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Dynamic adjustment of temporal preparation: Shifting warning signal modality attenuates the sequential foreperiod effect

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ABSTRACT

We examined sequential effects in the variable foreperiod (FP) paradigm, which refer to the finding that responses to an imperative signal (IS) are fast when a short FP trial is repeated but slow when it is preceded by a long FP trial. The effect has been attributed to a trace-conditioning mechanism in which individuals learn the temporal relationship between a warning signal (WS) and the IS in a trial-by-trial manner. An important assumption is that the WS in a current trial (i.e., trial FP_n) acts as a conditioned stimulus, such that it automatically triggers the conditioned response at the exact critical moment that was imperative in the previous trial (i.e., trial FP_{n-1}). According to this assumption, a shift from one WS modality in trial FP_{n-1} to another modality in trial FP_n is expected to eliminate or at least reduce the sequential FP effect. This prediction was tested in three experiments that included a random variation of WS modality and FP length within blocks of trials. In agreement with the prediction, a shift in WS modality attenuated the asymmetry of the sequential FP effect.

1. Introduction

The present study examines the role of warning signals (WS) in temporal preparation experiments. In such experiments, a WS precedes the imperative signal (IS) by a certain duration (referred to as foreperiod, FP), which enables non-specific preparation to the IS (Hackley & Valle-Inclan, 2003; Los & Schut, 2008). Reaction times (RTs) are especially short when the length of the FP interval is predictable and individuals can synchronize peak readiness with the imperative moment (i.e., the moment of IS presentation). But even when FP randomly varies across subsequent trials and the imperative moment cannot exactly be predicted (i.e., variable FP paradigm), the time flow after the WS event provides information that can be exploited to enhance their preparatory state. Since the conditional probability that the IS occurs at a particular moment increases with time, slow responses are observed in short FP trials but especially fast responses in long FP trials. That is to say, RT is a downward-sloping function of FP in the variable FP paradigm (e.g., Drazin, 1961; Klemmer, 1956).

A traditional strategic account attributes this FP-RT function to a process of conditional probability monitoring during the FP interval. In fact, the characteristic downward-sloping of RT with the length of FP is taken as evidence that the individual somehow converts the objective increase of the conditional probability of IS occurrence into a subjective expectation (Niemi & Näätänen, 1981, p. 137). An important theoretical assumption of this account is that the individual actively tracks the time flow after the WS and enhances preparation accordingly (Näätänen & Merisalo, 1977). The empirical fact that the FP-RT function changes in slope when different FP-distributions are used that correspond to different conditional probabilities is usually taken as support for this view. For example, when a FP distribution is used that equalizes the conditional probabilities for each imperative moment, termed a non-aging FP distribution, it is shown that the FP-RT function typically becomes flat (e.g., Baumeister & Joubert, 1969; Näätänen, 1971; Zahn & Rosenthal, 1966).

A trace conditioning account introduced by Los and colleagues (Los & Agter, 2005; Los & Heslenfeld, 2005; Los, Knol, & Boers, 2001; Los & Van den Heuvel, 2001) suggests an alternative

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explanation according to which the FP-RT function is shaped by an unintentional process of associative learning (cf. Machado, 1997; Moore, Choi, & Brunzell, 1998). Specifically, it is assumed that the individuals learn the temporal relationship between WS and IS in a trial-by-trial manner. Accordingly, the downward-sloping FP-RT function is considered to arise largely from sequential effects (Alegria & Delhaye-Rembaux, 1975; Los & Agter, 2005), which refers to the fact that RT in a current trial not only depends on the current FP (i.e., FP_n) but also on FP of the immediately preceding trial (i.e., FP_{n-1}). Specifically, responses in a short FP_n trial are slower when preceded by a long FP_{n-1} than when preceded by an equally long or shorter FP_{n-1} trial (e.g., Karlin, 1959; Klemmer, 1956; Steinborn, Rolke, Bratzke, & Ulrich, 2008; Vallesi et al., 2007; Vallesi & Shallice, 2007; Van der Lubbe, Los, Jaskowski, & Verleger, 2004; Van Koningsbruggen & Rafal, 2009). Thus, the sequential FP effect is asymmetric since it is restricted to short FP_n trials whereas long FP_n trials are not subject to a sequential modulation.

Los et al.'s model relies on the following assumptions (cf. Los & Van den Heuvel, 2001, p. 373). First, the conditioned strength at a critical moment (i.e., one of the three possible imperative moments) is reinforced when the IS occurs at this moment. Second, the conditioned strength at a critical moment remains unchanged when the IS occurs at an earlier critical moment, and third, the conditioned strength at a critical moment decreases when the critical moment is bypassed because the IS occurs at a later critical moment. The model makes specific predictions about possible FP sequences in the variable FP condition. When a short FP length is repeated, fast responses are predicted because response strength was reinforced at the same imperative moment in the preceding trial. When FP alters from long to short, especially slow responses are predicted because the imperative moment was bypassed in the preceding trial, resulting in a decrease of conditioned response strength at short FP_n. Finally, when FP alters from short to long, fast responses are predicted because later imperative moments are less frequently bypassed (e.g., Los & Agter, 2005) and thus less frequently associated with non-responding (e.g., Mattes, Ulrich, & Miller, 1997; Miller, 1998; Reynolds & Miller, 2007, for a discussion in a related domain).

A further yet important assumption of the trace conditioning model concerns the role of the WS in the process of preparation. Since conditioning processes are usually characterized as being unintentional, Los and Van den Heuvel (2001, p. 373) stated that the WS is not solely considered a starting point to intentionally enhance preparation, as would be implied by the strategic view. Instead, it acts as a conditioned stimulus (i.e., a retrieval cue) that unintentionally triggers response activation at previously reinforced critical moments during the FP interval. Like in other trace conditioning models (e.g., Grossberg & Merrill, 1992; Machado, 1997; Moore et al., 1998), the trace is represented as an ordered sequence of time-tagged components. It is assumed that specific features of the WS event initiate an activation cascade such that one component excites the next, and when the IS occurs during this cascade, a time-tagged associative link is established between the sensory representation of the WS and the IS (Los et al., 2001, p. 128). Thus, when a WS event occurs at the beginning of trial FP_n, which resembles FP_{n-1}, this event re-activates sensorimotor couplings that were acquired in trial FP_{n-1}. Consequently, response activation in trial FP_n is then achieved at the exact critical moment that was imperative in trial FP_{n-1} (see also Harris, 2006; Logan, 1990; Moore et al., 1998).

A conditioning view of variable FP phenomena implies that response activation at recently reinforced critical moments should be item-specific rather than concept-based since it involves an unintentional translation of sensory inputs into motor outputs. Given a specific set of stimulus features as components of the WS, even goal-directed action can be triggered directly by environmental stimuli without the need for intentional involvement (e.g., Bargh & Gollwitzer, 1994; Koch, 2001; Miller & Trevena, 2002; Verbruggen & Logan, 2008, for a similar view in related domains). Under the assumption that a successful retrieval of the previously encountered trial episode depends on the similarity between stimuli in the encoding and the test situation (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Rescorla, 1976; Tulving & Thompson, 1973), the pattern of sequential effects in the variable FP paradigm should depend on whether elementary attributes of the WS, for example, its sensory modality, are similar or different from those of the previous trial.

Three experiments were conducted in which WS modality was randomly varied within blocks of trials in a variable FP paradigm, considering different WS modality pairings and levels of temporal uncertainty. If temporal preparation depends on mechanisms of elemental associative learning, as proposed by the trace conditioning account of temporal preparation (Los et al., 2001; Los & Van den Heuvel, 2001), a shift in WS modality should eliminate or at least reduce the typical asymmetric sequential FP effect that is typically found in WS modality repetition trials.

2. Experiment 1

In Experiment 1 (choice RT task), a variable FP paradigm (FPs: 1200 and 3600 ms) was employed in which WS modality (auditory and visual) randomly varied within blocks of trials. As stated before, if the WS triggers the conditioned response rather automatically, the typical asymmetric sequential FP effect should be observed in WS modality repetition trials but should be reduced in WS modality shift trials.

2.1. Method

Participants. Twenty-four (9 males and 15 females) volunteers (mean age = 26.2 years, *SD* = 6.4) took part in this experiment. All participants but one were right-handed and all of them had normal or corrected-to-normal vision.

Stimuli and apparatus. The experiment was run in a dim and noise-shielded room; it was controlled by an IBM computer with color display (19", 150 Hz refresh rate) and programmed in MATLAB™ using the Psychophysics Toolbox extensions (Brainard, 1997). Participants were seated at a distance of 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 was either auditory or visual and appeared for 200 ms. The auditory WS (1000 Hz frequency; 70 dB SPL) was presented binaurally via headphones and the visual WS (a white star; 100 cd/m^2; $2.4° \times 2.4°$ angle of vision) was presented in the centre of a grey (38.4 cd/m^2) computer screen. 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 centre of the computer screen.

Design and procedure. Participants performed a two-choice response task and 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). We used a three-factorial within-subject design, with factors WS-modality sequence (WS-SEQ: repetition of WS modality vs. shift of WS modality), previous FP length (FP_{n-1}: short vs. long) and current FP length (FP_n: short vs. long).

A trial started with the presentation of the WS, followed by a blank FP interval after which the IS occurred. The IS was terminated either by the participant's response or when the response interval expired after 2000 ms. A constant intertrial interval of 1500 ms separated subsequent trials. Participants were instructed