

The scope and precision of specific temporal expectancy: evidence from a variable foreperiod paradigm

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Abstract Recent evidence from choice response time experiments with variable foreperiods (FPs) has shown that temporal expectancy can be event specific. When a certain target appears particularly frequent after one certain FP, participants tend to expect that target after that FP. This typically results in best performance for that target when it appears after that FP. In the present study, we investigated how temporally precise event-specific temporal expectancy is, and in which range of FPs it can be found. Two target stimuli were asymmetrically distributed over two “peak-FPs” and were equally distributed over 13 additional FPs. Event-specific expectancies were found for peak-FP pairs of 500/1,100 ms and 300/500 ms. Furthermore, the event expectancies generalized to a wide range of nonpeak FPs surrounding the peak FPs.

Keywords Foreperiod · Temporal cognition · Preparation · Expectation

Among the most intensely researched topics in temporal cognition is the formation of temporal expectancies in a temporally uncertain environment. An often-applied experimental design in this research area is the foreperiod (FP) paradigm (Grondin & Rammsayer, 2003; Moore, 1904; Requin, Granjon, Durup, & Reynard, 1973). In a typical FP paradigm, participants perform speeded responses to an

imperative stimulus that is preceded by a warning stimulus. The FP is commonly defined as the interval between the onset of the warning stimulus and the onset of the imperative stimulus (Niemi & Näätänen, 1981; Van Elswijk, Kleine, Overeem, & Stegeman, 2007). Temporal expectancy is, in this context, measured as preparedness (i.e., correctness and speed of responses) at a certain point in time. When the FP is constant over blocks, there is no uncertainty concerning the temporal occurrence of the imperative stimulus. Consequently, temporal expectancies for the imperative stimuli are relatively precise and responses are, thus, relatively fast. In this scenario, response times (RTs) typically slow down when the duration of the FP is increased, because temporal expectancy gets less precise over time (Dwelshauvers, 1891; Müller-Gethmann, Ulrich, & Rinkenauer, 2003; Wundt, 1874).

However, in order to investigate how temporal expectancies are formed when stimuli are less clearly predictable as with constant FPs, many researchers have applied *variable FP* paradigms (e.g., Della Valle, 1908; Lohmann, Herbolt, Wagener, & Kiesel, 2009; Los & Agter, 2005; Steinborn, Rolke, Bratzke, & Ulrich, 2009). In variable FP paradigms, the FP varies from trial to trial, with the order of FPs unknown to the participant. RTs after variable FPs are usually longer than in constant FP experiments (Awramoff, 1903; Cardoso-Leite, Mamassian, & Gorea, 2009). Although the current FP on any trial is not clearly predictable in variable FP experiments, participants tend to exploit various sources of information to form temporal expectancies during each trial. When, for example, the identity of the warning signal is informative about the FP, participants tend to use the warning signal as a cue, resulting in faster responses after validly cued FPs than after invalidly cued FPs (Correa, Lupiáñez, Milliken, & Tudela, 2004; Kingstone, 1992; MacKay & Juola, 2007).

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Combination of expectancy and expectancy for combination

In everyday life, one does rarely expect an FP as such, irrespective of a specific event to appear. One usually has expectancies about what will happen in the future *and* about when it will happen. The majority of previous research on expectancy has, however, studied both aspects of expectancy in isolation. One line of research has studied expectancy for events, while keeping FPs constant or counterbalanced (e.g., Posner, 1980). Another line of research has focused on expectancies for certain points in time, while keeping the expected events constant or controlled (e.g., Los, Knol, & Boers, 2001).

Presently, only a few studies have investigated expectancies for events and expectancies for FPs in conjunction. Kingstone (1992), for example, devised a combined cuing paradigm to investigate how expectancies for events interact with expectancies for FPs. Two types of target stimuli (upright or inverted orientation) were equally often paired with either a short or a long FP. The FPs were preceded by a dual cue. One part of the cue predicted with 80% probability the type of target stimulus, and the other part predicted with 80% probability the FP. Kingstone found an interaction between expectancy for events and expectancy for FPs. Only with cued forms did participants react faster after cued FPs than after uncued FPs. With uncued forms, participants reacted even slower after cued FPs than after uncued FPs.

Although Kingstone (1992) studied how expectancies for events interact in combination with expectancies for points in time, other recent studies have investigated temporal expectation in a scenario in which the probability of a certain event is conditional on an FP and vice versa (Wagener & Hoffmann, 2010a, 2010b). Wagener and Hoffmann (2010b), for example, used a paradigm with unequal distributions of pairs of events and FPs. Two events (stimulus–response episodes in a binary forced choice task) appeared equally often. The events were preceded by two FPs, which also appeared equally often. Neither events nor FPs were cued. But, each of the events was paired on 80% of its occurrences with one of the FPs, and on only 20% with the other one. Participants adapted to those conditional probabilities by responding faster to frequent event-FP pairs than to infrequent event-FP pairs.

We refer to the adaptation to conditional event-FP probabilities with the term *specific* temporal expectancy, because in those designs, an FP is expected only in conjunction with a certain event, but is particularly unexpected in conjunction with another event. With the term *general* temporal expectancy, we refer to unconditional temporal expectancies, because those temporal expectancies are not dependent on a certain event to occur

(although they might be, and usually are, combined with a general expectancy for a certain event, or for an event to interact with it). The temporal expectancies, which were induced by one part of the cue in Kingstone's (1992) study, were in this sense general temporal expectancies. Although the dual cue predicted with 64% probability a combination of FP and event, the probability for a particular FP was not dependent on the probability of the event. No matter whether the unpredicted or the predicted event appeared, it was always 80% likely that it was preceded by the predicted FP. Kingstone's results suggest, however, that even when the probabilities for event and FP are independent of each other, participants form "combined" expectancies.

In the present study, we focused on specific temporal expectancy, in the sense of adapting to conditional event-FP probabilities. As a working model for specific temporal expectancy, we assume that stimulus–response events get associated to their characteristic FPs, over the course of the experiment, by a simple conditioning process. Associative accounts of temporal expectancy, based on conditioning models, have previously been proposed elsewhere (see, e.g., Gallistel & Gibbon, 2000; Los & Agter, 2005; Los et al., 2001). These associations of event and FP explain the specific temporal expectancy effects that were found in Wagner and Hoffmann's (2010a, 2010b) studies. When a stimulus–response event is associated to a certain FP, the combination of event and FP is more easily processed than are nonassociated combinations. Thus, performance was better for frequent than for infrequent target-FP combinations.

The aim of the present study was to extend our knowledge about specific temporal expectancy with regard to three essential aspects of the phenomenon. First, we investigated the resolution of specific temporal expectancy. We asked, how far must two FPs be temporally separated to allow association of two distinct events to them via specific temporal expectancy? Second, we aimed to determine whether specific temporal expectancy can also be built for relatively short FPs below 500 ms. And third, we investigated the temporal generalization of specific temporal expectancy, by testing whether specific temporal expectancy for a certain event-FP combination also extends to other nearby FPs.

Resolution and range of specific temporal expectancy

With regard to the resolution of specific temporal expectancy, we manipulated the *inter-FP span*. With the term *inter-FP span*, we refer to the temporal distance between two FPs that are associated to different events via specific temporal expectancy. Previous studies of distribution-based specific temporal expectancy have applied *inter-FPs spans* of at least 800 ms (Wagener & Hoffmann, 2010a, 2010b).

Several studies in general temporal expectancy have, however, shown temporal orientation to FPs that are separated by considerably less than 800 ms. For example, Sanders and Astheimer (2008) recently showed that participants can easily explicitly reorient their general temporal expectancy, on a trial-by-trial basis, between FPs of 500, 1,000, and 1,500. In order to test specific temporal preparation for shorter inter-FP spans, we used, in two separate experiments, FP-pairs of 500 ms and 1,100 ms, and of 300 ms and 500 ms. This allowed us to test whether specific temporal expectancies can be built for FP-event combinations when the FPs are separated by 600 ms and by only 200 ms.

With regard to the absolute FP durations in specific temporal expectancy, previous studies have applied FPs in the range from 500 ms to 1,600 ms. It has, however, been doubted that any form of temporal expectancy—general or specific—can be built for FPs much shorter than 500 ms. Some authors in the general temporal expectancy literature have suggested that temporal expectancy operates only on a time scale above 500 ms, whereas shorter FPs facilitate performance rather by general arousal induced by the warning signal instead of expectancy (see, e.g., Hackley et al., 2009; Lewis & Miall, 2009; Matthias et al., 2010).

On the other hand, some studies have shown instances of temporal expectancy for a series of very short intervals (Bertelson, 1967; Pecenka & Keller, 2009).

In order to investigate whether event-specific temporal expectancy is restricted to FPs above 500 ms, or whether it can, on the contrary, also be found with shorter FPs, we chose a pair of very short FPs (300 ms and 500 ms) for the second experiment.

Generalization in specific temporal expectancy

Our experiments addressed a third aspect of distribution-based specific temporal expectancy, namely the potential generalization of specific temporal expectancy to temporal regions around the pair of FPs. When the high frequency of a combination of a certain event (e.g. a right keypress in response to a square) with a certain FP (e.g., 600 ms) induces a strong specific temporal expectancy for that event at that FP, does this expectancy also extend to other nearby points in time (e.g., 500 ms, or 700 ms after the warning signal), in the sense that the event is also expected at 500 ms and 700 ms despite having appeared only rarely or never after 500 ms or 700 ms? Or, is specific temporal expectancy for a certain event restricted to exactly that FP it was frequently coupled with? Put another way, can the high frequency of an event at one FP induce specific temporal expectancy at a nearby FPs at which it was not frequent? Previous studies on specific temporal expectancy (Wagener

& Hoffmann, 2010a, 2010b) have provided no evidence of whether specific temporal expectancy generalizes in such a way. Those studies applied only two distinct FPs, which induced specific temporal expectancy, but did not measure performance at a nearby point in time.

The present study overcomes this limitation by using a wider range of FPs than just two. Our experiments do also involve one pair of FPs, which induces specific temporal expectancies. One of those FPs occurs predominantly with one stimulus–response event, and the other one appears predominantly with a different event. We will refer to this pair of FPs from now on with the term *peak-FPs*, because one of the events is peak distributed at each of them. In Experiment 1, for instance, one stimulus–response event occurred 48 times per block after the peak FP of 500 ms and only two times at 1,100 ms, whereas the other event occurred 48 times at 1,100 ms and only once at 500 ms. But, in addition to these peak FPs, we also used 13 additional nonpeak FPs surrounding the pair of peak FPs. At the nonpeak FPs, both events appeared equally often, namely only once per block each. Trials with the nonpeak FPs did not induce any specific temporal expectancy, because event-FP combination with both events appeared equally often. Performance on the nonpeak FPs did, however, allow us to measure how temporally precise the specific temporal expectancy induced by the pair of peak FPs was scheduled to exactly those peak FPs.

We hypothesized that specific temporal expectancy would generalize to nearby points in time. There is related evidence from studies in general temporal expectancy. If a peak FP among a broad range of FPs is highly frequent (independent of the event after that FP), then performance on neighboring FPs usually also benefits (e.g., Karlin, 1966; Nickerson, 1967). Thus, temporal expectancy that has been induced by the high frequency of one particular FP is not precisely scheduled to exactly that particular FP.

Weber's law in specific temporal expectancy

The use of different inter-FP spans in different temporal regions allowed us to estimate whether the resolution of specific temporal expectancy relates to the absolute lengths of the involved FP pair. There is cumulative evidence, mostly from studies of explicit time estimation, for the dependence of the resolution of temporal cognition on absolute FP length (e.g., Killeen & Weiss, 1987). Those studies measure how accurately participants estimate time intervals (either by reproduction of an observed one, or by comparison with another observed reference interval). The common finding is that time estimation complies with Weber's law. That means that the fraction of the standard deviation of participants' estimates and the absolute interval

length is constant along different interval lengths. This regularity seems to obtain at least in the range between 200 ms and 2,000 ms (see, e.g., Getty, 1975; Grondin, 2001). Because time estimation plays a crucial role in general temporal expectancy, we assume that Weber's law for time estimation also affects specific temporal expectancy. Building up specific temporal expectancies for a pair of FP event combinations relies on the ability to discriminate between both FPs to a certain degree. Thus, we hypothesized that the magnitude of a specific temporal expectancy effect is affected by the ability to discriminate between the involved FP pair. When one assumes that the distinctiveness of two FPs complies with Weber's law, it follows that specific temporal expectancy effects of equal magnitude can be predicted only for FP pairs with equal Weber-fractions (i.e., with an identical ratio between the inter-FP span and the mean FP duration). When the Weber fraction for one FP pair is larger than for another FP pair, one should expect a larger effect for a specific temporal expectancy effect at the former one. Thus, we chose FP pairs with different Weber fractions for both experiments.

Our hypothesis can be extended by a further potential instantiation of Weber's law in the context of generalization of the specific temporal expectancy effect. A source of the expected generalization of specific temporal expectancy could be imprecision in the estimation of the peak FPs. According to Weber's law, this inaccuracy increases linearly with absolute length of the FP (Getty, 1975). Consequently, we expect a wider generalization of specific temporal expectancy for longer peak FPs than for shorter peak FPs. The target distribution at longer peak FPs should also affect performance at FPs rather far apart from them, whereas shorter peak FPs should affect performance only in their nearer temporal vicinity.

Experiment 1

In a speeded choice response experiment, two targets are unequally distributed over two peak FPs (500 ms and 1,100 ms), so that one target is frequently coupled with the short FP and the other target is frequently coupled with the long FP. On 13 additional FPs, from 100 ms to 1,500 ms, both targets appear with equal frequency. Experiment 1 had three main aims. First, we wished to confirm that specific temporal expectancy can also be built for an inter-FP span as low as 600 ms. Second, we attempted to investigate whether specific temporal expectancy generalizes to an FP other than the peak FPs. Third, we intended to investigate whether a potential generalization effect was due to timing imprecision. Because the precision of time estimation accords to Weber's law, the generalization should be more pronounced around the longer than around the shorter FP.

Method

Participants Eight females and four males (mean age = 23.00, $SD = 5.97$) received €5 each for participation.

Apparatus and stimuli Stimulus presentation and response collection were performed by an IBM-compatible computer with a 17-in. VGA display controlled by E-Prime (Schneider, Eschman, & Zuccolotto, 2002). A response box (Psychology Software Tools) was positioned centrally in front of the monitor. Responses were made by participants' dominant hand on two adjacent buttons of the response box. The buttons were operated by the index and middle fingers. Stimuli were a white-filled square and a white-filled circle displayed on a dark gray background. The stimuli were centrally presented and subtended an area of about 2×2 cm. The "+" symbol (Arial typeface, 1.3 \times 1.3 cm) served as a fixation cross.

Procedure Participants were instructed to respond as fast and as accurately as possible to the target stimuli. One group of participants had to respond with the left button to the circle and with the right button to the square. For another group of participants, this mapping was reversed. Participants were informed that the interval between the fixation cross and the target stimulus would vary randomly. Participants were not, however, informed about which possible FPs there were and about how those were distributed. Each trial began with the presentation of a fixation cross for the duration of the current FP. When the FP had elapsed, the fixation cross was substituted by the target stimulus. The target disappeared when a response was detected. During the intertrial interval of 500 ms, the screen was blank. The intertrial interval was defined from the participant's response in Trial n until the onset of the fixation cross in Trial $n + 1$. When participants responded incorrectly, or later than 1,000 ms, the words "falsche Taste" (German for "wrong key"), or "bitte schneller" (German for "faster, please") were displayed for 1,000 ms.

FPs ranged from 100 ms to 1,500 ms in steps of 100 ms. Each FP was paired with each target symbol. One target appeared 46 times per block at the 500-ms FP (referred to as the *early peak target*, from here on), whereas the other one appeared 46 times per block after the 1,100 ms FP (referred to from here on as the *late peak target*). All other combinations of targets and FPs appeared only once per block.

The order of trials (i.e., which combination of FP and target appeared on each trial) was randomized within each block of 120 trials. We counterbalanced across participants which target appeared frequently after 500 ms and which one appeared frequently after

1,100 ms. The experiment consisted of eight blocks, separated by pauses of 1 min.

Results

Mean percentages of errors (late and wrong responses) and mean RTs for nonerror trials were calculated for each combination of FP (ranging from 100 ms to 1,500 ms) and target (see Fig. 1).

Expectancy at peak FPs In order to analyze whether the different distribution of both targets over the peak FPs affected the target-specific expectancies at those FPs, we computed a 2×2 ANOVA with the factor peak FP (early FP = 500 ms vs. late FP = 1,100 ms), the factor target (500-peak target vs. 1,100-peak target), and average RT as the dependent variable. Neither the main effect for target, $F(1, 11) = 0.36, p = .559$, Cohen's $d = 0.16$,¹ nor the main effect for FP, $F(1, 11) = 4.51, p = .057, d = 0.57$, were significant. A significant interaction between both factors, $F(1, 11) = 27.50, p < .001, d = 1.41$, revealed a time–event-specific expectancy effect. Post hoc tests showed that the event-specific expectancies had been built at both peak FPs: RTs at the short peak FP (i.e., 500 ms) were, on average, faster for the target that appeared frequently at the short FP (484 ms, $SD = 53$) than for the target that appeared only rarely at the short FP (520 ms, $SD = 43$), $t(11) = 1.75, p = .035, d = 0.64$. At the longer peak FP (i.e., 1,100 ms), responses were faster for the target that appeared frequently at the long FP (459 ms, $SD = 57$) than for the target that appeared frequently at the short FP (513 ms, $SD = 54$), $t(11) = 2.81, p = .017, d = 0.76$.

An analogous ANOVA was conducted for mean percentages of errors. The interaction between FP (500 ms vs. 1,100 ms) and target (500-peak target vs. 1,100-peak target) was significant, $F(1,11) = 11.68, p = .006, d = 0.92$. Post hoc tests revealed that the percentages of errors significantly differed only at the late peak FP. At the FP of 1,100 ms, fewer errors were made for the target that appeared frequently at 1,100 ms (4.87%, $SD = 3.87$) than for the target that appeared infrequently after 1,100 ms (15.49%, $SD = 10.21$), $t(11) = 3.10, p = .001, d = 0.83$. At the 500-ms FP, the percentage of errors did not significantly differ for the target that appeared frequently at 500 ms (4.85%, $SD = 2.57$) and the target that appeared only rarely after 500 ms (5.00%, $SD = 6.74$), $t(11) = 0.08, p = .938, d = 0.02$.

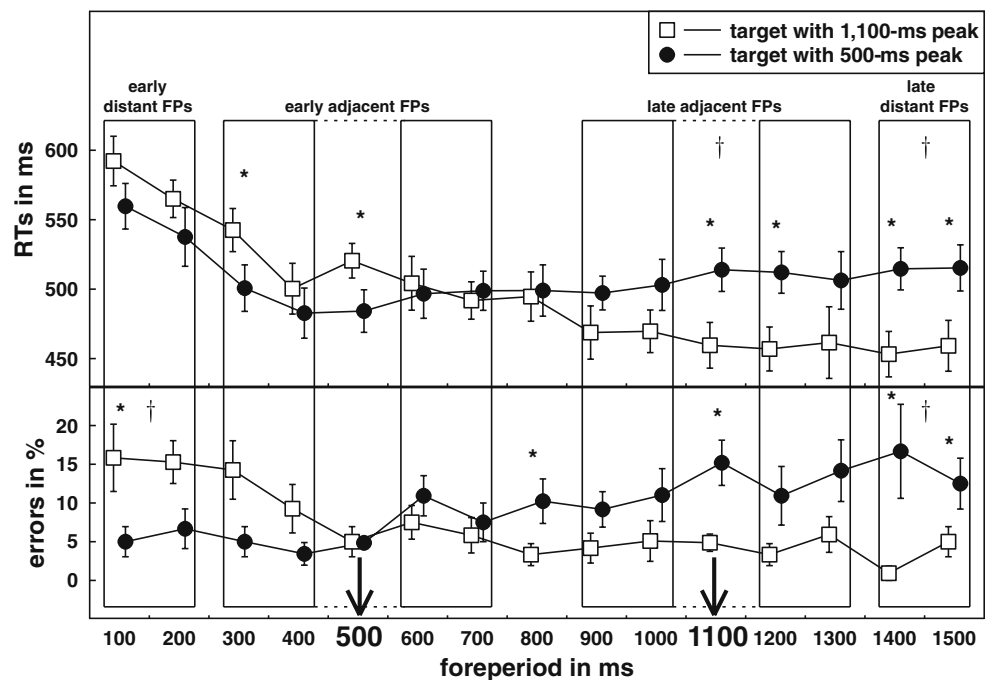
Generalization Next, we analyzed whether the distribution of targets over both peak FPs also affected the event-specific expectancies at the FPs adjacent to the peak FPs. The temporal region surrounding the early peak FP (500 ms) was represented by the average of the mean RTs at the four FPs nearest to 500 ms (i.e., 300, 400, 600, and 700 ms; see Fig. 1). The temporal vicinity of the late peak FP was represented by the average of the four FPs nearest to 1,100 ms (i.e., 900, 1,000, 1,200, and 1,300 ms). An ANOVA with the factors FP region (around 500 ms vs. around 1,100 ms) and target (500-peak target vs. 1,100-peak target) was conducted. The interaction was significant, $F(1, 11) = 18.32, p = .001, d = 1.15$, suggesting that the effects of the target distributions at the peak FPs are not restricted to performance at the peak FPs, but that, instead, target distribution also affects performance at the FPs surrounding the peak FPs. Post hoc tests for both FP regions revealed that the interaction was mainly due to performance differences at the region around the long FP. At the temporal region around 1,100 ms, responses were faster for the target that was peak distributed at 1,100 ms (464 ms, $SD = 57$) than for the target that appeared only rarely at 1,100 ms (505 ms, $SD = 47$), $t(11) = 2.63, p = .023, d = 0.71$. In the temporal region around 500 ms, the RTs for the 500-peak target (495 ms, $SD = 52$) were not significantly different from the RTs for the 1,100-peak target (509 ms, $SD = 49$), $t(11) = 1.37, p = .198, d = 0.37$.

Another ANOVA was conducted in order to determine whether the different target distributions at the peak FPs affected RT performance even at FPs that were temporally rather far away from the peak FPs. The factors were, again, FP region and target. The early-FP region was defined by the average of the RTs at 100 ms and 200 ms (see Fig. 1). The late-FP region was defined by the average of the RTs at the FPs of 1,400 ms and 1,500 ms. The main effect for FP was significant, $F(1, 11) = 121.89, p < .001, d = 2.96$, indicating faster responses at the longest FPs than at the earliest FPs. Furthermore, the interaction between FP and target reached significance, $F(1, 11) = 27.55, p < .001, d = 1.41$, suggesting that the different distribution of targets over the peak FPs affected performance even in temporally fairly distant time windows. The difference was more pronounced at the long-FP region than at the short-FP region. At the longest FPs, responses were faster for the target that was peak distributed at 1,100 ms (456 ms, $SD = 56$) than for the 500-peak target (515 ms, $SD = 53$), $t(11) = 3.48, p = .005, d = 0.93$. At the shortest FPs, the difference between responses for the 500-peak target (549 ms, $SD = 63$) and the 1,100-peak target (579, $SD = 49$) was marginally significant, $t(11) = 1.98, p = .073, d = 0.53$.

Two analogous ANOVAs were conducted for error rates. The ANOVA with the factors target (500-peak target vs. 1,100-peak target) and FP region (region around 500 ms vs.

¹ Effect sizes have been derived and corrected for bias according to Gibbons, Hedeker, and Davis (1993; Equations 3, 17, and 19).

Fig. 1 Mean response times (RTs, in milliseconds) and mean percentages of errors depending on FP. *Empty squares* represent the target that was peak distributed at 1,100 ms, and *filled circles* represent the target that was peak distributed at 500 ms. Peak FPs are printed in bold (see arrows). *Asterisks* mark significant differences (α -level=.05) for *t* tests at the individual FP. *Daggers* mark significant differences (α -level=.05) for groups of FPs, circumscribed by *boxes*, or by *pairs of boxes*. *Error bars* represent ± 1 SE



region around 1,100 ms, defined as above) showed a significant interaction, $F(1, 11) = 6.23, p = .030, d = 0.67$, indicating that the target distribution over peak FPs affects performance at FPs surrounding the peak FPs. Around the short peak FP, the average error rate for the 500-peak target (6.71%, $SD = 4.45$) did not significantly differ from the error rate for the 1,100-peak target (9.21%, $SD = 6.66$), $t(11) = 1.08, p = .302, d = 0.29$. Around the long FP, the difference between the error rate for the 500-peak target (11.32%, $SD = 9.67$) and the error rate for the 1,100-peak target (4.63%, $SD = 3.67$) was marginally significant, $t(11) = 1.91, p = .082, d = 0.51$.

A second ANOVA for error rates was conducted with the factors target (500-peak target vs. 1,100-peak target) and distant FP region (see Fig. 1). The factors interacted significantly, $F(1, 11) = 16.15, p = .002, d = 1.08$. At the earliest FPs (100 ms and 200 ms), fewer errors were made with the target that was peak distributed at 500 ms (5.83%, $SD = 5.97$) than with the target that was peak distributed at 1,100 ms (15.56%, $SD = 8.11$), $t(11) = 3.23, p = .008, d = 0.87$. At the latest FPs (1,400 ms and 1,500 ms), participants made fewer errors with the target that was peak distributed at 1,100 ms (2.96%, $SD = 3.38$) than with the target that was peak distributed at 500 ms (14.58%, $SD = 14.38$), $t(11) = 3.07, p = .011, d = 0.82$.

Discussion

The results of Experiment 1 confirmed our hypotheses in three important points. First, analyses of RTs and error rates uniformly showed better performance for frequent event-FP

couplings than for infrequent ones, confirming that specific temporal expectancy can be built for an inter-FP-span as low as 600 ms. Second, the specific temporal expectancy effect was not restricted to the peak FPs, but also generalized to the temporal regions around the peak FPs. RT and error data showed that expectancy for an event that appeared frequently at a certain FP was also increased at other nearby FPs. The generalization effect had a considerable spread, and was observed even 400 ms apart from the peak FPs. Third, the generalization was stronger around the long FP than around the short FP. With regard to adjacent FPs (FPs in a time window of ± 200 ms around the peak FPs), the specific temporal expectancy effect around the short FP was significant neither in RTs nor in error rates. Around the long peak FP, the effect was significant in RTs and marginally significant in error rates. A similar pattern was observed for distant FP regions (FPs in a time window of 300 ms to 400 ms before the short FP, and 300 ms to 400 ms after the long FP). Although the specific temporal expectancy effect was significant at both distant regions with regard to error rates, it was significant only in the late region with regard to RTs. When one assumes that the generalization of specific temporal expectancy to surrounding FPs is partly due to imprecision of FP estimation, these results are in accordance with Weber's law. Weber's law proposes that precision of temporal estimation decreases with absolute interval length. Consequently, generalization of the specific temporal expectancy effect increases with absolute FP length.

In sum, all hypotheses have been confirmed by the data. Specific temporal expectancy can be built for inter-FP spans as low as 600 ms, does generalize to regions as far as

400 ms away from peak FPs, and this generalization is stronger at longer than at shorter FPs.

Experiment 2

In Experiment 2, the inter-FP span between the peak-FPs was reduced to only 200 ms, and the peak FPs were both very short (300 ms and 500 ms). In Experiment 2, we had three main aims. First, we attempted to test whether specific temporal expectancy can also be built for a very short inter-FP span in a very short FP region. Second, we wished to investigate whether the strength of a potential specific temporal expectancy effect varies with inter-FP span and absolute FP length, by comparing the data with those of Experiment 1. According to Weber’s law, the ability to discriminate between two FPs is proportional to the inter-FP span divided by the mean absolute FP length. Because this fraction is lower in Experiment 2 (inter-FP span / mean FP duration = 200 ms / 400 ms = 1/2) than in Experiment 1 (600 ms / 800 ms = 3/4), the ability to distinguish between both peak FPs should be reduced in Experiment 2 relative to Experiment 1. Because we assume the ability to discriminate between both peak FPs to be an important precondition for building specific temporal expectancy at those FPs, we hypothesize that the specific temporal expectancy effect should be less pronounced in Experiment 2 as compared with Experiment 1. Third, we wished to validate the results from Experiment 1 concerning generalization of the specific temporal expectancy effect in a setting with shorter FPs and a shorter inter-FP span. Does specific temporal expectancy also generalize to nearby

points in time when the peak FPs are very short, and is a potential generalization effect also stronger at later FPs?

Method

Participants Eleven females and one male (mean age = 22.83, SD = 3.30) received €5 each for participation.

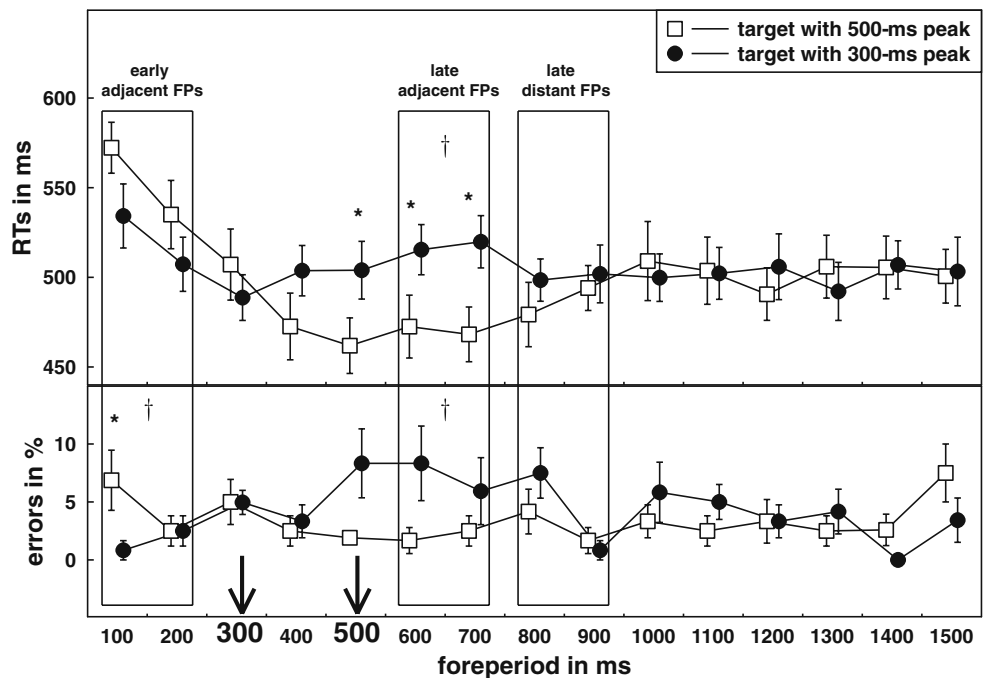
Apparatus, stimuli, and procedure The apparatus, the stimuli, and the procedure were identical to the ones used in Experiment 1, with the only exception that both targets were differently distributed over FPs. One target appeared 46 times per block at 300 ms and only once per block at every other FP. The other target appeared 46 times per block at 500 ms and only once at every other FP.

Results

Mean percentages of errors, and mean RTs for nonerror trials have been calculated for each combination of FP (ranging from 100 ms to 1,500 ms) and target (see Fig. 2).

Expectancy at peak FPs In order to analyze whether the different distributions of targets over both peak FPs affected the response latency at these FPs, an ANOVA with the factors target (300-peak target vs. 500-peak target) and FP (300 ms vs. 500 ms) was conducted. These factors

Fig. 2 Mean response times (RTs, in milliseconds) and mean percentages of errors in dependence on FP. Empty squares represent the target that was peak distributed at 500 ms, and filled circles represent the target that was peak distributed at 300 ms. Peak FPs are printed in bold (see arrows). Asterisks mark significant differences (α -level=.05). Daggers mark significant differences (α -level=.05) for groups of FPs, circumscribed by boxes. Error bars represent ± 1 SE



interacted, $F(1, 11) = 30.84$, $p < .001$, $d = 1.49$, indicating event-specific temporal expectancy at the peak FPs. This effect was mainly due to RT differences at the long peak FP. At 500 ms, responses to the 500-peak target (462 ms, $SD = 44$) were faster than responses to the 300-peak target (504 ms, $SD = 56$), $t(11) = 2.85$, $p = .016$, $d = 0.77$. At 300 ms, RTs for the 300-peak target (488 ms, $SD = 44$) and RTs for the 500-peak target (507 ms, $SD = 69$) did not differ significantly, $t(11) = 1.04$, $p = .320$, $d = 0.28$.

Analogous analyses have been conducted for error rates. An ANOVA with the factors target (300-peak target vs. 500-peak target) and peak FP (300 ms vs. 500 ms) yielded no significant interaction, $F(1, 11) = 2.93$, $p = .115$, $d = 0.46$. At the 300-ms FP, the error rates for the 300-peak target (4.96%, $SD = 3.61$) did not significantly differ from the error rates for the 500-peak target (5.00%, $SD = 6.72$), $t(11) = 0.02$, $p = .984$, $d = 0.01$. At the 500-ms FP, the difference between error rates for the 300-peak target (8.33%, $SD = 10.30$) and for the 500-peak target (1.19%, $SD = 1.27$) was marginally significant, $t(11) = 2.20$, $p = .050$, $d = 0.59$.

Generalization We further analyzed whether the distribution of targets over the peak FPs affected the performance at FPs next to the peak FPs. To this end, we averaged the performance for two pairs of nonpeak FPs. A total of 100 ms and 200 ms formed the “early adjacent region” (see Fig. 2), and 600 ms and 700 ms formed the “late adjacent region.” An ANOVA with the factors target (300-peak target vs. 500-peak target) and temporal region (early adjacent region vs. late adjacent region) was computed. A significant interaction, $F(1, 11) = 31.31$, $p < .001$, $d = 1.50$, revealed that the specific temporal expectancy effect spread to FPs adjacent to the peak FPs. This effect was more pronounced at the late adjacent region than at the early adjacent region. At the late adjacent region, responses were faster for the 500-peak target (470 ms, $SD = 51$) than for the 300-peak target (518 ms, $SD = 45$), $t(11) = 3.52$, $p = .005$, $d = 0.95$. At the early adjacent region, the difference between response latencies for the 300-peak target (521 ms, $SD = 53$) and response latencies for the 500-peak target (553 ms, $SD = 55$) was marginally significant, $t(11) = 1.87$, $p = .089$, $d = 0.50$.

We also analyzed whether the distribution of targets over FPs also affected FP regions rather far away from the peak FPs. To this end, we grouped the mean RTs and error rates for the FPs of 800 ms and 900 ms together (the late distant FP region).

Because of the short duration of the early FP, there were no FPs earlier than the early FP that were not already covered by the previous analysis on the adjacent FP areas. Consequently, we tested for a specific temporal expectancy effect in distant areas only for the late FP. In the late distant FP area, the RTs were not significantly shorter for the 500-

peak target (487 ms, $SD = 51.14$) than for the 300-peak target (500 ms, $SD = 44.10$), $t(11) = 0.821$, $p = .429$.

With regard to error rates, the ANOVA with the factors target (300-peak target vs. 500-peak target) and temporal region (early adjacent region vs. late adjacent region) revealed a significant interaction, $F(1,11) = 8.15$, $p = .016$, $d = 0.77$. At the early adjacent region, fewer errors were made for the 300-peak target (1.67%, $SD = 2.46$) than for the 500-peak target (4.69%, $SD = 3.99$), $t(11) = 2.59$, $p = .025$, $d = 0.70$. At the late adjacent area, fewer errors were made for the 500-peak target (2.08%, $SD = 3.34$) than for the 300-peak target (7.13%, $SD = 8.22$), $t(11) = 2.24$, $p = .047$, $d = 0.60$.

At the late distant FP region, error rates were not significantly lower for the 500-peak target (2.92%, $SD = 3.97$) than for the 300-peak target (4.17%, $SD = 4.69$), $t(11) = 0.821$, $p = .429$.

Weber's law Finally, we compared the effect magnitudes of both experiments. A mixed ANOVA with the factors experiment and frequency of combination was conducted, comparing performance for infrequent time–event combinations with performance for frequent time–event combinations in both experiments. Only performance on peak FPs was considered in this comparison. There was no significant difference between both experiments in RTs [interaction: $F(1, 22) = 2.171$, $p = .155$] or error rates [interaction: $F(1, 22) = 0.675$, $p = .420$].

Discussion

Our main hypothesis was confirmed by the RT data. A significant interaction between the factors peak FP and target showed that specific temporal expectancy can also be built for an inter-FP span of only 200 ms. This effect was, however, not visible in the error data. With regard to error rates, the specific temporal expectancy effect was found only for the relatively long 500-ms FP, and there it was only marginally significant. Furthermore, our data confirmed that specific temporal expectancy can be built for FPs as short as 200 ms. Note, however, that specific temporal expectancy was not found at the peak FP of 300 ms, but at the group of nonpeak FPs next to it (100 and 200 ms). This pattern is in accordance with previous studies on general temporal expectancy. These studies applied peak FPs and found the best performance to be often next to the peak FP instead of exactly at the peak FP (e.g., Baumeister & Joubert, 1969; Karlin, 1966). Our second hypothesis, that the strength of the specific temporal expectancy effect would be stronger in the first than in the second experiment, was not confirmed.

The finding from the previous experiment concerning generalization of the specific temporal expectancy effect was validated in the present experiment. RTs and error rates have consistently revealed that performance at FPs in the close vicinity of the peak FPs is also affected by the distribution of targets over peak FPs. As in Experiment 1, the generalization was more pronounced around the longer peak FP than around the shorter peak FP. The generalization effect did not, in contrast with Experiment 1, extend more than 200 ms away from the peak FPs. Neither error rates nor RTs were influenced by target, when measured more than 200 ms after the long peak FP.

In sum, results from Experiment 1 were fully replicated with even shorter FPs and with an even shorter inter-FP span, whereas an interexperiment comparison concerning effect magnitude was, contrary to our expectation, not significant.

General discussion

We conducted two speeded choice-response experiments, in which two target stimuli were differently distributed over 15 variable FPs. Each target was peak distributed at one of two peak FPs and was equally distributed at the other FPs. Peak FPs were 500 ms and 1,100 ms in Experiment 1, and 300 ms and 500 ms in Experiment 2. Participants adapted their responses to the distribution of targets over FPs (i.e., specific temporal expectancy occurred) in both experiments.

Analyses of response data revealed four main findings concerning specific temporal expectancy. First, specific temporal expectancy has a relatively high resolution. This means that specific temporal expectancy can be built with inter-FP spans of only 200 ms. Second, specific temporal expectancy affects behavior for very short FPs under 300 ms. Third, the effect is not precisely scheduled to the peak FPs, but also generalizes to regions as far as 400 ms apart from the peak FPs. Fourth, the precision of specific temporal expectancy (but not its resolution) seems to be affected by Weber's law for time estimation. Before integrating our findings in the broader context of temporal expectancy, we discuss each main finding in more detail.

Range and resolution

With regard to the range of time–event-specific expectancy, the present experiments have shown that the event-specific temporal expectancy effect exists for a broad range of FPs, from at least 200 ms to at least 1,500 ms. That specific temporal expectancy can be built at very early times after a warning signal is in line with earlier findings that have shown preparation phenomena for very short FPs (e.g., Bertelson, 1967; Pecenka & Keller, 2009). Yet, our results challenge models that assume that very short FPs can affect only

responses via arousal by the warning signal (e.g., Hackley et al., 2009), because arousal is, by definition, not event specific.

With regard to resolution, event-specific expectancy has previously been shown only with an inter-FP span above 700 ms (Wagner & Hoffmann, 2010a, 2010b). The present study has provided evidence for specific temporal expectancy with considerably lower FP spans. Experiments 1 and 2 have clearly shown that an expectancy effect is present in error rates and RTs with an inter-FP span of 600 ms, or even of 200 ms.

Generalization

In contrast with previous studies on specific temporal expectancy, we applied, in addition to two peak FPs, 13 FPs at which both targets appeared equally often. Those FPs allowed us to measure whether specific temporal expectancy is restricted to only the peak FPs, or whether it also generalizes to nearby points in time. We found generalization effects in both experiments, in a range of ± 200 ms around the peak FP.

To investigate the extensions and the boundaries of generalization in the specific temporal expectancy effect, we also analyzed for specific expectancy at temporal regions farther apart than 200 ms from the peak FPs. In Experiment 1, we found specific temporal expectancy in the entire spectrum of FPs, ranging from 100 ms to 1,500 ms. Thus, the effects can spread out to points in time at least 400 ms apart from a peak FP. Whether generalization goes even beyond 400 ms could not be assessed, due to the limited range of FPs used. The results of Experiment 2 were, however, different in this respect. A comparison of event expectancy at 300 ms and 400 ms after the longer peak FP of 500 ms confirmed no specific temporal expectancy effect in this late temporal region. The latter result allows us to further refine our working model of time–event associations. The absence of a specific expectancy effect 400 ms after the late peak FP suggests that events are indeed associated to the FP that they frequently appeared after, and not merely to a binary early/late category around the median of the peak FPs, as some other models have suggested (see Brown, McCormack, Smith, & Stewart, 2005; Kunde & Stöcker, 2002). If events would have been associated to binary early/late categories, then the specific temporal expectancy effect should have become even stronger—instead of disappearing—until the end of the FP spectrum in Experiment 2 (Brown et al., 2005).

Weber's law of time estimation

We hypothesized that Weber's law of time estimation affects event-specific temporal expectancy's resolution as

well as its precision. With regard to the resolution of the effect (i.e., the dependence of the effect on the inter-FP span), we expected a stronger specific temporal expectancy effect in the first experiment (with peak-FPs of 500 ms and 1,100 ms) than in the second experiment (with 300 ms and 500 ms). According to Weber's law, the ability to discriminate between a pair of FPs is proportional to the fraction of the inter-FP span and the absolute FP length. This fraction was larger in Experiment 1 than in Experiment 2. When one assumes that the ability to discriminate between the peak-FP is proportional to the strength of a specific temporal expectancy effect, then it follows that the effect should be stronger in Experiment 1 than in Experiment 2. We did not, however, observe any significant differences in effect strength between both experiments.

This suggests that the ability to discriminate between both peak FPs is not the major factor determining the effect magnitude in specific temporal expectancy. This conclusion should, however, be taken with caution, for mainly two reasons. First, the manipulation of Weber fractions between Experiment 1 and Experiment 2 was rather moderate (.75, and .5 respectively) in our study. To obtain full clarity on the impact of the Weber fraction on effect magnitude in specific temporal expectancy, a comparison between experiments with a more substantial difference in Weber fractions would be required. Second, an alternative explanation for an assumed absence of a difference could be that Weber's law does not perfectly hold for FP discrimination in the present paradigm. Despite a considerable amount of evidence for the applicability of Weber's law to temporal cognition (see, e.g., Getty, 1975; Grondin, 2001), there are some recent studies doubting the universality of Weber's law for any time-estimation paradigm and temporal region (e.g., Bizo, Chu, Sanabria, & Killeen, 2006; Grondin & Killeen, 2009). Grondin (2010), for example, recently found the Weber fraction to be lower at 200 ms than at 1,000 ms—two intervals comparable to the ones used in the present study.

Our hypothesis concerning another application of Weber's law to specific temporal expectancy has, however, been confirmed. The imprecision of specific temporal expectancy (i.e., the spread of event expectancy around a peak FPs) was more pronounced at longer FPs than at shorter FPs. This pattern was found in both experiments and is in accordance with Weber's law. As FPs get longer, specific event expectancy can less precisely be scheduled to the peak FP; thus, the temporal spread of the expectancy effect gets wider. The applicability of Weber's law to the precision of specific temporal expectancy suggests that the imprecision of FP estimation is the major cause of the generalization effect.

Motor and perceptual components in specific temporal expectancy

One obvious and important question about event-specific temporal expectancy has not been touched by the experiments in this study. It has not been clarified, yet, which aspect of the stimulus–response event is expected in event-specific temporal expectancy. One explanation for the performance advance for frequent, relative to infrequent, FP-event combination might be that participants visually expected the peak-distributed target at its characteristic peak FP, in the sense of preparing their visual systems for processing the peak-distributed target (e.g., a square). Such perceptual preparation could speed up the perceptual process and make it less error prone for the prepared target symbol. Thus, performance was better on trials with a symbol that was expected at its time of occurrence than on trials with a symbol that was unexpected at that time.

Research on general temporal expectancy has shown that it is possible to prepare the perceptual system for processing stimuli after a certain FP, in the sense of more accurate perception at expected points in time, relative to unexpected points in time (Bausenhardt, Rolke, & Ulrich, 2007; Lange, 2009; Rolke, 2008; Rolke & Hofmann, 2007; Seifried, Ulrich, Bausenhardt, Rolke, & Osman, 2010). Lange, Rösler, and Röder (2003), for instance, showed by EEG recordings that explicitly scheduling auditory attention to FPs of 600 ms and 1,200 ms—FPs similar to the peak FPs used in the present study—induced an enhanced N1. This EEG component has previously been shown to reflect amplification of early sensory input (Hillyard, Vogel, & Luck, 1998). Recently, perceptual temporal expectancy has also been demonstrated in the visual domain (see, e.g., Bausenhardt, Rolke, Seibold, & Ulrich, 2010; Bausenhardt, Rolke, & Ulrich, 2008; Bueti, Bahrami, Walsh, & Rees, 2010; Rolke & Seibold, 2010).

However, alternatively, one might speculate that participants in the present experiments prepared for the motor responses (instead of target processing) that were associated with the peak FPs. Research on general temporal expectancy has previously shown that motor preparations play, under some conditions, an important role in temporal preparation (Duclos, Schmied, Burle, Burnet, & Rossi-Durand, 2008; Hohle, 1965).

However, within the paradigm applied in the present study, it is not possible to dissociate behaviorally between the preparation for perception or for action. Participants react according to a fixed stimulus–response rule. This has the consequence that whenever a certain stimulus is frequently paired with a certain FP, there is also a response that is frequently paired with that FP. Thus, stimulus and response preparation would predict exactly the same behavioral pattern. Differentiating between both possibilities would require either nonbehavioral neuroscientific

measures (such as some of the studies cited previously used), or a design in which response-FP pairings are not automatically associated with stimulus-FP pairings. Thus, the issue to what degree specific temporal expectancy relies on perceptual or motor components still awaits investigation.

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