Acta Psychologica 158 (2015) 36–42

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

A startling acoustic stimulus interferes with upcoming motor preparation: Evidence for a startle refractory period

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ARTICLE INFO

Article history:
Received 23 July 2014
Received in revised form 16 March 2015
Accepted 10 April 2015
Available online 25 April 2015

Keywords:
Psychological refractory period
Dual-task performance
Response preparation
Startle reflex

ABSTRACT

When a startling acoustic stimulus (SAS) is presented in a simple reaction time (RT) task, response latency is significantly shortened. The present study used a SAS in a psychological refractory period (PRP) paradigm to determine if a shortened RT1 latency would be propagated to RT2. Participants performed a simple RT task with an auditory stimulus (S1) requiring a vocal response (R1), followed by a visual stimulus (S2) requiring a key-lift response (R2). The two stimuli were separated by a variable stimulus onset asynchrony (SOA), and a typical PRP effect was found. When S1 was replaced with a 124 dB SAS, R1 onset was decreased by 40–50 ms; however, rather than the predicted propagation of a shortened RT, significantly longer responses were found for RT2 on startle trials at short SOAs. Furthermore, the 100 ms SOA condition exhibited reduced peak EMG for R2 on startle trials, as compared to non-startle trials. These results are attributed to the startling stimulus temporarily interfering with cognitive processing, delaying and altering the execution of the second response. In addition to this "startle refractory period," results also indicated that RT1 latencies were significantly lengthened for trials that immediately followed a startle trial, providing evidence for longer-term effects of the startling stimulus.

1. Introduction

A common technique used over the past century to examine people's ability to perform multiple activities concurrently is the psychological refractory period paradigm (Telford, 1931), in which participants are required to identify and respond to two stimuli (S1 and S2) which are separated in time. Typically, as the time interval between the two stimuli (stimulus onset asynchrony; SOA) shortens, the reaction time (RT) to respond to the first stimulus (RT1) is unaffected, while the response latency to the second stimulus (RT2) is increased. The delay in RT2 is known as the *psychological refractory period* (PRP) and is thought to be indicative of the cost associated with processing two stimulus–response streams simultaneously (see Lien & Proctor, 2002; Pashler, 1994, 1998 for reviews).

Explanations offered for a delayed RT2 in PRP tasks can typically be divided into capacity sharing or "bottleneck" models (Pashler, 1994). Capacity theories assume that processing resources are shared among tasks and thus when multiple tasks are performed there is less resource available for each task, leading to impaired performance (Kahneman, 1973). Conversely, bottleneck theories posit that certain processing stages cannot be performed in parallel and thus processing multiple stimuli reaches a rate-limiting stage at some point whereby only one item can be processed at a time. Although the location of the bottleneck is still debated, considerable evidence exists suggesting that stimulus perception can occur in parallel and therefore is unlikely to contribute to the bottleneck (Pashler, 1994). While some research has provided support for a response selection bottleneck (e.g., Karlin & Kestenbaum, 1968; Smith, 1969), a PRP effect also occurs in a simple RT paradigm where response selection is minimal, indicating the bottleneck may involve the response production stage (Bratzke, Rolke, & Ulrich, 2009; Maslovat et al., 2013). It is also possible that a bottleneck occurs at multiple stages or that a central bottleneck affects both response selection and movement production (De Jong, 1993; Pashler, 1994).

In order to examine the PRP effect and which stage of processing is affected, the bottleneck theory offers a number of testable predictions. One such prediction is that any modification to task 1 that changes the central processing time required (up to or including the bottleneck stage), should have an equal effect on both RT1 and RT2 (Pashler, 1994). That is, at short SOAs, any RT change of task 1 should be *propagated* to task 2 (see Fig. 3, middle panel), whereas propagation effects would not be predicted at long SOAs as there is no overlap in processing (Miller & Reynolds, 2003). Propagation effects have been confirmed by manipulating response selection variables such as number of response alternatives (Karlin & Kestenbaum, 1968; Smith, 1969), as well as response production variables such as sequence length (Bratzke et al.,

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http://dx.doi.org/10.1016/j.actpsy.2015.04.003
0001-6918/

2008) or movement amplitude (Bratzke et al., 2009; Ulrich et al., 2006). In these experiments, increasing the time required to process task 1 resulted in similar magnitude increases for both RT1 and RT2 at short SOAs, consistent with the predictions of the bottleneck theory. Additionally, other research has reduced the response latency of RT1 through increased temporal predictability (Bausenhart, Rolke, Hackley, & Ulrich, 2006) or practice (Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003), resulting in a similar decrease in RT2 at short SOAs.

The purpose of the current study was to examine response propagation effects in a PRP paradigm by reducing task 1 latency through the use of a startling acoustic stimulus (SAS). When a SAS is presented in a simple RT task, RT is significantly shortened as the SAS acts as an involuntary trigger of the prepared response, bypassing response selection processes and shortening stimulus detection and response initiation stages (see Carlsen, Maslovat, & Franks, 2012; Valls-Solé, Kumru, & Kofler, 2008 for reviews). Specifically, it is thought that the SAS activates subcortical brain structures via connections between the cochlear nucleus and reticular formation, leading to both a reflexive startle response as well as involuntary activation leading to the initiation of a prepared response (provided a sufficient level of advance preparation of the movement; see Carlsen et al., 2012 for more details). As the pathways and processes associated with the startle-mediated release of a response are faster than voluntary response initiation, responses to the SAS are significantly shortened as compared to non-startle trials (e.g., muscle activation onset <80 ms; Valls-Solé, Rothwell, Goulart, Cossu, & Munoz, 1999).

In the current study, participants performed two simple RT tasks in a PRP paradigm, in which they were required to respond to an auditory stimulus (S1) with a vocal response (R1), which was followed by a visual stimulus (S2) requiring a key-lift movement (R2). On selected trials, S1 was replaced with a SAS, with the expectation that this would shorten RT1 latency in the range of 40–60 ms, as has been previously shown for a vocal response (Stevenson et al., 2014). Of primary interest was whether the RT "savings" associated with startle trials would propagate to RT2 for short SOAs, as predicted by the central bottleneck model. As both responses were known in advance, any propagation effects would be attributed to a shortened response execution stage of R1, leading to a similar reduction in the latency of R2. Although this logic is similar to previous work examining propagation effects, the use of a SAS provides unique benefits, as the SAS is considered to act via a separate and involuntary response initiation pathway, thus bypassing any response initiation bottleneck (Bratzke et al., 2009; De Jong, 1993). Indeed, a SAS has been successfully used in a dual-task paradigm to assess the attentional demands of a continuous task (Begeman, Kumru, Leenders, & Valls-Sole, 2007), as well as in a PRP paradigm as a probe to determine the preparation level of the second response (Maslovat et al., 2013).

2. Methods

2.1. Participants

Data were collected from 17 right-handed volunteers with no sensory or motor dysfunctions. However, five participants were excluded due to a lack of activation in the sternocleidomastoid (SCM) muscle within 120 ms following a SAS (a reliable indicator of a startle response; see Carlsen, Maslovat, Lam, Chua, & Franks, 2011 for inclusion criteria) on all four startle trials in the single-task vocal RT block (see Section 2.2 Experimental Design). Thus, data are presented from twelve participants (7 male, 5 female; $M = 24.8$ yrs, $SD = 6.1$ yrs). All participants signed an informed consent form and were naïve to the hypothesis under investigation. This study was approved by the University of British Columbia ethics committee and was conducted in accordance with the ethical guidelines set forth by the Declaration of Helsinki.

2.2. Apparatus, task, and experimental design

Participants sat in a height-adjustable chair in front of a table with a 22-inch computer monitor (Acer X233W, 1152 × 864 pixels, 75 Hz refresh) placed on it. Participants placed the right hand on a telegraph key (E.F. Johnson Speed-X, Model 114-300) located on the table that required 2 N of force to close (i.e., simply resting the hand on the switch was sufficient to close it). A microphone (Sennheiser, MKH 416-P48) was placed in front of the participant, below the monitor to capture vocal responses.

To determine baseline performance, participants began by performing 20 trials of each of the two required responses in a single-task situation. All trials began with the word "Ready!" presented on the computer screen, followed by a variable foreperiod of 2500–3500 ms. For the first block of trials, participants were instructed to respond to an auditory stimulus by vocalizing the word "TAT" as quickly as possible. The auditory stimulus consisted of a non-startling tone on 16 trials (82 ± 2 dB, 40 ms, 1000 Hz) and a startling tone on 4 trials (124 ± 2 dB, 40 ms, 1000 Hz, <1 ms rise time). Startle trials were interspersed pseudorandomly such that the first trial was never a startle trial and there were never two consecutive startle trials. Acoustic signals were generated by a customized computer program and were amplified and presented via a loudspeaker placed behind the head of the participant. Acoustic stimulus intensity was measured at a distance of 30 cm from the loudspeaker (approximately the distance to the ears of the participant) using a sound level meter (Cirrus Research model CR:252B; "A"-weighted decibel scale, impulse response mode). In the second block of trials, participants were instructed to respond to the presentation of a green circle (10 cm diameter) in the middle of the computer screen by lifting their right hand off the telegraph key as quickly as possible. During the single-task testing blocks, RT was presented on the screen for five seconds following each trial with a monetary reward of CDN $0.05 per trial for RTs below 250 ms.

Following the single-task trials, participants were informed that they would be performing both the vocal response and key-lift in a dual-task situation, and that they should give equal priority to performing each task as quickly as possible. The auditory stimulus (S1) was always presented first and required a vocal response of "TAT" (R1), followed by the visual stimulus (S2) requiring a right hand key-lift response (R2). A practice block of 20 trials was conducted, with SOAs of 100 ms (10 trials), 200 ms (4 trials), 500 ms (2 trials), 1000 ms (2 trials), and 1500 ms (2 trials) randomly presented. A high proportion of short SOA trials were used, as propagation effects are only expected for these conditions. Following the practice block, participants performed 5 blocks of 25 test trials whereby 20 trials involved the same distribution of SOAs as the practice trials, but one additional trial was presented at each SOA where the 124 dB SAS was presented in place of the normal 82 dB auditory stimulus (S1) (i.e., 5 startle trials per test block, 25 startle trials total). Startle trials were interspersed pseudorandomly within each block in a similar manner to the single-task testing condition. During the dual-task testing blocks, RT for each task was presented simultaneously on the screen for seven seconds following each trial with a monetary bonus of CDN $0.05 per task (i.e., up to $0.10 per trial) for fast RTs (<250 ms for RT1, <300 ms for RT2). Participants were instructed to try and maximize their reward bonus by minimizing total RT and thus receiving the reward bonus for both responses. Participants were allowed a rest period of approximately one minute in between blocks and the testing session lasted approximately 1 h.

2.3. Recording equipment

Surface EMG data were collected from the muscle bellies of the right extensor carpi radialis longus (ECR — agonist), and right and left sternocleidomastoid (SCM — used as a startle indicator only) using preamplified surface electrodes connected via shielded cabling to an external amplifier system (Delsys Model DS-80). Recording sites were prepared and cleansed in order to decrease electrical impedance. The