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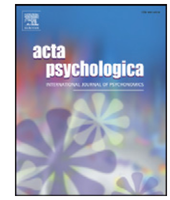

Distraction by irrelevant sound during foreperiods selectively impairs temporal preparation

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ABSTRACT

When the interval between a warning signal (WS) and an imperative signal (IS), termed the foreperiod (FP), is variable across trials, reaction time (RT) to the IS typically decreases with increasing FP length. Here we examined the auditory filled-FP effect, which refers to a performance decrement after FPs filled with irrelevant auditory stimulation compared to FPs without additional stimulation. According to one account, irrelevant stimulation distracts individuals from processing time and probability information during the FP (distraction-during-FP hypothesis). This should predominantly affect long-FP trials. Alternatively, the filled-FP effect may arise from a failure to shift attention from FP modality to IS modality (attention-to-modality hypothesis). The first hypothesis focuses on preparatory processing, predicting a selective RT increase on long-FP trials, whereas the second hypothesis focuses on target processing, only predicting a global RT increase irrespective of FP length. Across four experiments, a filled-FP (compared to a blank-FP) condition consistently yielded a selective RT increase on long-FP trials, irrespective of FP–IS modality pairing. This pattern of results contradicts the attention-to-modality hypothesis but corroborates the distraction-during-FP hypothesis. More generally, these data have theoretical implications by supporting a multi-process view of temporal preparation under time uncertainty.

1. Introduction

Time given to prepare a speeded response to an imperative signal (IS) generally improves performance in reaction-time (RT) tasks (Hackley, 2009; Rolke & Ulrich, 2010). In experiments on effects of temporal preparation, a warning signal (WS) typically announces the start of a trial, which is followed by a blank interval (i.e., the foreperiod, FP), and the IS (Los & Schut, 2008). Individuals are assumed to establish a state of nonspecific preparation during the FP interval in order to optimally process task-relevant information and respond to the IS at the moment of its occurrence (i.e., at the imperative moment). With constant FPs, individuals can synchronize peak preparation with the imperative moment (i.e., the moment of IS occurrence). When, however, FP varies randomly across trials, deterministic synchronization is impossible. That is, under time uncertainty, probability information needs to be processed in addition to time estimation. Responses in such variable-FP paradigms are usually slow in short-FP trials but fast in long-FP trials, yielding a downward-sloping FP–RT function, which is explained by assuming that the time elapsed after the WS is informative, since the conditional probability of IS occurrence monotonously increases during the FP interval (Niemi & Näätänen, 1981, pp. 137–141). Researchers agree that individuals must somehow be capable to convert the objective conditional-probability increase into a subjective expectation; yet, the precise mechanism is still being debated (Bueti, Bahrami, Walsh, & Rees, 2010; Los & Van den Heuvel, 2001; Vallesi, Shallice, & Walsh, 2007).

1.1. Theoretical models of temporal preparation

A strategic account assumes that individuals use the WS as a symbolic time marker to begin with focusing on the task, from which they actively monitor the time flow during the FP interval and increase preparatory state according to the time-related increase in the conditional probability of IS occurrence (Näätänen, 1970; Rabbitt & Vyas, 1980). Accordingly, manipulations that change the conditional IS probability (e.g., Los & Agter, 2005; Requin & Granjon, 1969) or explicit information about the impending imperative moment at the

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beginning of a particular trial (e.g., Correa, Cappucci, Nobre, & Lupiáñez, 2010; Coull, Frith, Büchel, & Nobre, 2000; Coull & Nobre, 1998) are predicted to cause a change in the FP–RT slope. Strategic preparation is considered to require cognitive control for monitoring conditional IS probability (Requin & Granjon, 1969; Stilitz, 1972), for shielding against distraction (Dreisbach & Haider, 2008, 2009), and for intentionally enhancing preparatory state (Näätänen & Merisalo, 1977). The critical variable thus is the availability of attentional resources, ensuring the normal operation of preparatory processing at any time during the FP interval. A strategic model implies that when resources are reduced for some reason (e.g., due to insufficient attention, high cognitive load, etc.), these processes should operate less efficiently, and performance thus is predicted to decline under these conditions.

This classic account, however, cannot appropriately explain the typical sequential modulation of the FP–RT slope across subsequent trials. In particular, responses on short-FP trials are slower when preceded by a long-FP trial, compared to when preceded by an equally long or shorter one. The effect is asymmetric in that responses only vary on short-FP trials and are unaffected by previous FP length on long-FP trials (e.g., Alegria, 1975a; Karlin, 1959; Langner, Steinborn, Chatterjee, Sturm, & Willmes, 2010; Los, Knol, & Boers, 2001; Los & Van den Heuvel, 2001; Steinborn, Rolke, Bratzke, & Ulrich, 2008, 2009, 2010; Van der Lubbe, Los, Jaskowski, & Verleger, 2004). A further argument that imposes difficulties for the classic view is that the asymmetry of the sequential FP effect decreases when sensory WS features changes across trials (Steinborn et al., 2009, 2010), indicating that the WS is more than a symbolic marker and also acts as a memory retrieval cue.

Vallesi and his collaborators (Vallesi, McIntosh, & Stuss, 2009; Vallesi & Shallice, 2007; Vallesi, Shallice et al., 2007) developed the classic strategic explanation of the variable-FP effect into a dual-process model, which can account for the sequential FP effect. Maintaining the idea of a strategic preparatory process based on conditional-probability monitoring, the sequential FP effect is assumed to arise from a trial-to-trial variation in motor excitation due to the variable spacing (i.e., the temporal distance) of two subsequent responses (Vallesi, Mussoni et al., 2007). That is, responses on short-FP_n trials are assumed to be facilitated when following a short-FP_{n-1} trial, due to an increase in the motor-activation level. In contrast, responses on short-FP_n trials are slowed when following a long-FP_{n-1} trial, due to a decrease in the motor-activation level. On long-FP_n trials, however, responses are fast, irrespective of FP_{n-1}, because the motor-activation decrement following long-FP_{n-1} trials is compensated by strategic preparation based on conditional-probability monitoring. According to this view, the asymmetry of the sequential FP arises from the combined impact of two different processes: an originally symmetric sequential effect, resulting from different residual activation levels produced by prior responses, is rendered asymmetric by a selective probability-based preparation process during a long-FP_n trial.

Recently, strategic accounts were challenged by a trace-conditioning model, developed by Los and colleagues (Los & Heslenfeld, 2005; Los et al., 2001; Los & Van den Heuvel, 2001). This model accounts fo the variable-FP effect and its sequential modulation (i.e., the sequential FP effect) by arguing that the former results from the asymmetry inherent in the latter. In particular, states of peak preparation at critical moments are assumed to be attained by dynamic learning and re-learning of temporal intervals. Elapsed time during the FP is represented as a sequence of time-tagged events (Los et al., 2001, p. 128), with each event capable of being associated with features from external stimuli, internal representations, and responses. The model resembles other trace-conditioning models in related domains, which similarly assume that discrete events along a time line activate each other until target occurrence (e.g., Desmond & Moore, 1991; Dickinson, 1980; Machado, 1997; Moore, Choi, & Brunzell, 1998; Sutton & Barto, 1981). The WS event is considered to act as a retrieval cue that automatically initiates an activation cascade along this sequence until the IS occurs (Steinborn et al., 2009, 2010). When the IS occurs, an associative link is established between the IS and activated components on the event sequence, increasing the so-called response strength associated with that specific moment.

The main predictions of the model are derived from three conditioning rules (Los & Van den Heuvel, 2001, p. 372): Response strength (i.e., preparedness) at a particular moment (1) increases when the IS occurs at that moment, due to excitatory reinforcement, (2) remains unchanged when the IS occurs earlier, and (3) decreases when the IS occurs later, due to extinction. Based on these rules, the model predicts fast responses on short-FP repetition trials, since response strength was reinforced at the same critical moment on the previous trial. Fast responses are also predicted to occur on short–long FP sequences, since the critical moment was not bypassed on the previous trial (and, thus, its previously acquired response strength was not reduced). Conversely, in long–short FP sequences, slow responses are predicted, since the critical moment was bypassed on the previous trial. In sum, the trace-conditioning model explains both the variable-FP effect and its sequential modulation by a set of rules governing associative trial-to-trial learning, which produce asymmetric sequential dependencies that – as a necessary "side-effect" – result in the well-known variable-FP effect.

1.2. Effect of irrelevant stimulation during foreperiods on temporal preparation

As mentioned previously, the dual-process model (Vallesi & Shallice, 2007) points to the importance of attentional capacity for tracking time and probability information during the FP. Hence follows that any manipulation that effectively reduces capacity during FP should impair preparatory processing, which should manifest itself in a specific RT increase on long-FP_n trials. Empirical support for this prediction is mainly derived from studies comparing group-related individual differences in cognitive-control functions. In particular, subgroups of individuals considered less capable to adequately implement and/or sustain cognitive control have been shown to exhibit a selective RT increase on long-FP_n trials (yielding a flattening of the FP_n–RT function), compared to matched normal controls. This has been shown for individuals with a variant of attention-deficit disorder (Zahn, Kruesi, & Rapoport, 1991), trait impulsivity (Correa, Trivino, Perez-Duenas, Acosta, & Lupiáñez, 2010), or patients with damage in the right dorsolateral prefrontal cortex (rDLPFC) (Trivino, Correa, Arnedo, & Lupiáñez, 2010). Vallesi, Shallice, and Walsh (2007) provided experimental evidence that the FP_n–RT slope, but not the sequential FP effect, is reduced after inhibiting the rDLPFC with transcranial magnetic stimulation (TMS). According to Vallesi et al., decreasing rDLPFC functioning via TMS is equivalent to a reduction of attentional resources.

Further, irrelevant stimulation during preparatory processing has been shown to interfere with RT performance in FP experiments. In a pioneering study, Terrell and Ellis (1964) examined temporal preparation in a simple-RT task as a function of concurrent irrelevant stimulation during the FP interval (FP length was 2, 4, 8, or 12 s). In one condition, a visual WS was presented for 1500 ms and followed by a standard (blank) FP until auditory IS presentation. In the other condition, the visual WS remained present after its onset for the entire FP interval. The authors found a global RT increase in the filled-FP compared to the blank-FP condition but no selective RT increase on long-FP_n trials. Since the study mainly focused on sustained-attention differences between normal and individuals with mental retardation, it should be noted that normal individuals were more severely affected by the filled-FP condition than retarded ones. Baumeister and Wilcox (1969) replicated these results using an almost identical