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Evidence for a response preparation bottleneck during dual-task performance: Effect of a startling acoustic stimulus on the psychological refractory period

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ABSTRACT

The present study was designed to investigate the mechanism associated with dual-task interference in a psychological refractory period (PRP) paradigm. We used a simple reaction time paradigm consisting of a vocal response (R1) and key-lift task (R2) with a stimulus onset asynchrony (SOA) between 100 ms and 1500 ms. On selected trials we implemented a startling acoustic stimulus concurrent with the second stimulus to determine if we could involuntarily trigger the second response. Our results indicated that the PRP delay in the second response was present for both control and startle trials at short SOAs, suggesting the second response was not prepared in advance. These results support a response preparation bottleneck and can be explained via a neural activation model of preparation. In addition, we found that the reflexive startle activation was reduced in the dual-task condition for all SOAs, a result we attribute to prepulse inhibition associated with dual-task processing.

1. Introduction

Although it may seem quite common in everyday life for one to perform several actions concurrently, research investigating the performance of multiple tasks suggests that the human capacity for parallel motor processing is actually quite limited. One of the simplest and most common methods used to examine the limitations of human processing is a dual-task technique whereby participants are required to identify and respond to two separate stimuli presented in succession. A consistent finding is that as the time interval between the two stimuli (known as the stimulus onset asynchrony or SOA) becomes short, the reaction time (RT) to respond to the second stimulus is increased while the latency of the first response is typically unaffected. The delay in responding to the second stimulus as a result of processing the first stimulus is known as the psychological refractory period (PRP). The PRP was first reported by Telford (1931) and represents an apparent limitation of the human information processing system to simultaneously process two stimulus–response streams. The PRP effect is extremely robust and occurs when the responses required are presented in a simple or choice RT task, and regardless of the degree of difficulty in cue perception, response selection, or task complexity (see Lien & Proctor, 2002; Pashler, 1994; 1998 for reviews).

The processing difficulties associated with responding quickly to two closely spaced stimuli suggest that dual-task performance requires the use of a common processing mechanism or limited resource. Specific explanations for the PRP effect are commonly split into two categories: bottleneck models and capacity-sharing models. Bottleneck models generally theorize that the processing of multiple stimuli at some point reaches a bottleneck whereby only one item can be processed at a time (i.e., a “central bottleneck”). This serial limitation postpones some aspect of processing of the second task until the first task is completed, resulting in the PRP effect. A number of studies have focused on determining where the bottleneck occurs but there is currently no consensus. Considerable evidence suggests that stimulus perception can occur in parallel and thus is unlikely to contribute to the bottleneck (Pashler,

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1994), therefore, the most common explanation is a response selection bottleneck (Karlin & Kestenbaum, 1968; Smith, 1969; Welford, 1952). However since a PRP effect is still observed in tasks that might not require response selection (e.g., simple RT; Telford, 1931; Welford, 1952) others have suggested that the bottleneck may be located in response production processes (Bratzke, Rolke, & Ulrich, 2009; Keele, 1973). Finally it is possible that a bottleneck occurs at both response selection and movement preparation/initiation processing stages, or that these processes are all subject to the same central bottleneck (Bratzke et al., 2009; De Jong, 1993; Pashler, 1994).

An alternative to the bottleneck model is a capacity-sharing model whereby processing capacity is divided among the two tasks in a flexible and graded fashion (Kahneman, 1973; McLeod, 1977; Navon & Miller, 2002). It is thought that processing capacity is typically allocated to the first task until a second stimulus occurs, at which time the two tasks can share the allocated capacity until the first response is completed; the second task can then proceed with full processing capacity. The capacity-sharing model can be used to explain many previous PRP experimental results (Tombu & Jolicœur, 2003), and is thus argued to be a viable alternative to the bottleneck model.

Since the main differentiator between the bottleneck and capacity models involves the capability for parallel processing during response selection and production, researchers have attempted to encourage dual processing by emphasizing the importance of the second response. Nevertheless, these manipulations have still resulted in a strong PRP effect supporting a central bottleneck model (Levy & Pashler, 2008; Ruthruff, Johnston, & Remington, 2009; Ruthruff, Pashler, & Hazeltine, 2003). However, these conclusions have recently been criticized for not optimally encouraging parallel processing. Using a performance optimization model, Miller, Ulrich, and Rolke (2009) suggested that parallel processing would be a more efficient strategy when there is a high incidence of short SOAs. Indeed, these authors showed that a dual-response task employing mostly short SOAs reduced the PRP effect and thus, they argued, caused a shift from serial to parallel processing (Miller et al., 2009). Thus, while the PRP effect is a robust phenomenon, the processes underlying response delays are still a subject of debate, requiring further exploration.

The purpose of the current study was to examine dual-task processing by using a startling acoustic stimulus (SAS) to probe the preparatory processes associated with the second response in a PRP paradigm. When a SAS is presented in a simple RT task, RT is facilitated (shortened) to such an extent that it is thought to bypass the usual voluntary command processes (see Carlsen, Maslovat, & Franks, 2012; Carlsen, Maslovat, Lam, Chua, & Franks, 2011; Rothwell, 2006; Valls-Solé, Kumru, & Kofler, 2008 for reviews). Early studies involving a SAS decreased voluntary RTs from 150–170 ms to reflexive-like latencies of 70–80 ms (Valls-Sole, Rothwell, Goulart, Cossu, & Munoz, 1999; Valls-Sole et al., 1995). Given the required 60–65 ms for neural transmission and auditory transduction times on a typical control RT trial, these SAS-induced RTs left insufficient time for cortical processing, leading to the hypothesis that the SAS acts through a faster neural pathway as an automatic trigger for a pre-programmed movement (see Carlsen, Chua, Inglis, Sanderson, & Franks, 2004b; Valls-Sole et al., 1999 for timing details). Whereas a non-startling "go" signal is processed via primary auditory cortex leading to voluntary initiation of a response, the SAS is thought to directly and involuntarily trigger the prepared response (assuming sufficient levels of preparatory activation) via ascending reticulo-thalamo-cortical circuits (Carlsen et al., 2012). These circuits are activated through reticular structures which also mediate the short latency startle reflex (Yeomans & Frankland, 1996). Additional support for this altered initiation mechanism has been provided by using a SAS during a choice RT paradigm, in which response selection processes are required. In these experiments the SAS produced little or no RT facilitation (Carlsen, Chua, Inglis, Sanderson, & Franks, 2004a; Kumru et al., 2006; Maslovat, Hodges, Chua, & Franks, 2011a), confirming that the SAS does not simply speed up voluntary processes and only results in short latency responses (i.e. <100 ms) when the movement is prepared in advance of the "go" signal.

By presenting a SAS prior to the second response, we hoped to exploit this separate and involuntary initiation pathway to examine the processes involved in preparing and initiating two separate responses. Although previous experiments have provided evidence in support of a "motor" bottleneck, it is currently unclear what processes this encompasses. Some researchers have suggested that response preparation processes can occur in parallel but a response initiation bottleneck occurs such that there is a fixed refractory period after R1 initiation in which no other responses can occur (De Jong, 1993; Keele, 1973). Alternatively, some have argued that multiple processes in the preparation/execution chain can contribute to the motor bottleneck (Bratzke et al., 2009). In the current experiment we used a SAS to examine the possibility of a response preparation bottleneck, in which only one response can be held at a high level of preparatory neural activation. If both responses are able to be prepared in advance (supporting parallel response preparation), we predicted that the response triggering effect of a SAS would bypass any response initiation bottleneck and trigger the second response at a short latency (similar to what is found in startle trials during single-task, simple RT paradigms), regardless of the SOA. Alternatively, if the two responses could not be prepared concurrently (supporting a response preparation bottleneck), we predicted that a PRP effect would be observed for both startle and non-startle trials, as the lack of preparation of the second response would preclude any triggering by the SAS.

Although the use of a SAS has not been employed in a PRP, dual-task paradigm, it has been used successfully to probe motor preparation in a simple RT situation, when advance preparation can occur. A number of research groups have examined diverse movements such as wrist and elbow flexion/extension, stepping, sit-to-stand, eye and head movements and have consistently found mean RTs in the 70–100 ms range for startle trials (see Carlsen et al., 2012 for a more detailed review). While the current study does differ from a single-task RT paradigm in that the preparation of two distinct responses likely involves additional decision making processes, by knowing the required responses in advance the participant may be able to prepare both responses independently. We encouraged participants to prepare both responses in advance by using simple RT tasks that involved limited structural interference between responses, a high incidence of short SOAs, and an emphasis on task equality.

2. Methods

2.1. Participants

Data were collected and analyzed from eleven right-handed volunteers (4 males, 7 females; $M = 22.5$ yrs, $SD = 3.4$ yrs) who showed a consistent activation (three of four trials) in the sternocleidomastoid (SCM) muscle within 120 ms following a SAS (a reliable indicator of a startle response; see Carlsen et al., 2011 for inclusion criteria) in a simple RT task involving a single response (see Section 2.2). It was critical to ensure participants showed a consistent startle response as engagement of the startle reflex circuitry generally indicates sufficient subcortical activation to lead to involuntary response triggering (Carlsen, Dakin, Chua, & Franks, 2007). This single-task pre-screening was necessary because activation in the SCM during dual-task trials was unreliable as our methods involved the presentation of an auditory signal prior to the SAS, which has been shown to be able to modify and reduce the startle reflex through prepulse inhibition (Graham, 1975; although this inhibition does not affect early response triggering, see Maslovat, Kennedy, Forgaard, Chua, & Franks, 2012; Valls-Solé, Kofler, Kumru, Castellote, & Sanegre, 2005). All participants signed an informed consent form and were naïve to the hypothesis under investigation. This study was conducted in accordance with ethical guidelines established by the University of British Columbia.