

The analysis of the long foreperiod in the transfer phase (see Figure 6D) showed main effects of interval part, $F(1, 31) = 63.73, p < .001, \eta_p^2 = .67$, with higher relative saccade frequencies during the second as compared to the first interval part. Moreover, frequency cueing and task sequence cueing significantly interacted, $F(1, 31) = 14.94, p = .001, \eta_p^2 = .33$. Differences in relative frequencies between cues previously indicating frequent and infrequent foreperiod–task combinations were significant neither for task repetition, $t(31) = 0.42, p = .680, d = 0.07$, nor for task switch trials, $t(31) = -1.20, p = .240, d = 0.21$. The interaction emerged due to opposite result patterns. This interaction was further explained by a three-way interaction of interval part, frequency cueing, and task sequence cueing, $F(1, 31) = 5.75, p = .023, \eta_p^2 = .16, BF_{01} = 0.68$ (inconclusive, anecdotal evidence in favor of the alternative hypothesis). Frequency cueing and task sequence cueing significantly interacted in the first interval part, $F(1, 31) = 14.60, p = .001, \eta_p^2 = .32$, but not in the second interval part, $F(1, 31) = 2.30, p = .139, \eta_p^2 = .07$. All other effects failed to reach significance, $F_s < 1$.

Overall, findings in the transfer phase are in line with our hypothesis that the influence of the frequency cues on participants' eye movements should be reduced in the transfer phase as compared to the acquisition phase, as the frequency cues were no longer predictive.

³ Please note that we speak of frequency cueing and task sequence cueing for the sake of consistency across the analyses of Experiment 2. In the acquisition phase of Experiment 2 in which the frequency cue is 100% valid, frequency cueing and task sequence cueing are the same as the factors frequency and task sequence used in Experiment 1. In the transfer phase of Experiment 2, however, in which the frequency cue is not always valid, the frequency and task/task sequence that the frequency cue indicates can both correspond to or differ from the actual frequency and task/task sequence. We therefore chose the terms *frequency cueing* and *task sequence cueing* to represent that we are analyzing the data with respect to what the frequency cue indicates and irrespective of whether this indication holds true when the target appears or not.

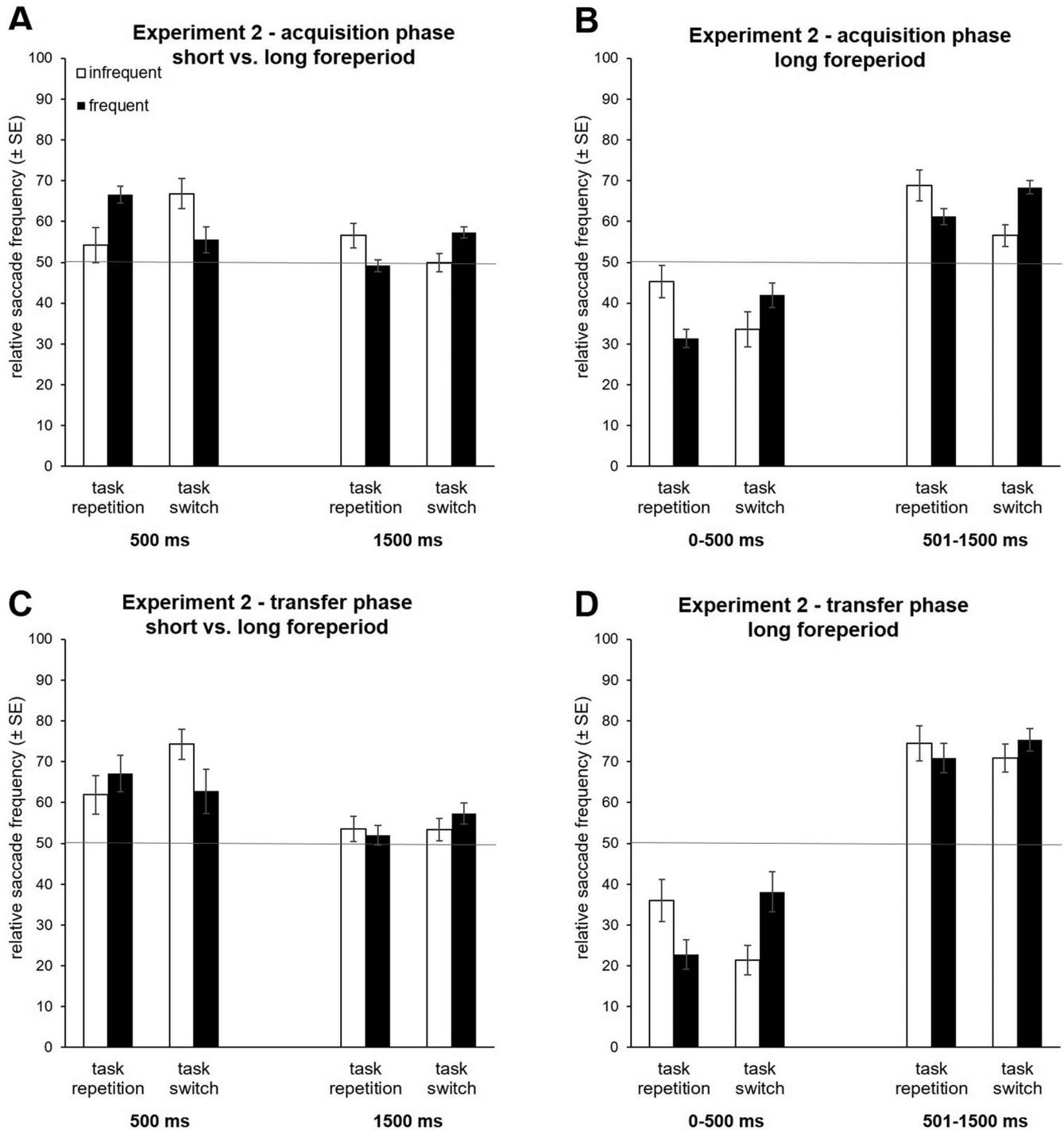


Figure 6. Relative saccade frequencies ($N_{\text{matching}}/[N_{\text{matching}} + N_{\text{mismatching}}]$) in the acquisition (Panels A and B) and transfer phase (Panels C and D) of Experiment 2. A, C: Relative saccade frequencies as a function of foreperiod (500 ms vs. 1,500 ms), frequency cueing (10% vs. 90%), and task sequence cueing (task repetition vs. task switch). B, D: Relative saccade frequencies in trials with a long foreperiod as a function of interval part (0–500 ms vs. 501–1,500 ms), frequency cueing, and task sequence cueing. Note that in the acquisition phase (A and B) frequency cueing and task sequence cueing were always valid, whereas they were partly valid and partly invalid in the transfer phase (C and D). Error bars indicate the standard error of the mean (SE).

At the same time, both in the acquisition and transfer phase, the overall saccadic gain was larger for conditions with higher relative saccade frequencies and smaller for conditions with lower relative saccade frequencies (or did not differ significantly between conditions). Thus, findings regarding saccadic gain mirrored results in relative saccade frequencies and a reversed pattern of overall saccadic gain cannot account for the observed differences in relative frequencies.

Saccade latency. Again, to assess how fast shifts in time-based expectancy were reflected in participants' eye movements during the first and second interval part and to determine whether we could replicate the results of Experiment 1, we analyzed the latency of participants' saccades.

In the acquisition phase, the latency of the first expectancy-congruent saccade during the first interval part ($M = 230$ ms) occurred significantly earlier than the first expectancy-congruent saccade during the second interval part ($M = 467$ ms), $t(31) = 23.32, p < .001, d = 4.12$. In the transfer phase, saccades occurred earlier during the first ($M = 226$ ms) rather than second interval part ($M = 461$ ms), $t(31) = 14.87, p < .001, d = 2.63$.

Again, we approximated the time at which participants' time-based expectancy shifted. In both the acquisition and transfer phase, our findings were in favor of a shift between 500 and 800 ms.

In addition, $2 \times 2 \times 2$ repeated measures ANOVAs were conducted to examine saccade latencies in the acquisition and transfer phase separately for the two interval parts, frequency cueings, and task sequence cueings. Note that only the data of 30 (acquisition phase) and 28 (transfer phase) participants provided trials in all cells to conduct these analyses. In the acquisition phase, this analysis found only a main effect of interval part, $F(1, 29) = 317.48, p < .001, \eta_p^2 = .92$, with earlier saccade latencies during the first rather than second interval part. All other effects failed to reach significance, $F_s \leq 1.56, p_s \geq .221, \eta_p^2 \leq .05$. In the transfer phase, there was a significant main effect of interval part, $F(1, 27) = 175.33, p < .001, \eta_p^2 = .87$, with earlier saccade latencies in the first rather than second interval part. All other effects failed to reach significance, $F_s \leq 1.38, p_s \geq .251, \eta_p^2 \leq .05$.

Apart from the main effect of interval part we also observed in Experiment 1, there was no indication of any influence of the frequency cue on participants' saccade latencies. As such, saccade latency results also do not contradict the findings observed for relative saccade frequencies and saccade amplitudes.

Correlations. Again, correlations between participants' individual time-based task expectancy effects in manual responses and their relative saccade frequencies could serve as another indicator that anticipatory saccades also reflect time-based task expectancies. We therefore also assessed these correlations in the acquisition and transfer phase.

We correlated the time-based expectancy effects in RTs and error rates in the acquisition and transfer phase with the relative saccade frequencies in the acquisition and transfer phase. In the acquisition phase, the time-based expectancy effect in RTs significantly correlated with relative saccade frequencies, $r = -.45, p = .011$; error rates: $r \leq -.03, p \geq .878$. In the transfer phase, none of the correlations between time-based expectancy in RTs and error rates and relative saccade frequencies reached significance, $r \leq .07, p \geq .698$.

We found that time-based expectancy effects in RTs and relative saccade frequencies correlated in the acquisition phase, in which

the frequency cues predicted the task, but not in the transfer phase, in which the frequency cues were not predictive of the task any more. That is, participants who developed stronger time-based expectancies, as evidenced by frequent saccades toward the later target location, apparently also were better able to learn about the meaning of the frequency cues (acquisition phase) and consequently showed reduced time-based expectancy effects when the frequency cues were predictive. When the frequency cues were no longer predictive (transfer phase), this correlation vanished.

Postexperiment questions. One participant indicated the correct foreperiod-task regularities when asked about regularities in the experiment. Three participants indicated that they had observed that their eye movements first went in one direction and then shifted when no target had appeared there for a while. When asked whether they had noticed different time intervals in the experiment, 16 participants said yes. Three of them indicated that there were two different time intervals and one participant indicated that there were at least two different time intervals. Two participants were not able to name the two symbols used as fixation when asked.

Discussion

In Experiment 2, participants were again largely unaware of the number of foreperiods and the frequencies of the foreperiod-task combinations. Furthermore, they were unable to report what the two frequency cues indicated. Nevertheless, in the acquisition as well as in the transfer phase, we replicated both the time-based expectancy effect in manual responses (Aufschnaiter, Kiesel, Dreisbach, et al., 2018; Aufschnaiter et al., 2018; see also Experiment 1) and the time-based expectancy effect in anticipatory saccades (see Experiment 1). That is, participants looked more often in the direction in which a task would appear given the current foreperiod progression rather than in the opposite direction.

Most important for the question whether participants' anticipatory saccades also reflect time-based task expectancy, we found that, in the acquisition phase, participants' anticipatory saccades were affected by the expectations they could derive from the frequency cue. This indicates that participants' anticipatory saccades were not only affected by the location participants expected the target to appear at, but also by the task participants expected to perform. This was further underlined by the observation that the influence of the frequency cues on participants' anticipatory saccades diminished in the transfer phase in which frequency cues were no longer predictive. Similarly, we observed (negative) correlations between participants' time-based expectancy effects in manual responses and relative saccade frequencies in the acquisition phase, but not in the transfer phase. Thus, not only time-based location but also time-based task expectancy is reflected in a person's eye movements. This is a first indication that anticipatory saccades can also be used to assess the temporal dynamics of other types of time-based expectancy. However, further studies will be necessary to ascertain this claim.

Finally, though the interaction pattern was less pronounced in the transfer phase, it still persisted. In Experiment 1, we found that participants showed fast adaptation to changes in foreperiod-task contingencies. In contrast to this fast adaptation, however, participants apparently needed much longer to adapt to changes in the validity of the frequency cue.

General Discussion

Two experiments explored whether time-based expectancy and shifts thereof were reflected in spontaneous anticipatory eye movements toward the locations at which a target would appear after a short/long foreperiod. This short/long foreperiod predicted whether a target would appear on the right or left side of the screen. Targets were numbers that, via a left/right keypress, had to be judged either according to their magnitude or parity as indicated by their color. Crucially, the foreperiod preceding the target also predicted the task participants would have to perform with 90% validity. Participants were not informed about the contingencies between foreperiod and target location and foreperiod and task and they did not receive any instructions regarding their eye movements.

Overall, the present experiments represent the first study assessing time-based location and task expectancy online in their time course. Thus, we extend findings by Volberg and Thomaschke (2017) using an EEG paradigm that can only be applied to assess time-based response expectancy. Our experiments demonstrate that anticipatory saccades reflect not only time-based location expectancy, but also time-based task expectancy. That is, participants did not only learn that, for instance, after a short foreperiod, a target would appear on the right and thus anticipatorily direct their gaze there (Experiment 1). They also learned that, for instance, after a short foreperiod, they would have to perform the parity judgment task and this time-based task expectancy was reflected in their gaze (Experiment 2). This was indicated by an influence of the frequency cues in Experiment 2, which predicted whether a frequent or infrequent foreperiod–task combination would follow, on relative saccade frequencies. Furthermore, the influence of the frequency cue on relative saccade frequencies appeared to be stronger in the acquisition than in the transfer phase in which frequency cues were not predictive anymore. Similarly, relative saccade frequencies (negatively) correlated with manual time-based task expectancy effects in the acquisition but not transfer phase.

It is important to note that saccades that crossed at least a horizontal distance of 1° and were included in the analyses occurred only on a proportion of trials. Furthermore, participants' anticipatory saccades, on average, (relatively homogeneously) crossed only up to around half the distance between fixation and target (see Figure 4). This means that anticipatory saccades were not sufficient to foveate the later targets. Participants still had to perform additional saccades toward the target once it appeared to foveate it. Thus, although time-based expectancies can clearly be inferred from anticipatory saccades, the benefits derived from the observed anticipatory saccades might be limited. Within this regard, it has to be considered that in a more volatile environment, completely shifting one's attention toward an expected target location might not be the most efficient strategy due to the risk to miss other relevant stimuli. Moreover, it is typical especially for memory-guided saccades to undershoot remembered target locations substantially (see, e.g., Nuthmann, Vitu, Engbert, & Kliegl, 2016, for a recent demonstration). In the present experiment, the two possible target locations remained marked on screen. Nevertheless, time-based expectancy relied on the memory retrieval of time-event associations. As such, the substantial undershoots observed in the present experiment might be related to limitations observed for memory-guided saccades in other contexts.

A question that remains to be addressed in the context of anticipatory saccades and time-based task expectancy is why we

observed exactly the complex interaction pattern we did for the frequency cues in Experiment 2 (three-way interaction between interval part, frequency cueing, and task sequence cueing). At present, we speculate that the shift between the first and second interval part could possibly be driven by differences in the certainty of participants' expectations. During the first 500 ms, participants could prepare on the basis of time, but they could not be certain that their expectancy would accurately reflect the ultimate target position and task as the foreperiod could continue, requiring a shift in expectancies. After the short foreperiod had passed, however, both task and task frequency could be predicted with absolute certainty. Alternatively, or in addition to time-based changes in certainty, foreperiod duration itself might play a role. It is a well-known finding in task switching research that task switch costs reduce with longer cue-stimulus intervals (e.g., Koch, 2001, 2003; Meiran, 1996; Monsell & Mizon, 2006). In this context, anticipatory saccades might also be usable for assessing the temporal dynamics of task preparation (see Longman, Lavric, & Monsell, 2013, for a similar idea).

Although further studies will be necessary to elucidate these questions, the present findings indicated that the eye tracking paradigm we developed can be adapted to study the temporal dynamics of not only time-based location expectancy, but also other types of time-based expectancy. Thus, the present study presents a new eye tracking method for assessing time-based expectancies that can be applied in a variety of research contexts. One promising avenue for future research might, for instance, be the assessment of temporal dynamics in time-based valence (Thomaschke et al., 2018) or reward expectancy.

Furthermore, a comparison of the temporal dynamics of different types of time-based expectancy could provide new insights into the ease of retrieval of different types of foreperiod-event associations. By assessing anticipatory saccades, differences in the onset of time-based expectancies during the short foreperiod and in the time of shifts in time-based expectancies during the long foreperiod could, for instance, be used to gain new insights into retrieval mechanisms underlying different types of foreperiod-event associations.

Eye tracking is also especially suited to assess time-based expectancy in the human factors context, for instance, when humans interact with websites. In addition, as the present method of assessing time-based expectancy via anticipatory saccades also does not necessarily require participants to respond to temporally predicted stimuli as instructed to assess time-based expectancy, it can be used even on populations that cannot be assessed with common RT-based paradigms. Anticipatory saccades, thus, for instance, also allow for an investigation of time-based location and stimulus expectancies in young children or the elderly.

New Insights Into Time-Based Expectancy

In addition, as indicated, our findings corroborate the findings of Volberg and Thomaschke (2017) for time-based response expectancy by suggesting that time-based location and task expectancy apparently also shifts shortly after the short foreperiod has passed. This finding also indicates that participants' temporal expectation during the foreperiod mirrors objective time quite well.

A descriptive assessment of relative saccade frequencies over time revealed that shifts in participants' time-based expectancies closely matched the duration of the short foreperiod. Participants'

saccade directions on average shifted between 500 ms and 800 ms. However, relative saccade frequencies are also affected by the overall frequency of saccades in the given time interval around 500 ms and can therefore only provide an approximation of shifts in participants' time-based expectancies.

In addition to this descriptive assessment, we therefore examined the latency of participants' first expectancy-congruent saccade in the second interval part (501–1,500 ms) in trials with a long foreperiod. Here, participants' first expectancy-congruent saccades on average occurred about 470 ms after the end of the first interval part. Taking the time it takes to program a saccade (~150–200 ms) into account, participants' expectations, on average, shifted around 250 to 350 ms after the short foreperiod ended (at the earliest). This could be interpreted as evidence suggesting that temporal perception is not very accurate, whereas processes associated with time-based expectancy are ongoing. This idea fits the notion that attentional resources are necessary for precise timing (e.g., Block, Hancock, & Zakay, 2010; Brown, 1997). When attentional resources are not available, timing mechanisms are less precise (Ruthruff & Pashler, 2010). Thus, possibly the timing of temporal shifts in participants' time-based expectancy did not accurately reflect foreperiod duration, because attentional resources were allocated to the generation of expectations regarding target location (and/or upcoming task).

Interestingly, the mean latency of participants' first expectancy-congruent saccades during the first (0–500 ms) and second interval part (501–1,500 ms) of the foreperiod seemed to mirror the temporal relation between the two interval parts. During the first 500 ms, participants' first expectancy-congruent, anticipatory saccades occurred after about 230 ms on average. After the short foreperiod had passed, it took participants on average about 460 ms to perform their first anticipatory saccades. Thus, saccade latencies mirrored the 1:2 relation of the interval part durations. First, this supports the idea that participants' temporal expectations must be quite accurate. Otherwise, it is inconceivable how saccade latencies could reflect the relation of the interval part durations so accurately. In line with Thomaschke, Kunchulia, and Dreisbach (2015), this finding could also be taken as additional support for a relative rather than absolute representation of time in foreperiod-event associations and time-based expectancy. Nevertheless, it has to be taken into account that we arbitrarily split the long foreperiod into two parts (before and after the duration of the short foreperiod). As the long foreperiod provided participants with ample time, there was no pressure to bring their eyes to the target location fast. Thus, these findings are, at present, largely descriptive and should not be overinterpreted. Further experiments that systematically manipulate the relation between the duration of the short and long foreperiod as well as foreperiod durations themselves will be necessary to further unravel this pattern of results and draw conclusions about time-based expectancy from it.

Introspection and Time-Based Expectancy

Interestingly, in line with the findings of Aufschnaiter, Kiesel, Dreisbach, et al. (2018, see also Aufschnaiter et al., 2018), none of the participants were able to report the foreperiod–location or foreperiod–task contingencies when asked. Furthermore, although about half of the participants stated that they had observed that there were differences in foreperiod duration, none of them could even correctly report the number of foreperiods. These findings suggest that explicit knowl-

edge about foreperiod–location and/or foreperiod–task contingencies is not necessary for manual (see the [online supplemental materials](#)) as well as saccadic time-based expectancy effects to emerge.

This raises interesting questions regarding participants' introspections about the foreperiods and the relation between these introspections and participants' time-based expectancies. Our temporal judgments and introspections about time are not always accurate (e.g., Bratzke & Bryce, 2016; Bryce & Bratzke, 2017; Eagleman, 2008; Grondin, 2010) and there are interindividual differences in our introspective abilities (e.g., Hayashi, Kantele, Walsh, Carlson, & Kanai, 2014). These influences might not show in time-based expectancy effects. First, because behavioral investigations of time-based expectancy effects average across responses. Second, because the exactness of temporal perception and introspection might not become evident when clearly distinct foreperiods are used in experiments on time-based expectancy. In addition, it has been suggested that explicit timing (e.g., introspective judgments) and implicit timing (e.g., time-based expectancy effects) are processed in different parts of the brain (e.g., Coull & Nobre, 2008). However, using anticipatory eye movements, we can assess time-based expectancy in its time course. It would be of utmost interest to assess whether the degree to which participants' anticipatory saccades show time-based expectancy (i.e., relative saccade frequencies or saccade latencies) corresponds with the accuracy of a person's temporal perception (i.e., a person's explicit timing abilities). Such research could indicate to what degree time-based expectancy effects depend on a person's explicitly reportable introspections about time.

Temporal Cognition and the Brain

Furthermore, a preeminent question in research on temporal cognition is how time is represented in the brain. Interestingly, for instance, gray matter volume in different brain regions seems to be associated with timing abilities in the subsecond and suprasedond range, respectively (e.g., Hayashi et al., 2014). In the present experiments we used one subsecond (500 ms) and one suprasedond (1,500 ms) foreperiod duration and were able to observe shifts in time-based expectancy in the subsecond range. Future studies should compare different subsecond and suprasedond foreperiods to assess the time of shifts in time-based expectancy as evidenced by shifts in eye movement direction in different foreperiod time ranges. For instance, it would be interesting to see whether the timing of shifts in time-based expectancy between foreperiods in the suprasedond range is as precise as in the subsecond range. In manual responses, a recent study showed that participants can form time-based expectancies even when both foreperiods are from the sub-/suprasedond range (Aufschnaiter, Kiesel, & Thomaschke, 2019), establishing the preconditions for such investigations. In addition, correlations with participants' timing abilities and gray matter volume could further elucidate human temporal cognition in different time ranges. Thus, anticipatory saccades could complement locally precise but temporally imprecise studies regarding the localization of different aspects of temporal cognition in the brain.

Conclusion

To conclude, we present anticipatory saccades as a new method for assessing the temporal dynamics of time-based location expectancy as well as time-based task expectancy. Thus, we highlight spontaneous

eye movements as a window into cognitive processes that cannot be assessed otherwise. Future research can build on these findings to further explore, for instance, the time course of different types of time-based expectancy and the mechanism underlying them.

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