When specific action biases meet non-specific preparation:

Event repetition modulates the variable-foreperiod effect

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Word count: 5,654

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Abstract

Preparing for the moment of action speeds up reaction-time performance even if the particular response is unknown beforehand. When the preparatory interval, or foreperiod (FP), varies unpredictably between trials, responses usually become faster with increasing FP length. This variable-FP effect has been demonstrated to partly originate from trial-to-trial sequential effects of FP length, which are asymmetric as they occur mainly in short-FP but not in long-FP trials. In two experiments, we examined whether and how event-specific biases arising from previous target processing and responding affect both variable-FP and sequential FP effects. We found that trial-to-trial repetitions (vs. alternations) of imperative events produced response time benefits in short-FP but not in long-FP trials, almost eliminating the variable-FP effect, while the sequential FP effect remained intact. This asymmetric contribution to speeded performance in variable-FP settings suggests that sequential event-specific biases may be highly transient and not necessarily an integral part of the mental representations that guide time-based expectancy, or may be overridden by high levels of non-specific preparation in long-FP trials. In conclusion, temporal preparation appears to be a non-specific mechanism (i.e., generally not bound to particular event features) for prioritizing certain positions on the mental time line, on which event-specific short-term biases are superimposed if time-based preparation is weak.

Keywords: temporal preparation; sequence effects; repetition priming; response bias; temporal attention; episodic memory; cognitive action control

Public Significance Statement: This study highlights the importance of considering action repetition benefits when evaluating the effect of getting ready for the moment of speeded action: our response speed appears to strongly depend on whether or not we gave the same response just before – but only if the moment our next response is due comes unexpectedly early.

Our responses to environmental events are most efficient when we have advance knowledge about *what* will occur *at what time* and *how to respond* to it. Fitts and Posner (1967, p. 96) provided several examples of everyday situations where temporal synchronization is critical for superior performance: "…*A baseball batter playing against a pitcher who always throws with the same speed can time his swing almost perfectly. Similarly, an automobile driver, as long as he can see the road ahead of his car, is able to time his steering motion to coincide precisely with variations in the road…*". While everyone would agree that people are well able to synchronize mental processes (e.g., response readiness) with events that occur within regular (and relatively short) intervals, there is less agreement about what happens when uncertainty is introduced about when precisely the critical event will occur. And what will happen if the event by itself is subject to uncertainty, that is, when there is *event uncertainty* in addition to *time uncertainty*? In this case, people should not be able to implement any predictions (cf. Kahneman, Treisman, & Gibbs, 1992). Empirical evidence, however, favors a different view, indicating that our reactions heavily rely on previous time (and event) experiences despite uncertainty about the upcoming event (cf. Los & Van den Heuvel, 2001). That is, if there is a priori uncertainty about the timing and type of an impending event, predictions (and preparation) are based on information carried over from previous events. Here, we investigated whether and how event-specific biases, resulting from preceding actions, interact with the non-specific preparation to act at a given time (temporal preparation) under conditions of time and event uncertainty.

The variable-foreperiod effect

The ability to prepare for an impending event can be studied by means of the foreperiod (FP) paradigm, where FP length and variability is systematically manipulated and their effects on reaction time (RT) are measured (cf. Drazin, 1961; Karlin, 1959; Klemmer, 1956, 1957). Since the pioneering work of Woodrow (1914), this situation is commonly structured as follows: A warning signal (WS) starts a trial and is followed by an FP interval of a certain length after which the target (or imperative stimulus, IS)

will occur. Participants are instructed to respond to the IS as fast and accurately as possible, and RT is then plotted as a function of FP length (Hackley & Valle-Inclan, 2003; Niemi & Näätänen, 1981). When the FP interval is constant within a block of trials (and varies only between blocks), responses are usually fast with short-FP but slow with long-FP intervals, yielding an upward-sloping FP–RT function (e.g., Müller-Gethmann, Ulrich, & Rinkenauer, 2003). In contrast, when FP length is variable within a block of trials, deterministic synchronization of peak readiness with the moment of IS occurrence is impossible, and responses are slow in short-FP but fast in long-FP trials. This downward-sloping FP–RT function is not a trivial effect, given that time estimation becomes worse with longer FPs, and that the imperative moment cannot be predicted (cf. Niemi & Näätänen, 1981, pp. 136-141).

The classic explanation of the downward-sloping FP–RT function in variable-FP settings where the different FP lengths are equally distributed across trials relies on the fact that the conditional probability of target occurrence (or: hazard rate) increases monotonically during a trial, given that the target has not yet occurred (cf. Baumeister & Joubert, 1969; Los & Agter, 2005). It is assumed that, during the FP, individuals strategically increase their internal state of (subjective) target expectancy and motoric readiness in correspondence to the (objective) increase in conditional probability, but the mechanism by which this probability is converted into preparedness has remained underspecified. Importantly, the classic view of temporal preparation as a top-down process has an essential shortcoming: it ignores the fact that the downward-sloping FP–RT function derives its shape to a substantial degree from sequential FP effects (Alegria & Delhaye-Rembaux, 1975; Los & Agter, 2005). The term "sequential FP effect" refers to the influence of the preceding trial's FP length on performance in the current trial, which usually is asymmetric as it is strongest in short-FP trials and decreases in trials with longer FPs. Thus, responses in short-FP_n trials are usually slower if preceded by a long-FP_{n-1} trial, as compared to if preceded by a short-FP_{n-1} one. In contrast, responses in long-FP_n trials are always fast, irrespective of the preceding trial. An extension of the classic account aimed to explain these sequential effects by adding a second, non-strategic process, assuming that sequential FP effects reflect trial-to-trial

up- or down-swings of motoric arousal caused by preceding short or long FP_{n-1} intervals, respectively (Vallesi & Shallice, 2007; Vallesi, Shallice, & Walsh, 2007; Vallesi, Lozano, & Correa, 2013).

An influential alternative account, the trace-conditioning model developed by Los and colleagues (Los & Heslenfeld, 2005; Los, Knol, & Boers, 2001; Los & Van den Heuvel, 2001), explains variable-FP phenomena by an entirely different mechanism, namely trial-to-trial associative learning. Here, a trace is represented as an ordered sequence of time-tagged components with the WS thought to initiate an activation cascade that works through this ensemble such that one component excites the next until the IS occurs. When the IS occurs during this cascade, a time-tagged associative link is established between the sensory representation of the WS and the IS, and importantly, the response. Peak readiness at critical (i.e., potentially imperative) moments is attained through adjustments of "response strength" (i.e., the degree of readiness) via associative learning: It is assumed that response strength at a given moment increases after having responded to the IS at that temporal position, and decreases at all earlier (bypassed) critical moments, where responding has been inhibited. Hence, the model predicts fast responses in short-FP_n trials if this early critical moment was reinforced previously, but slow responses if it was bypassed previously. Critically, responses in long-FP_n trials are expected to be always fast, irrespective of previous FP_{n-1} length, since the latest critical moment is never bypassed and, thus, never associated with response inhibition (Los, 2013).

Los, Kruijne, and Meeter (2014; 2017) have recently presented an extended version of the original model, which combines reinforcement-learning dynamics with a multiple-trace model of episodic memory, in order to account for both recency (short-term) and aggregate (long-term) effects in variable-FP settings. In particular, the extended model assumes that any trial episode leaves a direct episodic trace in memory, storing the current preparatory experience in terms of accumulated inhibition during FP and activation at the imperative moment. At each new trial, the WS is thought to act as retrieval cue that reactivates all relevant previously stored traces. Although the immediately preceding trial arguably has the strongest impact (i.e., the most recent trace has the largest weight), thereby explaining the sequential

FP effect, the joint influence of earlier traces contributes to the preparatory state of each critical moment, representing a form of aggregate activation–inhibition ratio for each critical moment, which captures, for instance, the characteristics of the FP distribution. Presumably, over a longer series of trials, the memories of individual episodes accumulate into generalizable experience, or abstraction (Hintzman, 1986).

Event-specific effects in temporal preparation

A common thread through all recent theoretical accounts of variable-FP phenomena is the notion that temporal preparation refers to processes of creating representational codes designed for expecting critical (i.e., behaviorally relevant) moments in time. These temporal representations are usually considered to be non-specific with respect to the particular behavior (i.e., independent of particular stimulus–response events; cf. Steinborn, Langner, & Huestegge, 2016). Nevertheless, it can be asked whether (non-specific) event timing information and (specific) event type information interactively affect RT performance in FP experiments. For instance, it is well known that RT in choice-reaction tasks is affected by probabilistic biases towards particular stimulus–response (S-R) events such that more likely events are more strongly expected and faster responded to in general (Eickhoff, Pomjanski, Jakobs, Zilles, & Langner, 2011; Miller, 1998; Miller & Pachella, 1973) or at certain temporal positions (Thomaschke & Dreisbach, 2015; Thomaschke, Hoffmann, Haering, & Kiesel, 2016; Wagener & Hoffmann, 2010). Using constant-FP paradigms, two early studies tested for an interaction between probabilistic S-R biases and temporal preparation (Bertelson & Barzeele, 1965; Holender & Bertelson, 1975).but produced mixed results, essentially leaving the question open.

Another source of event-specific bias are non-strategic influences from the immediate past such as non-predictive S-R repetition biases conferred between successive trials (Bertelson, 1963; Jentzsch & Leuthold, 2005; Kirby, 1976; see also Fecteau & Munoz, 2003). To our knowledge, however, the only direct evidence bearing on the question of whether such sequential event biases affect temporal preparation in variable-FP settings is reported in a footnote by Los and van den Heuvel (2001, p. 374).

The authors referred to this issue since FP effects in choice-RT situations (as compared to simple-RT tasks) might be confounded by differential sequential effects of particular S-R pairs at different critical moments. This is because sequential effects (of S-R pairs) in serial choice-RT tasks usually decline with increasing response–stimulus intervals[1] (cf. Bertelson, 1961; Jentzsch & Leuthold, 2005; Kirby, 1976; Soetens, Boer, & Hueting, 1985). Los and van den Heuvel, however, found this effect to be additive to the sequential effect of FP length (i.e., the RT pattern was qualitatively similar in both response repetition and response shift conditions) and concluded that event-specific sequence effects are of minor importance in variable-FP settings. Although being in line with the trace-conditioning model, this single result raises the question of whether it might have been due to idiosyncrasies of that particular data set.

Providing discrepant (albeit indirect) evidence pertaining to event sequence effects on temporal preparation, Steinborn, Rolke, Bratzke, and Ulrich (2009) demonstrated more efficient preparation processes if WS modality is repeated, as compared to if it is shifted across trials. While a repetition of WS modality (from FP_{n-1} to FP_n) yielded the standard variable-FP effect, a shift yielded an increased FP_n–RT slope. This implies that a successful re-instantiation of a previously encountered trial episode has not taken place when the WS is not identical in modality. Hence, WS-triggered preparatory processes depend on WS surface features, supporting a non-strategic account of variable-FP temporal preparation (cf. Steinborn, Rolke, Bratzke, & Ulrich, 2008, for a review). Under some circumstances, within-modality alternations between qualitatively different WS stimuli have also been found to be effective (cf. Steinborn, Rolke, Bratzke, & Ulrich, 2010). These findings suggest specificity in temporal preparation driven by a non-strategic mechanism.

Present Study

Inspired by the above-mentioned sparse and equivocal evidence as well as by current theorizing (Capizzi, Correa, Wojtowicz, & Rafal, 2015; Huestegge & Adam, 2011; Los et al., 2014, 2017; Yashar & Lamy, 2013), we aimed to investigate systematically whether or not temporal preparation under variable-

FP conditions is modulated by specific action biases conveyed from the preceding trial. To this end, we chose a standard variable-FP paradigm (three FP durations; uniformly distributed) implemented in a choice-RT task with two S-R alternatives (S-R events) similar to Los and van den Heuvel (2001). The critical comparison here is made between FP effects for an S-R event repetition and an S-R event shift, respectively.

As alluded to above, Los and van den Heuvel (2001) reported an additive effect on the FP–RT slope, suggesting that sequential action biases contribute equally to performance irrespective of FP length. According to the additive-factors logic, this may seem plausible as long as it is assumed that both factors act on different processing stages. Such an additive pattern would also agree with the tenets of multiple-trace theory (Hintzman, 1986; Los et al., 2014, 2017; Mattiesing, Kruijne, Meeter, & Los, 2017), which, however, is silent as to the question whether two facets of the most recent memory trace (e.g., event type and event time), which contributes most to sequential effects, would interactively affect subsequent responding. That is, if the most recent trace activates the wrong timing and S-R codes (e.g., in long–short FP sequences with event shift), it may or may not be that both invalid biases produce additive costs relative to a situation where only one of the activated codes is invalid (e.g., in short–short FP sequences with event shift or in long–short FP sequences with event repetition). Therefore, from the perspective of multiple-trace theory, a three-way interaction is also conceivable, where event sequence modulates the asymmetry of the sequential FP effect (i.e., the standard $FP_n \times FP_{n-1}$ interaction). This modulation should mainly occur at early critical moments, where sequential FP effects are maximal. In particular, for long–short FP sequences, which usually produce the slowest responses, automatic facilitation brought about by repeating the S-R pair from the previous trial might be especially beneficial, largely making up for the double "disadvantage" of having to respond at the earliest imperative moment (variable-FP effect due to aggregating across previous traces) after a preceding long-FP trial (sequential FP effect due to most strongly weighting the most recent trace). This specific response facilitation at moments of low general

response readiness would lead to a larger RT difference between event-repetition and event-shift trials in long–short FP sequences, relative to that difference in short–short FP sequences.

The competing dual-process account of variable-FP phenomena (Vallesi & Shallice, 2007; Vallesi et al., 2007), which assumes two independent mechanisms, conditional probability monitoring and sequential arousal changes, to explain variable and sequential FP effects, is similarly silent as to the effects of event-specific biases on temporal preparation. However, different from multiple-trace theory, this account does not make the assumption of episodic memory traces that jointly code event time and event type information encountered in previous trials. Therefore, the most natural prediction of a rational observer taking the perspective of dual-process theory would be to assume that the above-mentioned rapid decay observed for sequential event-specific biases in serial responding (i.e., event repetition benefits) also applies in variable-FP settings. In particular, features of a task situation that are non-predictive for future trials, such as event-specific codes that follow a random sequence across trials, are considered irrelevant and should be subject to "decay" over time[2]. Hence, assuming that non-predictive (irrelevant) event-specific codes quickly decay after a given trial predicts an asymmetric influence of event sequence type on the FP–RT slope, similar to what was observed by Steinborn et al. (2009, 2010) when examining a repetition (vs. shift) of WS attributes on the FP–RT slope. That is, besides standard variable- and sequential FP effects and the standard event-sequence effect (i.e., faster responses for IS repetitions vs. shifts), a two-way interaction of both variables was expected, resulting from a larger event repetition benefit in short-FP (vs. long-FP) trials. Of note, such a pattern of results would imply that event-specific information (manifested in action biases) and non-specific timing information (manifested in temporal preparation) do *not* have a shared mental representation. This is because representations of the conditional probability of critical moments would be updated throughout the entire FP (including long FPs), while event-specific information would be bound to decay towards late critical moments, precluding a stable integrated representation of event type and event timing.

Experiment 1

For reasons of comparability with the relevant literature, we started out with an experiment where the temporal context was very similar to that previously employed in several studies by Los and colleagues (Los et al., 2001; Los & Van den Heuvel, 2001; Van der Lubbe, Los, Jaskowski, & Verleger, 2004). In Experiment 1, therefore, the influence of event-specific contributions to performance in the context of temporal preparation was examined using three relatively short FPs of 300, 600, and 900 ms (uniformly distributed).

Method

Participants. A sample of 50 participants (mean age = 25.0 years, *SD* = 6.0) took part in the experimental session. All participants had normal or corrected-to-normal vision.

Apparatus and Stimuli. The experiment was run in a dim and noise-shielded room; it was controlled via a personal computer with color display (19", 150 Hz refresh rate) running MATLAB™ and using the Psychophysics Toolbox extension. Participants sat about 60 cm in front of the computer screen. A dot ($0.5° \times 0.5°$ angle of vision) in the middle of the screen served as fixation point and was constantly present throughout the experimental session. The WS (sine tone, 1000 Hz; 70 dB) was presented binaurally via headphones. The letter "L" or "R" ($1.14° \times 0.86°$ angle of vision) served as the IS and was displayed in blue (7.1 cd/m^2) at the center of the screen.

Design and Procedure. The three-factorial within-subject design contained the factor target-event sequence (repetition vs. shift of S-R pair), previous foreperiod (FP$_{n-1}$, short vs. medium vs. long) and current foreperiod (FP$_n$, short vs. medium vs. long). Trials started with an auditory WS (70 Hz sine tone presented for 100 ms), which was followed by the variable FP interval, followed by the target event to which participants were required to respond with either the left shift-key (left index finger, if "L" was presented) or the right shift-key (right index finger, if "R" was presented). The target event was

terminated either by response or after expiration of 2000 ms. Participants were instructed to respond quickly and accurately. In case of an erroneous response, the German word "falsch" (wrong) was presented for 300 ms on the screen; in case of response-interval expiration, the phrase "zu langsam" (too slow) was presented. An intertrial interval of 1000 ms separated subsequent trials. Participants performed 60 warm-up trials and 600 experimental trials. Short breaks were given after each block of 100 trials (cf. Steinborn & Huestegge, 2016).

Results and Discussion

    Data treatment. Responses faster than 100 ms and slower than 1000 ms were considered outliers, and corresponding trials were discarded (0.3 % on average). Correct responses were used to compute mean RT, while incorrect responses (pressing the wrong response key) were used to compute error percentage (EP). Effects of the experimental factors on RT and EP were tested via within-subject general linear model (GLM) analysis. Complete statistical effects are listed in the Appendix (Table 1), and only the theoretically relevant effects are subsequently reported in the main text. Figure 1 displays RT and EP as a function of FP_{n-1} and FP_n, separately for IS-repetition and IS-shift trials.

    Experimental effects (GLM). Responses were generally faster for IS-repetition than for IS-shift trials [$F(1,49) = 6.6$, $p < .05$], indicating a typical repetition benefit in two-choice RT tasks. Responses became faster with increasing FP_n length [$F(2,98) = 64.2$, $p < .001$], demonstrating the usual variable-FP effect. There also was a significant $FP_{n-1} \times FP_n$ interaction effect on RT [$F(4,196) = 12.7$, $p < .001$], replicating the well-established asymmetric sequential FP effect. Critically, S-R event sequence interacted with FP_n length [$F(2,98)$, $p < .01$], yielding a flatter FP–RT slope in those trials where S-R events were repeated from the preceding trial, as compared to those where S-R events differed (cf. Table 1). There was, however, no significant three-way interaction [$F(4,196) = 1.1$]. This pattern of results indicates a non-additive influence of sequential action biases on responding in a variable-FP setting, in line with our prediction. The fact that event-specific biases, reflecting residual activation from the previous trial, did

not affect performance similarly across different FP durations agrees with the assumption that such biases are rather short-lived and not a stable part of the mental representation of event timing. The absence of a three-way interaction suggests that the two sequential effects of preceding S-R pair and FP length do not exert their actions at the same processing stage, precluding mutual compensation.

Experiment 2

In Experiment 2, we analyzed the event-specific modulation of variable-FP temporal preparation in a situation that was optimized for testing our hypotheses. We used a more widely spaced temporal context (FPs: 800, 1600, and 2400 ms), which is, however, still within the range of FP durations usually employed in this domain, including our own work (Langner, Steinborn, Chatterjee, Sturm, & Willmes, 2010; Niemi & Näätänen, 1981; Steinborn & Langner, 2011; Trillenberg, Verleger, Teetzmann, Wascher, & Wessel, 2004; Vallesi et al., 2013). Further, the intertrial interval was reduced to zero so that any decrease of sequential action bias can be unequivocally attributed to processes occurring during the FP interval, rather than to dissipating effects of rest breaks (cf. Steinborn & Huestegge, 2016, for a review). Of note, average FP length in Experiment 2 (i.e., 1600 ms) was identical to the average sum of intertrial interval and subsequent FP length in Experiment 1, while the FP range was larger in Experiment 2. Thus, the potential post-response decay time was effectively the same for medium-length FP trials across experiments, whereas it was shorter or longer in Experiment 2 for short- or long-FP trials, respectively. This way we sought to maximize the treatment effect of our "event sequence" manipulation while holding the average level constant across experiments.

Method

Participants. A sample of sixty volunteers (mean age = 27 years, *SD* = 6.5) was tested, with most participants being right-handed and having normal or corrected-to-normal vision.

Stimuli and Apparatus. The set-up was retained from Experiment 1, except for the more widely spaced temporal context (FPs: 800, 1600, 2400 ms, uniformly distributed). Additionally, the intertrial interval was set to zero to exclude any contribution of this variable to the examined effects (cf. Steinborn & Langner, 2012; Vallesi et al., 2013).

Task, Design and Procedure. The setting was equal to Experiment 1.

Results and Discussion

Data treatment. Data processing and statistical procedures were equal to Experiment 1. Complete statistical effects are listed in the Appendix (Table 2), and, again, only relevant effects are subsequently reported in the main text. Figure 2 displays RT and EP results of Experiment 2 .

Experimental effects. As expected, imperative-event repetitions yielded faster responses than did shifts [$F(1,59) = 19.3$, $p < .001$]. Further, the typical variable-FP and sequential FP effects were obtained: responses became faster as a function of increasing FP length [$F(2,118) = 36.8$, $p < .001$] and varied asymmetrically according to the interaction with previous FP_{n-1} length [$F(236) = 27.8$, $p < .001$]. Crucially, the slope of the FP_n–RT function was again flatter for imperative-event repetitions than for imperative-event shifts, as indicated by a significant two-way interaction [$F(2,118) = 39.2$, $p < .001$], again demonstrating asymmetric sequential event specificity in temporal preparation (Table 2). This outcome agrees with our findings from Experiment 1, with the wider temporal context of Experiment 2 inducing even stronger event repetition benefits in short-FP trials. An analogous interaction was obtained for the FP_n–EP function [$F(2,118) = 26.7$, $p < .001$], which argues against a shift in the speed–accuracy trade-off toward accuracy as an explanation for the RT costs occurring with S-R pair alternations (vs. repetitions). Furthermore, there was a just-significant three-way interaction [$F(4,236) = 2.4$, $p = .049$]. As can be seen in Fig. 2, however, this interaction was different from our prediction, since long–short FP trials did *not* benefit more than short–short FP trials from event repetitions (the RT difference between event repetitions and alternations was almost identical for either FP sequence type). Rather, there was an

unexpected response slowing at late (vs. early) critical moments of event repetition trials when the preceding FP was short. Thus, the three-way interaction was not due to a modulation of the sequential FP effect by event repetitions at early moments (i.e., when the event-specific bias should have been strongest). Importantly, however, Experiment 2 corroborated our prediction that sequential action biases differentially affect speeded performance in the context of temporal preparation, in line with the notion that such biases are subject to quick decay over time and not part of a stable representation of event timing.

General Discussion

Näätänen and Merisalo (1977) described preparation as *"...performing in advance what can be performed in advance of a response" (p. 133)*. This means that individuals, if provided with sufficient information, will proactively tune attentional selectivity and pre-configure effector systems to optimize responsiveness to the stimulus event. Such information can be given either explicitly via cues or implicitly via inducing probabilistic expectancies about certain stimulus events and their response requirements (Bertelson & Barzeele, 1965; Eickhoff et al., 2011; Miller, 1998; Sudevan & Taylor, 1987). Here, we examined whether temporal preparation in a variable-FP setting is, to some degree, event-specific even when no advance information is available, since all imperative-event alternatives are presented with equal probability. In two variable-FP experiments, we compared the slopes of the FP_n–RT function between imperative-event shift and imperative-event repetition trials, expecting an asymmetric influence (i.e., strong with short FPs and diminishing with longer FPs) of event sequence on the downward-sloping FP_n–RT function. Our results corroborated this prediction and can be summarized as follows: In Experiment 1, there was a downward-sloping FP_n–RT function, originating partly from asymmetric sequential FP effects. More importantly, there was a modulation of the FP–RT slope by the sequence (repetition vs. shift) of imperative S-R pairs (Figure 1). In Experiment 2, in which an optimized (wider) FP context was used (FPs: 800, 1600, 2400 ms), we observed a similar but more pronounced modulation of the variable-

FP effect by the type of imperative event sequence (shift vs. repetition). A complementary pattern was obtained for the error rate in Experiment 2: the FP–EP slope was increased in event shift trials as compared to event repetition trials. Thus, our results demonstrate asymmetric sequential event specificity in temporal preparation, arising from larger benefits of imperative-event repetitions (vs. shifts) in short-FP trials relative to long-FP trials (cf. Figures 1 and 2).

These results agree with the dual-process account of variable-FP phenomena (Vallesi & Shallice, 2007; Vallesi et al., 2007) but contrast with Los and van den Heuvel's (2001, p. 374) earlier incidental finding that sequential effects of S-R pair are negligible in variable-FP settings. The observed interaction is also at odds with the recently proposed multiple-trace theory of temporal preparation (Los et al., 2014, 2017; Mattiesing et al., 2017): According to this model, the FP interval provides a window of episodic memory encoding until the individual responds to the IS. In any given trial, therefore, the WS is held to act as a retrieval cue that automatically activates sensorimotor and timing representations of the previously encountered trial episodes as stored in episodic memory traces. Since this model assumes that all relevant features of a trial episode are jointly coded in a trace, a decline of only event-specific but not time-related information with longer FPs would be incompatible with this particular aspect of the model.

As mentioned in the introduction, the diminishing impact of the S-R event sequence with increasing FP duration might be rooted in irrelevant-feature decay processes affecting representational codes carried over from the preceding trial. With regard to the present case, all S-R pairs were equally probable, rendering them non-informative for future behavior as any action-specific prediction based on preceding events was impossible. Still, such obviously non-predictive (i.e., irrelevant) event-specific information is carried from trial to trial. This somehow mandatory carry-over of irrelevant information might be similar in nature to what has been observed in task switching, where (residual) switch costs are observed despite knowledge of an upcoming switch and the resulting irrelevance of the previous action set (for a review, see Kiesel et al., 2010). In our context, we would argue that these irrelevant-feature influences carried over from the preceding trial are not part of the mental representation underlying

temporal preparation, since they are short-lived and contribute to performance only as long as they are available (i.e., as long as their quickly decaying remnants are sufficiently strong) to dock onto a current mental representation of event timing. This agrees with a conceptual differentiation between the assumed origins of the two dynamic effects observed here (i.e., sequential event-specific biases vs. sequential FP effects), which has been endorsed outside multiple-trace theory: Trial-to-trial S-R biases are thought to reflect priming-based automatic facilitation, whereas non-specific timing (FP length) influences carried over to the next trial are thought to reflect FP-specific arousal after-effects or associative learning (Los et al., 2001; Vallesi & Shallice, 2007). It should be noted, though, that this is not meant to say that time-related and event-specific information cannot be jointly coded in a shared mental representation – it just does not appear to be mandatory: For instance, if a given FP duration indeed is predictive of a particular S-R event, this association is (implicitly) learnt, and joint coding seems to occur (cf. Thomaschke & Dreisbach, 2015; Thomaschke et al., 2016; see also Bouton & Garcia-Gutierrez, 2006). Furthermore, our conclusions hold only for unbiased choice-RT paradigms, that is, situations with response uncertainty, in which a given S-R event is not predictive of subsequent events.

Intriguingly, the observed pattern can be quite easily reconciled with multiple-trace theory if it is assumed that generating multidimensional memory traces, containing "what" and "when" information about encountered stimuli and responses, is not an obligatory all-or-none process. This is a plausible assumption since the notion that episodic traces contain all the *task-relevant* information (cf. Los et al., 2014) suggests selection before encoding. Such a selection could be achieved by some form of (attentional) feature binding, which creates "object files" (Treisman & Gelade, 1980) or entire "event files" linking perception and action (Hommel, 2004) based on the task-relevance of event features (see also Laurent, Ensslin & Mari-Beffa, 2016). In typical variable-FP settings, participants implicitly learn about the temporal structure of events (which may then become a relevant feature) and about the non-predictiveness of S-R events (whose initial relevance for doing the task may then drop). Analogous differences in forming episodic memories for object identity versus location have been observed when

focusing attention on either the one or the other feature (Köhler, Moscovitch, & Melo, 2001). At any rate, perceived differential relevance might prevent waiting time (FP) from being bound together with the S-R event occurring after the given FP is over, leading to a situation where both pieces of information are not jointly coded in a single memory trace. Under these circumstances, the here observed interaction may be expected to arise, since this would allow for differential decay rates of either trace such that non-predictive (irrelevant) S-R information can decay rather quickly and is thus not carried on far into the next trial.

In addition to passive decay, a second, more active mechanism might contribute to the results pattern observed: At late critical moments (i.e. in long-FP trials), any residual specific action bias induced by the preceding trial may be overridden by the strong readiness to respond – in whichever possible way – at that particular moment. That is, peak levels of alertness, or non-specific response readiness, may outweigh any remaining event-specific bias. In contrast, at times when participants are, on average, least prepared to respond (i.e., in short-FP trials), event-specific biases might gain traction up to a degree where non-specific current-FP effects essentially disappear when the S-R pair is repeated (cf. Exp. 2). We take this pattern to suggest that event-specific carry-over effects from the previous trial are superimposed on the time-point-related global level of response strength (general response readiness): At early critical moments, non-specific readiness is weak, while event-specific activation is strong and thus biases performance. In contrast, event-specific representations decay towards late critical moments, while non-specific readiness increases, thus becoming the predominant determinant of response behavior. This notion also offers another possibility for reconciling our findings with the multiple-trace theory of temporal preparation: In contrast to FP effects, which result from both long-term (aggregate learning) and short-term (preceding trial dominance) effects, event sequence effect arise only from short-term carry-over, since the unbiased distribution of S-R pairs and their orthogonal combination with FP durations preclude aggregate learning. This single-source origin may make the behavioral contribution of event-

specific sequential biases less impactful and amenable to being quenched under high levels of preparation (i.e., when FP is long).

The view of temporal preparation as a dynamic balance of two juxtaposed mechanisms[3] agrees well with the neurophysiological evidence for separate excitatory and inhibitory processes (Jennings & van der Molen, 2005; Langner et al., 2012; Los, 2013; Tandonnet et al., 2012). This evidence suggests that, at the neural level, response-specific activation processes are mainly excitatory, whereas non-specific preparatory processes are inhibitory. In particular, it is assumed that global inhibitory control signals target downstream functional units to (i) keep any prepared responses in check and thereby prevent premature responding as well as to (ii) increase the signal-to-noise ratio in the cortico-spinal system and thereby enhance its sensitivity for the upcoming voluntary motor command (Greenhouse, Sias, Labruna, & Ivry, 2015; Hasbroucq, Kaneko, Akamatsu, & Possamai, 1997; Hasbroucq et al., 1999). With respect to our findings, we conjecture that repetition-based event-specific biases are mediated by excitatory neural activity, which facilitates responding as long as non-specific inhibitory control processes are only moderately strong (i.e., early during the FP) but which fails to have any substantial impact when inhibition is maximized (i.e., late during the FP; cf. above). The error scores observed (cf. Exp. 2) are in line with this view: In short-FP trials, when non-specific inhibition is thought to be weak, imperative-event repetitions facilitated correct responding (indicated by fast and accurate responses), while imperative-event shifts did induce false response tendencies (indicated by slow and often inaccurate responses).

Conclusion

Taken together, we observed a clear-cut modulation of the variable-FP effect by the type of imperative-event sequence (shift vs. repetition from the preceding trial), which provides evidence for asymmetric event-related specificity in non-specific (temporal) preparation. In particular, the FP–RT slope was steeper for imperative-event shifts than it was for repetitions, as event repetition benefits predominantly

occurred at earlier critical moments, when time-related non-specific preparation is volatile and rather weak on average. Our results, therefore, indicate that besides non-specific sequential FP effects, preparation in settings with time and event uncertainty is independently influenced by another powerful but transient sequential effect, presumably reflecting action priming: a specific bias toward the same stimulus–response compound as experienced on the preceding trial. Extending our knowledge about the mechanisms behind temporal preparation, these findings suggest that time-related information can be encoded and retrieved independently of non-predictive event-specific information, which in turn biases information processing only if time-based general preparation is weak.

Acknowledgements

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Footnotes

Footnote 1. Note that the pronounced repetition benefit observed after short response–stimulus intervals (e.g., constant RSI = 50 ms) is typically reduced when the interval is increased, and vanishes almost completely when the interval is sufficiently long (beyond 2000 ms). Kirby (1976, p. 569) provided an impressive visualization of how the sequential RT pattern changes with increasing response–stimulus interval, which is commonly explained by assuming a decay of irrelevant-feature activation (Jentzsch & Leuthold, 2005; Jentzsch & Sommer, 2002; Kirby, 1972, 1976; Notebaert & Soetens, 2003; Soetens, 1998; Soetens et al., 1985; Soetens & Notebaert, 2005).

Footnote 2. In the literature on cognition and memory, the term "decay" is often specifically used to denote the passive disintegration of purposeful mental representations. A passive "decay" hypothesis is often contrasted against an active "interference" hypothesis. Since this differentiation can be problematic, as presumably passive decay might be due to actually not registered (and theoretically not covered) kinds of interference such as from mind-wandering (Langner & Eickhoff, 2013; Smallwood, 2013; Thomson, Besner, & Smilek, 2015), we use "decay" as an umbrella term for denoting a decrease of irrelevant-feature influences over time.

Footnote 3. A note on applying Sternberg's additive-factors logic to the observed interaction: We would like to emphasize that the interactive effect of sequential action bias and FP duration is not to be interpreted in terms of same or different underlying "processes." Sternberg (1969, pp. 309-310) argued that the additive-factors method cannot distinguish processes but only processing stages, and this distinction is crucial for understanding the mechanism underlying FP effects. In particular, he pointed to the effect of the interaction of FP length (short vs. long) and probabilistic bias (relative signal frequency: low vs. high) found by Bertelson and Barzeele (1965), which he regarded important in the understanding

of preparation. Accordingly, this interaction does allow one to reject the idea of separate stages (i.e., no stage influenced by both factors), while it does not allow one to reject the more general proposition of separate processes. The reason is that a pair of independent processes influenced separately by the factors could conceivably operate in parallel and therefore produce the interaction.

Appendix

Table 1. Effects of experimental manipulations on performance speed and accuracy in Experiment 1.

	Source	df	Reaction Time			Error Percentage		
			F	p	η_p^2	F	p	η_p^2
1	SR-Seq	1,49	6.6	.012	.12	0.0	.869	.00
2	FP_{n-1}	2,98	43.4	< .001	.47	2.1	.134	.04
3	FP_n	2,98	64.2	< .001	.57	6.4	.002	.12
4	SR-Seq × FP_{n-1}	2,98	0.8	.464	.17	0.3	.766	.01
5	SR-Seq × FP_n	2,98	5.1	.007	.10	3.3	.043	.06
6	FP_n × FP_{n-1}	4,196	12.7	< .001	.21	0.3	.848	.01
7	SR-Seq × FP_{n-1} × FP_n	4,196	1.1	.342	.02	1.5	.201	.03

Note. Experimental factors: Imperative-event sequence (SR-Seq: repetition vs. shift of stimulus–response pair); previous foreperiod length (FP_{n-1}: short vs. medium vs. long); and current foreperiod length (FP_n: short vs. medium vs. long). η_p^2 = effect size.

Table 2. Effects of experimental manipulations on performance speed and accuracy in Experiment 2.

	Source	df	Reaction Time			Error Percentage		
			F	p	η_p^2	F	p	η_p^2
1	SR-Seq	1,59	19.3	< .001	.25	6.5	.013	.10
2	FP_{n-1}	2,118	43.0	< .001	.42	1.1	.333	.02
3	FP_n	2,118	36.8	< .001	.38	11.8	< .001	.17
4	SR-Seq × FP_{n-1}	2,118	2.0	.146	.03	1.2	.303	.02
5	SR-Seq × FP_n	2,118	39.2	< .001	.40	26.7	< .001	.31
6	FP_n × FP_{n-1}	4,236	27.8	< .001	.32	5.2	< .001	.08
7	SR-Seq × FP_{n-1} × FP_n	4,236	2.4	.049	.04	1.6	.176	.03

Note. Experimental factors: Imperative-event sequence (SR-Seq: repetition vs. shift of stimulus–response pair); previous foreperiod length (FP_{n-1}: short vs. medium vs. long); and current foreperiod length (FP_n: short vs. medium vs. long). η_p^2 = effect size.

Figure Captions

Figure 1. Effects of repetition versus shift of stimulus–response pair on dynamic temporal preparation in Experiment 1 (FPs: 300, 600, 900 ms). Reaction time and error percentage displayed as a function of the preceding foreperiod (FP_{n-1}), and the current foreperiod (FP_n), separately for the repetition condition (panel A, C) and the shift condition (panel B, D).

Figure 2. Effects of repetition versus shift of stimulus–response pair on dynamic temporal preparation in Experiment 2 (FPs: 800, 1600, 2400 ms). Reaction time and error percentage displayed as a function of the preceding foreperiod (FP_{n-1}), and the current foreperiod (FP_n), separately for the repetition condition (panel A, C) and the shift condition (panel B, D).
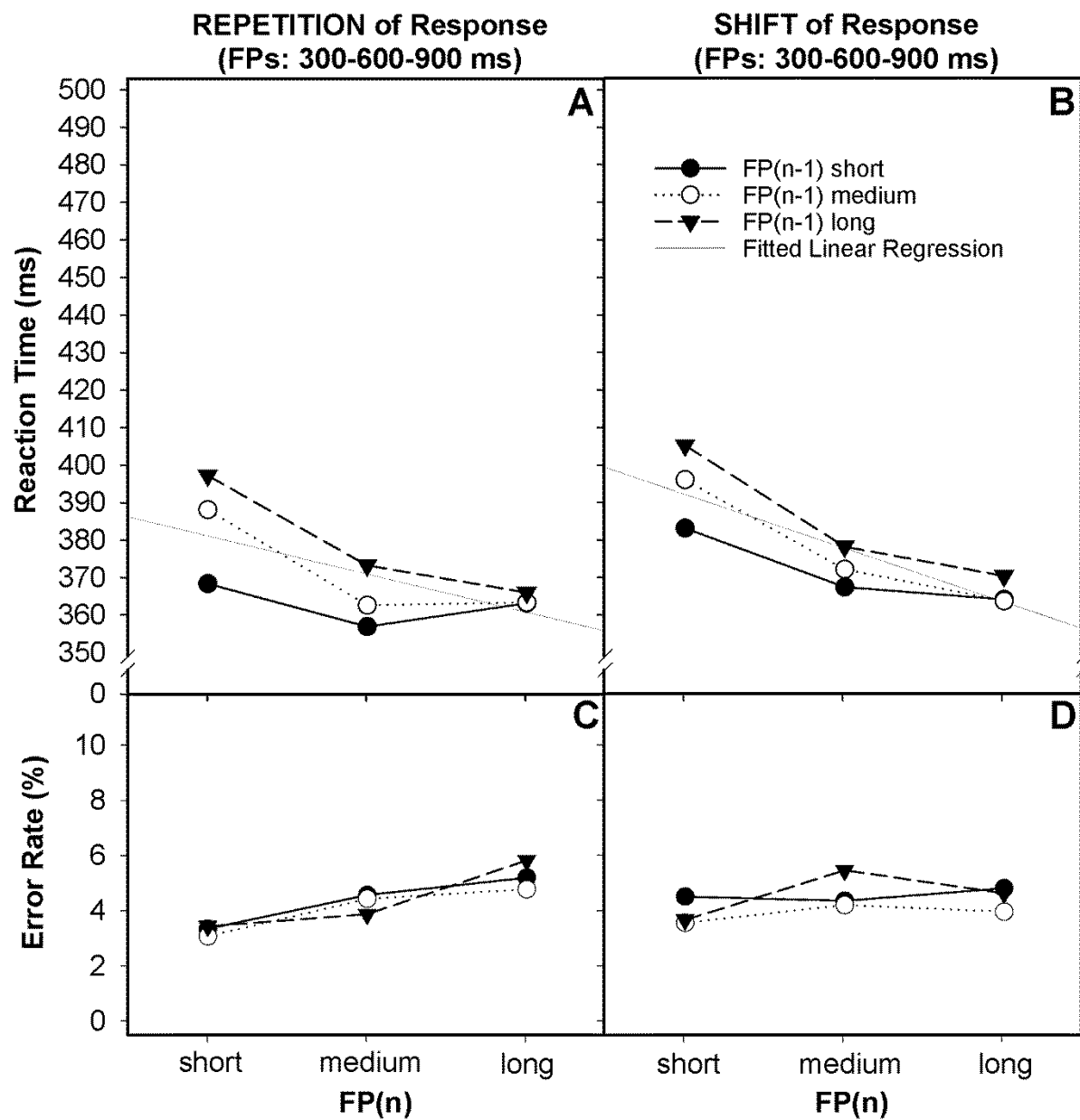
Figure 1

Figure 2