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The costs and benefits of temporal predictability: impaired inhibition of prepotent responses accompanies increased activation of task-relevant responses

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ABSTRACT

While the benefit of temporal predictability on sensorimotor processing is well established, it is still unknown whether this is due to efficient execution of an appropriate response and/or inhibition of an inappropriate one. To answer this question, we examined the effects of temporal predictability in tasks that required selective (Simon task) or global (Stop-signal task) inhibitory control of prepotent responses. We manipulated temporal expectation by presenting cues that either predicted (temporal cues) or not (neutral cues) when the target would appear. In the Simon task, performance was better when target location (left/right) was compatible with the hand of response and performance was improved further still if targets were temporally cued. However, Conditional Accuracy Functions revealed that temporal predictability selectively increased the number of fast, impulsive errors. Temporal cueing had no effect on selective response inhibition, as measured by the dynamics of the interference effect (delta plots) in the Simon task. By contrast, in the Stop-signal task, Stop-signal reaction time, a covert measure of a more global form of response inhibition, was significantly longer in temporally predictive trials. Therefore, when the time of target onset could be predicted in advance, it was harder to stop the impulse to respond to the target. Collectively, our results indicate that temporal cueing compounded the interfering effects of a prepotent response on task performance. We suggest that although temporal predictability enhances activation of task-relevant responses, it impairs inhibition of prepotent responses.

1. Introduction

Efficient adaptation to a complex environment requires not only that appropriate responses are selected and unwanted ones prevented, but also that these responses (or lack thereof) occur at appropriate moments in time. The ability to select precise moments in time in order to optimise behaviour depends upon the ability to make temporal predictions. Studies have shown that using abstract, yet temporally informative, cues to predict when an event will occur - a phenomenon known as the temporal orienting of attention - enhances sensorimotor processing of the event by improving accuracy (Correa, Lupiáñez, & Tudela, 2005; Davranche, Nazarian, Vidal, & Coull, 2011; Martens & Johnson, 2005; Visser, 2014) and speeding response times (Coull & Nobre, 1998; Nobre, 2001; Correa, Lupiáñez, & Tudela, 2006). It is unknown, however, whether the beneficial effect of temporal cues on response time is due to more efficient selection of a response appropriate to the target and/or better inhibition of an inappropriate one. The goal of the present study was to examine the effects of temporal orienting on these two complementary aspects of motor control.

These control processes have traditionally been investigated with so-called "conflict" tasks, such as the Simon (Simon, 1969), Flanker (Eriksen & Eriksen, 1974) or Stroop (Stroop, 1935) tasks. In such tasks, stimuli are composed of two perceptual dimensions: one is relevant for the task at hand and defines the to-be-given response (for example a plus or a cross associated with a left or right hand response, respectively); the second dimension, although irrelevant for the task, shares conceptual properties with the relevant dimension and/or response, and hence interferes with task goals (in the Simon task for example, the plus sign could be presented on the left side of the screen, compatible with the correct response, or on the right side, incompatible with it). Typically, reaction times to incompatible targets are slower than those to compatible ones, and this behavioural cost can be used to index the interference effect of response conflict. Recently, Menceloglu, Grabowecky and Suzuki (2017) failed to find an effect of temporal cueing on response conflict in the Flanker task. However, using both Flanker and Simon tasks, Correa, Cappucci, Nobre, and Lupiáñez (2010)

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found that temporal cueing significantly exacerbated the behavioural cost of response conflict. Specifically, the interference effect was even greater when participants were expecting the target to occur at a particular moment in time. The authors suggested that temporal orienting increased motor readiness for all targets, thereby facilitating correct responses on compatible trials but increasing interference on incompatible trials (see also Weinbach and Henik, 2013).

This effect could, however, stem from any one of the different processes that are needed to make a correct response. First, intention-guided action selection allows the appropriate goal-directed response to be deployed according to task instructions (Vohs and Baumeister, 2004). For example, a left-handed response can be activated after a presentation of a '+'. At the same time however, strong extraneous stimulus-action associations (for example, activation of a left-handed response to presentation of a target on the left side of the screen) might activate inappropriate actions, through a process called response capture, which is fast and automatic in nature. In conflict tasks, the relevant dimension (e.g., the shape of the target in the example above) causes the intention-guided response to be activated, while the irrelevant one (target position) automatically triggers a stimulus-action association, which can be either compatible or incompatible with the intention-guided response. Since the intentional component of the selection process is thought to take time to build up (Ridderinkhof, 2002), fast responses are more likely to have been driven by prepotent stimulus-action associations. The relative strength and the time course of these processes can be estimated by Conditional Accuracy Functions (CAF), which plot the probability of making a correct response as a function of response speed. In conflict tasks, CAF usually reveal that fast responses to incompatible targets are more error-prone, indicating that fast action selection is driven more by strong, extraneous stimulus-action associations than by deliberate intentions (Ridderinkhof, Forstmann, Wylie, Burle, & van den Wildenberg, 2011).

Another crucial mechanism in action control therefore, is response inhibition – active suppression of the inappropriate action. It can be engaged to suppress inappropriate responses (incorrect or premature) in favour of more goal-directed ones, or to suppress any action in general (Mostofsky & Simmonds, 2008; Ridderinkhof et al., 2011). Two of the most predominantly used experimental paradigms for investigating response inhibition are the Simon task (Simon, 1969, 1990) and the Stop-signal task (Logan, Cowan, & Davis, 1984; Verbruggen & Logan, 2008). In the Simon task, selective inhibition is indexed by successful suppression of the response triggered by the task-irrelevant feature in favour of the response associated with the task-relevant feature. In the example given above, a '+' presented on the right of the screen would require selective inhibition of the right-hand response, allowing the left-hand response to be deployed. It has been proposed that the dynamics of such suppression can be revealed in "delta-plots" (Ridderinkhof, 2002), which depict the magnitude of the interfering effect of the task-irrelevant feature as a function of reaction time. Specifically, slower response times show less of an interference effect than faster ones, because the inhibition process has had sufficient time to take effect. Accordingly, the greater the difference in the size of the interference effect between fast and slow response times (i.e., a more negative-going slope) the greater the influence of inhibition on performance.

By contrast to this selective inhibition of an inappropriate response in the Simon task, the Stop-signal task requires a more global form of inhibition. The Stop-signal paradigm involves two concurrent tasks, termed a go task, which is usually a discrimination task, and a stop task occurring on 25% of trials. During stop trials, an auditory tone is presented, which informs the subjects to refrain completely from giving their response on that trial. Performance on the task has been suggested to depend upon a race between two independent processes: the go process and the stopping process (Logan, 1994; Logan et al., 1984). If the stop process is faster than the go process, the response is successfully inhibited (i.e., no response is emitted). Conversely, if the go process is faster than the stop process then a response is incorrectly produced. Importantly, this race model allows the time taken to inhibit a response to be inferred, which is often termed the "Stop-signal reaction time" (SSRT).

The aim of our study was to measure the effects of temporal cueing on response activation and inhibition using both the Simon task (see also Correa, Triviño, Pérez-Dueñas, Acosta, & Lupiáñez, 2010) and, for the first time, the Stop-signal task. The use of both tasks allowed us to compare the effects of temporal predictability on response inhibition processes that were implemented either to selectively suppress erroneous responses to irrelevant stimulus-driven associations (Simon task) or to withhold responses entirely (Stop-signal task). Many previous studies of response inhibition have shown that presentation of non-specific warning cues in the Flanker paradigm increases interference effects, due either to a deleterious effect on cognitive control (e.g., Callejas, Lupiàñez, Funes, & Tudela, 2005) or to enhanced sensory processing of irrelevant, as well as relevant, stimuli (e.g., Nieuwenhuis & de Kleijn, 2013; Weinbach & Henik, 2012b). Indeed, enhanced sensory processing has also been used to explain the beneficial effects of warning cues in the Stop-signal paradigm (Weinbach, Kalanthroff, Avnit, & Henik, 2015). These authors have also made a clear distinction between warning cues (a non-specific state of alertness before target onset) and temporal cues (prediction of target onset) (Weinbach & Henik, 2012a, 2013), and suggested that each might influence processing in similar, yet independent, ways. We extend this literature by measuring the effects of cues carrying temporally precise information on processes of response inhibition. We also aimed to refine the results of previous studies by using sensitive chronometric measures (CAF, delta plots) to more fully characterize the effects of temporal predictability on action control in terms of both response activation and response inhibition.

Finally, in contrast to previous studies (Correa et al., 2010, Menceloglu et al., 2017) in which the length of the delay between the cue and the target (the "foreperiod [FP]") was manipulated in a blockwise fashion (equivalent to a fixed FP paradigm), we investigated the effects of trial-by-trial temporal cueing. In our variable FP paradigm, temporal cues predicted whether the target would appear after either a short or long FP, allowing the temporal focus of attention to be flexibly oriented from one trial to another within a block. In the control condition, targets also appeared after either short or long FPs but uninformative "neutral" cues did not predict the duration of the upcoming FP. This control condition not only allowed us to measure the performance benefits of temporal versus neutral cues, but also allowed us to measure more implicit forms of temporal expectation induced by the variable length of the FP itself. Typically, in a neutrally cued variable FP paradigm, response times are faster to targets presented after long, rather than short, FPs ("variable FP effect") or to targets presented after a FP that is identical to that of the preceding trial ("sequential effects" of FP) (Niemi & Naatanen, 1981). Participants appear to automatically form temporal predictions about FP length based on the temporal statistics inherent in the trial or task structure (Los, Kruijne, & Meeter, 2014) in order to speed responses. Different mechanisms have been proposed to account for observed data. For example, in the multiple trace theory, the memory trace of the FP encountered in more recent trials is stronger than that encountered in more distance ones and so contributes more to current behaviour (Los et al., 2014). Alternatively, in the dual-process model, hazard-based preparation is combined with automatic carryover of a refractory cost (Vallesi & Shallice, 2007). Regardless of the theoretical account, results have revealed that sequential effects remain more resistant to different experimental manipulation such as dual-task interference and spatial context (Vallesi, Arbula, & Bernardis, 2014; Los, 2004, respectively). Collectively, results suggest that sequential effects are driven by automatic processes, whereas the variable FP effect may be underpinned by more controlled processes.

Based on previous findings, we formulated two hypotheses. If