The bottleneck of the psychological refractory period effect involves timing of response initiation rather than response selection

Stuart T. Klapp¹ · Dana Maslovat² · Richard J. Jagacinski³

Published online: 3 July 2018
© Psychonomic Society, Inc. 2018

Abstract

The Psychological Refractory Period (PRP) effect is a delay in responding that is assumed to be caused by a bottleneck that prevents preparation of a second action until preparation of the previous action has been completed. The bottleneck is usually attributed to a limitation that prevents concurrent selection of two responses. However, evidence reviewed here challenges this selection interpretation. We propose instead that the bottleneck is due to a process that programs the timing of response initiation, and which must be completed immediately prior to responding. This hypothesis is based on two conclusions from recent developments in research, which includes findings from paradigms that do not involve the PRP. The first conclusion is from studies involving the startle response and single-task simple (precued) reaction time; these studies indicate that programming the timing of response onsets is needed to enable response initiation. This programming takes longer for more complicated timing, and must be delayed until just prior to responding. The second conclusion is from studies of concurrent rhythmic movements demonstrating that the representation of timing is restricted to one temporal frame unless very rapid performance enables parallel timing. These findings reveal limitations that can combine to produce the PRP bottleneck. This interpretation clarifies otherwise puzzling aspects of the PRP effect and indicates that a fundamental restriction concerning response timing may underlie both limitations and the PRP effect that they produce. This restriction might arise because timing is controlled by subcortical neural structures with limited working memory.

Keywords Psychological Refractory Period · Divided attention · Multitasking · Response timing · Response initiation

Introduction

Although people appear to be able to carry out actions simultaneously, closer examination of performance when multiple actions are required often reveals a bottleneck due to a stage of processing that cannot be shared by concurrent tasks. This bottleneck delays preparation of a second action until preparation of an earlier action is completed. Although this phe-

nomenon is called the Psychological Refractory Period (PRP) effect, the analogy to neural refractoriness may not be appropriate because the PRP effect is attributed to a high-level limitation (bottleneck) rather than to individual neurons. The present analysis concerns the locus of this bottleneck within the flow of information between stimuli and responses. There are other forms of limitation in dual task performance that do not create an absolute bottleneck; these are described briefly after discussion of the PRP effect.

✉ Stuart T. Klapp
Stuart.Klapp@csueastbay.edu

¹ Department of Psychology, California State University, East Bay, Hayward, CA, USA
² School of Kinesiology, University of British Columbia, Vancouver, BC, Canada
³ Department of Psychology, Ohio State University, Columbus, OH, USA

Overview of PRP

The PRP effect has been studied in the laboratory using a speeded reaction time (RT) paradigm (Fig. 1) in which two stimuli, S1 and S2, appear in succession. Each stimulus requires a unique response, R1 and R2. A consistent finding is that, if the time interval separating the onsets of the two stimuli (the stimulus onset asynchrony or SOA) is made shorter, the

Fig. 1 Research paradigm and theoretical models of the Psychological Refractory Period. All panels illustrate the research paradigm used to study the Psychological Refractory Period (PRP) effect. Onsets of two stimuli are separated by the stimulus onset asynchrony (SOA) interval and the reaction time (RT) to each stimulus is measured. The theoretical sequence of processing stages between the first stimulus (S1) and response (R1) applies to all panels. The stage labeled (R1 or R2) Timing Initiation is unique to the interpretation proposed in the present article and involves the programming of the timing structure of the response. Panels **b**, **c**, and **d** represent different models concerning

which stage or stages of processing between the second stimulus (S2) and response (R2) are impacted by the PRP bottleneck (delay interval). In panel **b** no S2-R2 processing can occur in the delay interval; in panel **c** only S2 perception can occur; in panel **d** both S2 perception and R2 selection can occur during the delay interval so that only programming of timing of response initiation is blocked by the bottleneck. The present analysis supports the version in panel **d**. Note that R1 and R2 are extended with dashed lines to indicate that responses continue for a longer length of time but do not affect any stages of processing

RT to respond to the first stimulus (RT1) is unaffected (Fig. 1A) but the time to respond to the second stimulus (RT2) is increased compared to that observed if this task is performed in isolation. In Fig. 1B this increase in RT2 is interpreted as being due to postponement of all processing related to R2 until processing related to R1 is completed at the end of RT1. In this model the delay interval during which processing is postponed, the bottleneck, can be identified as the refractory period because it blocks all processing related to the second response. After this postponement delay, processing related to the second response (R2) can begin; this processing requires the same time (RT2ref) that would be needed if there was no previous action. Thus, the increased RT2 beyond RT2ref is not attributed to slower processing but instead is assumed to reflect postponement of initiation of processing related to the second response. Welford (1952; see also Smith, 1967), described this interpretation of the PRP effect as the *single channel hypothesis*.

According to this interpretation, RT2 increases when SOA is made shorter because the delay interval becomes longer. This is analogous to a situation in which customers arrive to be served by a clerk who refuses to serve customers simultaneously (Pashler, 1993). If the second customer arrives earlier he must wait longer while the first customer is being served

before the clerk will begin taking care of him. Once service is started, the previous presence of the first customer does not influence the time needed for completion of the second transaction.

This model can be described algebraically in conjunction with Fig. 1A and B as follows: A bottleneck delays the start of planning R2 until the end of RT1, i.e. until all planning of R1 has been completed. The actual production of R1 is not part of the bottleneck; this applies only to planning R1. After the bottleneck delay is over, the additional time required to plan R2 is identical to the time required to react to S2 in isolation (RT2ref). Thus, if $SOA > RT1$, $RT2 = RT2ref$. The interesting prediction applies when SOA is shorter, $< RT1$, as in Fig. 1B. Then RT2 is increased beyond RT2ref by an amount equal the delay interval so that:

$$RT2 = (\text{delay interval}) + RT2ref$$

From Fig. 1B we see that the delay interval is $RT1 - SOA$. Thus, we can write:

$$RT2 = (RT1 - SOA) + RT2ref$$

Or, after rearranging:

$$RT2 = (-1) SOA + (RT1 + RT2ref)$$

This prediction, which applies for $SOA < RT_1$, together with the predicted constant RT_2 at longer SOA is illustrated in Fig. 2.

The slope of -1 in the above equation indicates that a decrease in SOA should produce an equal magnitude increase in RT_2 ; the model attributes this to a corresponding increase in the delay interval (Fig. 1B). Several studies have reported a slope approaching the predicted -1 (see Lien & Proctor, 2002; Pashler, 1994a, 1998 for reviews). This bottleneck interpretation of the PRP effect can be contrasted with the assumption that any increase in RT_2 may be due instead to graded attentional demands (for a review see Tombu & Jolicoeur, 2003). Subsequent analyses support the bottleneck interpretation (Bratzke, Rolke, & Ulrich, 2009; Levy & Pashler, 2008; Ruthruff, Johnston, & Remington, 2009; Ruthruff, Pashler, & Hazeltine, 2003).

These equations and Fig. 1A and B assume that all processing is blocked during the bottleneck of RT_1 . Alternatives to be considered later relax this assumption based on findings that indicate that perception of S2 and selection of R2 are not subject to the bottleneck. Instead our interpretation is that programming the timing of response initiation produces the bottleneck (Fig. 1D).

Hesitations (pauses) as another symptom of the bottleneck

In the PRP paradigm, processing of the second response is assumed to be *postponed* by a bottleneck until processing related to the first response has been completed. A bottleneck could also cause processing for a newly introduced task to *interrupt* processing of an ongoing task. This interruption can cause the ongoing action to stop, i.e., to hesitate. For example, Cliff (1973) examined manual tracking with and without concurrent verbal shadowing and reported episodes of inactivity or holds in tracking in the presence of articulatory responses. Hesitations in manual tracking are also induced by a second manual response (Klapp, Kelly & Netick, 1987; Netick & Klapp, 1994). These hesitations in tracking begin prior to the start of the second response indicating that hesitations are produced by planning rather than by executing this response (Netick & Klapp, 1994).

Some of the secondary responses did not produce hesitations. This would be expected if tracking is controlled as an intermittently corrected servo (Craik, 1947) in which tracking is directed by an overall goal but control of action specifics is programmed (corrected) only intermittently. This mode of control would produce brief episodes during which tracking continues open-loop; a secondary response required during these episodes should not produce a

hesitation. The secondary task would cause tracking hesitations only if its programming is required at the same time that the next open-loop segment of tracking would need to be programmed. If programming the secondary task is favored, a bottleneck would prevent programming for the next segment of tracking, thereby causing this action to stop temporarily producing a hesitation. Otherwise, no hesitations occur.

The frequency of hesitations was reduced by practice. This improvement may occur because durations of the open-loop segments of tracking increase with practice. As these segments become longer, fewer segments are required, and thus there would be fewer instances in which tracking requires programming of the next segment. That would reduce the frequency of tracking hesitations because the bottleneck would be encountered less often (Klapp & Jagacinski, 2011, p. 452; Netick & Klapp, 1994).

Postponement of processing leading to the PRP effect and interruption of processing leading to hesitations may represent two symptoms with one underlying cause – a bottleneck in processing. Our theoretical interpretation of this bottleneck accounts for findings from both paradigms.

Exceptions to the PRP/hesitation effect

Interpretation of the PRP/hesitation bottleneck should incorporate exceptions in which the two tasks can be carried out without encountering a bottleneck. One type of exception occurs if control of concurrent actions is not required. An example, described above, is that hesitations do not occur during open-loop episodes of tracking. Another example is that the PRP effect can be eliminated if the response coding is changed to represent a single action in which R1 and R2 are combined as one response (Pashler & Johnston, 1989). This central re-organizing, called grouping (Pashler, 1994b), can eliminate the PRP effect because only one response is processed. Each of these exceptions occurs because the situation does not require simultaneous programming for two responses.

Ideomotor compatibility reinterpreted as isolation

Another exception to the PRP effect, described in this section, occurs even though two responses must be controlled concurrently. In this case the responses become isolated from each other. The interpretation of this exception has evolved from research that studied a high degree of stimulus-response compatibility known as ideomotor compatibility (IMC). This applies if the stimulus is the same as the sensory feedback that is produced by the response. RT is very short for IMC stimuli (Greenwald, 1970). This finding has been interpreted within a framework introduced by

Fig. 2 Prediction of reaction time to task 2 (RT2) as a function of stimulus onset asynchrony (SOA) for the original model of the psychological refractory period (PRP) described in Fig. 1B

William James (1890), which attributes selection of motor action to mental imagery. This theory can be extended as follows. The image that is needed to select a response is typically generated during RT. However, it is not necessary to generate an image if it is already contained in the stimulus, and thus RT becomes very short for IMC stimuli. A compelling example of this role of IMC is shadowing speech in which hearing a word enables its rapid articulation (McLeod & Posner, 1984).

Considerable evidence indicates that the PRP effect is eliminated if both relations between stimuli and responses are IMC (Greenwald, 2003; Greenwald & Shulman, 1973). However, this research has been challenged by methodological issues (for discussions see Halvorson, Ebner & Hazeltine, 2013 and Lien, McCann, Ruthruff, & Proctor, 2005). In the typical interpretation of the role of IMC stimuli to eliminate the PRP effect, selection of a response is assumed to occur automatically if the stimulus-response pairing is IMC. According to this possibility, if the PRP effect were due to a selection bottleneck, it would be eliminated when only one stimulus-response relation is IMC. Although processing for selection would still be required for the response that is not IMC with its stimulus, the PRP effect would be eliminated because a bottleneck prevents two processes from occurring simultaneously and in this case only one selection process is involved. But instead the PRP effect is eliminated only if both actions are IMC (Greenwald, 2003; Greenwald & Shulman, 1973; Halvorson et al., 2013; Kantowitz & Knight, 1976; Klapp, Porter-Graham, & Hoifjeld, 1991). To anticipate a point to be developed later, this finding creates difficulty for claims that response selection is the cause of the PRP effect.

A promising alternative perspective that is consistent with this finding was proposed by Halvorson et al. (2013). In this view the PRP effect is eliminated if both stimulus-response relations are IMC because of the “separability of the two tasks” (p. 431) rather than because the stimuli represent images of the goals of the responses. For IMC relationships the stimuli are strongly associated with the responses so that there is “minimal confusion regarding which stimulus belongs with each task.” A confirmation of the conclusion that the role of IMC stimuli to eliminate the PRP effect is not that the stimulus is an image of the response is that Halvorson and Hazeltine (2015) reported elimination of the PRP effect when participants were to “do the opposite” of the response that would be IMC with the stimuli. These findings indicate that isolation of the actions from each other can eliminate the PRP effect. The interpretation of the PRP bottleneck proposed in the present article is fully consistent with this type of isolation.

Locus of the bottleneck

The present theoretical analysis seeks to identify the locus of the PRP bottleneck within the flow of information from stimuli to responses. One way to analyze the stages of information processing assumes that there are separable, non-overlapping stages that must occur between the input of a sensory stimulus and output of a motor response (Donders, 1868/1969). For the PRP effect these stages would include perception of the stimulus, selecting the response, processing related to initiation of the response, and finally overt production of the response. We consider evidence relative to each of these four stages and, to anticipate, conclude that the bottleneck lies late in the

sequence with respect to programming the timing of response initiation.

The bottleneck does not impact perception

Parallel perceptual processing

A process that can occur concurrently with (in parallel with) other processing cannot produce a bottleneck. Perception fits this description. Examples indicating that perceptual processes can occur in parallel include: (1) the lack of decrement in a visual search task when this is accompanied by a perceptually guided RT task (Pashler, 1989) and (2) the McGurk effect in which an auditory speech phoneme is paired with a visual display of lip movement representing a different phoneme. The fact that these stimuli combine to produce an illusory percept (McGurk & MacDonald, 1976) implies parallel perceptual processing across modalities.

Evidence based on Fig. 1 (locus of slack)

Evidence for parallel perceptual processing specifically for the PRP paradigm is based on the locus of slack approach developed by Pashler and others (De Jong, 1993; Pashler, 1984; Pashler & Johnston, 1989). This method can be explained in terms of our Fig. 1C, which expands the model of Fig. 1B to provide strong evidence that perceptual processes are not part of the PRP bottleneck, i.e., that perception of S2 can occur in parallel with processing related to R1 during RT1. The difficulty of perception of stimuli, and thus the time required for perceptual processing, can be varied by parameters such as stimulus brightness or clarity. According to Fig. 1A, if these variables increase the time needed to perceive S1, they would increase RT1.

Predictions for RT2 are more interesting because they permit a test of whether a perceptual bottleneck exists. Two alternatives can be considered. If perceptual processes are blocked by the bottleneck as in Fig. 1B, then any increased time for perception of S2 should result in a corresponding increase in RT2. Thus, this model predicts no interaction of SOA by difficulty of S2 perception (additive effects).

However, the actual findings display an interaction that fits a different model in which perception of S2 is not blocked by a bottleneck during RT1 so that perceptual processing could occur during the delay interval (Fig. 1C). According to that possibility, RT2 would not be influenced by an increase in the time needed to perceive S2 provided that unused time, the “slack,” available in the delay interval is long enough to absorb the additional time. The duration of the delay is longer if SOA is shorter so that more slack time would be available to absorb perceptual processing of S2 when SOA is short. Therefore, increasing the time needed to perceive S2 should have a smaller effect on RT2 when the SOA is shorter yielding

an under-additive interaction of difficulty of perception by SOA. Several findings confirm this predicted interaction thereby indicating that there is no bottleneck due to perception (Pashler, 1984; Pashler & Johnston, 1989).

Although this treatment of the locus-of-slack approach to examine whether perception can occur during the delay interval is intuitively plausible, the role of slack can also be analyzed formally (Schweickert & Fisher, 1987). It is also useful to specify the exact functions that make up the predicted interaction. This analysis appears in Appendix A in the Online Supplementary Material.

Although the under-additive interaction of SOA by the time required for perception of S2 is the critical prediction of Fig. 1C compared to Fig. 1B, it is also the case that overall predicted RT2 is shorter in Fig. 1C because at least some perceptual processing is assumed to be absorbed into the slack component of the delay interval. This implication could be tested by numerical evaluation of the terms in the equation related to Fig. 1B, but we are not aware of any attempts to do this. For the present purposes it is sufficient that the two models, Fig. 1B and C, differ sharply with respect to predictions concerning the role of changes in difficulty in perception of S2 to influence RT2. As indicated above, these predictions have been tested and the findings converge with other evidence to support the interpretation that perception is not part of the bottleneck.

Whereas there is little controversy concerning the conclusion that the bottleneck that causes the PRP effect is not with respect of perception of the stimuli, opinions have differed regarding the second stage, response selection. The next section reviews relevant evidence on this point.

Bottleneck is not related to response selection

The generally accepted interpretation attributes the PRP effect to a bottleneck in response selection (McCann & Johnston, 1992; Pashler, 1994a; Smith, 1967; Welford, 1952). However, a finding considered earlier is difficult to reconcile with this interpretation; making only one stimulus-response pairing ideomotor compatible did not eliminate the PRP effect. If the PRP bottleneck prevents concurrent selection of responses, no PRP effect would be expected in this situation because ideomotor compatibility would have automatized selection of one of the responses. Extensive converging evidence that the PRP bottleneck is not due to response selection is reviewed in this section.

PRP effect and hesitations occur even in the simple RT paradigm

Although most experiments regarding the PRP have used a choice RT paradigm in which the imperative stimulus also

identifies which response is required, the PRP effect is also observed for simple RT tasks in which the response is identified in advance (Maslovat, Chua, Spencer, Forgaard, Carlsen, & Franks, 2013; Maslovat, Chua, Carlsen, May, Forgaard, & Franks, 2015; Pashler, 1994a, p. 229; Welford, 1952). A corresponding finding is that hesitations occur when the secondary task is a simple RT paradigm (Klapp, Kelly, & Netick 1987; Netick & Klapp, 1994). Response selection is not needed during simple RT because the advance cue would permit selection to occur prior to RT. Therefore, the bottleneck causing the PRP effect and hesitations in simple RT versions of these paradigms is unlikely to be due to response selection. Only a process that must occur during RT even if the response has been precued can produce a bottleneck for simple RT. Data reviewed later shows that the process that programs timing of response, which is the basis of the interpretation that we propose, has this property.

Parallel response selection processes

Another approach to determine whether selection creates a bottleneck is based on the consideration that response selection could not create a bottleneck if responses can be selected in parallel. The remaining studies reviewed in this section demonstrate that parallel selection is possible.

Stroop effect The Stroop effect is interference when one tries to pronounce the name of the color of ink used to spell a different color. MacLeod (1991) indicated that there had been approximately 400 studies of this effect. He concluded that explanations that incorporate parallel processing of relevant and irrelevant stimulus features are the best fit to the data. This conclusion implies that there is no bottleneck in response selection although other types of bottleneck can occur.

Simon effect In the Simon effect RT is faster when the stimulus occurs at the same location as that of the response even though stimulus location is irrelevant. An example is pressing a switch located to the left or right based on a word (LEFT vs. RIGHT), which is presented at random in either the right or left ear. Lu and Proctor (1995) reviewed alternative explanations of faster responding with corresponding location; all of these incorporate variations of parallel response selection. Although the strength of the Simon effect can fade with practice, presumably because participants may learn to ignore the irrelevant location information, the fact that the Simon effect occurs early in practice implies that parallel selection is possible.

Eriksen flanker effect In the Eriksen effect the visual stimulus that signals the appropriate response is surrounded by irrelevant stimuli, which slow responding when they are misleading. This effect appears to be due to parallel processing of relevant and irrelevant stimuli followed by response competition (Sanders & Lamers, 2002).

Backward-crosstalk effect The Stroop, Simon, and Eriksen effects suggest that responses can be selected in parallel. But this is demonstrated with respect to different aspects of the same stimulus or for stimuli that appear at the same time. The PRP paradigm involves stimuli appearing at different times. Does parallel selection generalize to this situation? The answer apparently is yes. In the “backward-crosstalk effect” performance on the first task of a PRP paradigm is improved when the second task requires a response that is compatible with the response required on the first task (Hommel & Eglau, 2002; Janczyk, 2016). This result implies that at least some aspect of selection of the second response occurred in parallel with processing for the first task.

Analysis based on Fig. 1 (locus of slack)

The evidence reviewed above indicates that parallel response selection can occur in situations other than the standard PRP paradigm. This argues against a bottleneck with respect to response selection. Additional research on this issue relates directly to the PRP paradigm using the “locus of slack” analysis that was used to demonstrate parallel perception (Fig. 1C). Just as increased time for more difficult perception can be absorbed into the slack which arises if perceptual processing of S2 can occur in parallel with other processing, the increased time needed for more difficult response selection could also be absorbed into the slack if selection of R2 can occur in parallel with other processing (Fig. 1D). Thus, if parallel selection is possible (no selection bottleneck), an under-additive interaction is predicted such that when SOA is shorter the effect of increasing R2 selection difficulty on RT2 would be weaker because more slack time is available. The findings that are reviewed next are generally consistent with this prediction.

Studies that vary the number of alternative responses A variable that is unambiguously related to the time required for response selection is the number of alternative responses (Hick, 1952). An under-additive interaction of SOA by number of alternatives was first reported by Karlin and Kestenbaum (1968). In their Fig. 3 increasing the number of alternatives for R2 from 1 (simple RT) to 2 produced a strong under-additive interaction; this pattern occurred both when task 1 had one alternative and also when it had two alternatives. This finding of an under-additive interaction of SOA by number of alternative responses for S2 was extended by Schumacher, Lauber, Glass, Zurbriggen, Gmeindl, Kieras, and Meyer (1999) to selection between two versus four responses (Experiment 1) and two versus eight responses (Experiment 2). This type of interaction is predicted if there is no bottleneck due to response selection.

Studies that vary stimulus-response compatibility In contrast to these consistent findings of an under-additive interaction when

selection difficulty was varied in terms of the number of alternative responses, findings reported when selection difficulty was varied in terms of stimulus-response compatibility have not been completely consistent. Findings that support the claim of no bottleneck in response selection appeared in Experiments 3 and 4 of Schumacher et al. (1999) in which an under-additive interaction occurred for stimulus-response compatibility by SOA as expected if there is no selection bottleneck. However, McCann and Johnston (1992) reported an additive pattern when compatibility was varied in their Experiment 2 (see their Fig. 4) and perhaps also in Experiment 1 in which only a small and non-significant trend toward an under-additive interaction appeared (their Fig. 3).

How might these differences in findings be reconciled? One approach (Schumacher et al., 1999) is based on “adaptive control of task scheduling” in which the interference is assumed to be due to a variable strategy rather than to a fixed bottleneck. Another possible explanation is based on a second role of compatibility. Strong stimulus-response compatibility reduces difficulty of response selection (Fitts & Seeger, 1953), but it may also reduce dual-task interference by inducing isolation of the two tasks as demonstrated by studies related to ideomotor compatibility reviewed earlier. Isolation is more likely to occur if compatibility is higher. Because isolation would be effective across levels of SOA, compatibility can produce an additive effect regardless of the existence or lack of existence of a bottleneck related to response selection. However, isolation would not be relevant when the number of response alternatives rather than compatibility is varied. That could explain why the under-additive interaction seems to be more consistent with respect to number of response alternatives.

It is important to note that neither of these interpretations of the inconsistency of findings with respect to stimulus–response compatibility provides any support for a selection bottleneck.

Studies of locus of slack using Stroop and Simon effects As mentioned earlier, the Simon and Stroop effects indicate that parallel selection is possible. These effects have also been used in the locus of slack methodology. One example is a second aspect of Experiment 2 reported by McCann and Johnston (1992). These authors varied compatibility of spatial location (Simon effect) and reported the under-additive interaction (their Fig. 5). However, an additive relation was reported by Fagot and Pashler (1992) with respect to Stroop interference (Experiment 7). There seems to have been no attempt to account for this difference in findings. However, the locus of slack approach using variables related to the Stroop and Simon effects may not be relevant to determining whether a bottleneck in response selection exists because these variables may not influence the duration of the selection process. Instead they relate to response conflict after responses have been selected.

Is parallel retrieval from memory possible?

Response selection requires retrieval of the memory representation relating the stimulus to the required response. Thus, if parallel memory retrieval is not possible it could be presumed that parallel response selection is also not possible. Consistent with this hypothesis Carrier and Pashler (1995) reported an additive relationship between retrieval difficulty and SOA. However, subsequent research that encouraged participants to attempt parallel processing yielded an under-additive interaction indicating that parallel retrieval is possible (Green, Johnston, & Ruthruff, 2011). Also consistent with parallel memory retrieval is the result that performance in a dual-task paradigm depends on whether the two retrieval operations on the same trial match in category (Logan & Schulkind, 2000) and, for recognition judgment, whether they correspond with respect to validity (Logan & Delheimer, 2001). These results indicate that parallel retrieval had occurred. The conclusion from these two lines of research indicates that there is no bottleneck with respect to memory retrieval.

Conclusion

Findings considered in this section contradict the hypothesis of a bottleneck with respect to response selection because the PRP effect and hesitations both occur in simple RT paradigms and also because selection processes can occur in parallel. Other evidence, associated with the present theory is discussed later. Thus, we conclude that the PRP bottleneck is not at perception (previous section) or response selection (this section). The next possible locus for a bottleneck in the sequence of stages is related to response initiation; this will be described later as the most viable interpretation. The final stage is overt responding; this is discussed next.

Overt responding does not create a bottleneck

As mentioned earlier, the finding that tracking hesitations begin prior to the onset of the secondary response that triggers them is strong evidence that the bottleneck is with respect to response preparation rather than overt responding (Netick & Klapp, 1994). Evidence for the same conclusion, that the bottleneck is not due to overt response production, has been reported for the PRP effect. In all versions of Fig. 1 the delay is represented as a bottleneck involving processing preliminary to the onset of the first response; this bottleneck does not extend into this response. According to these models, increasing the time required to execute R1 should not affect RT2; R1 would occur after the bottleneck. This prediction was confirmed by Pashler and Christian (1994), who manipulated R1 complexity by requiring responses involving either a

single element or multiple elements. Movement duration for R1 was considerably longer for the more complex movement but only a small portion of this increased response duration was reflected as an increase in RT2. Although this finding indicates that the bottleneck essentially ends when R1 begins, the propagation of a small portion of the increased R1 response duration into RT2 suggests that this hypothesis may be only a first approximation. As it turns out this result is fully consistent with the interpretation of the PRP that we propose; this matter is discussed later.

The new interpretation: bottleneck in programming timing of response initiation

Overview

The evidence considered so far indicates that the bottleneck that produces the PRP effect is not at perception, response selection, or overt responding. We now consider evidence that the bottleneck is at the remaining possibility, response initiation. The proposal that the PRP effect is related to some aspect of response initiation, often attributed to Keele (1973), has not received much attention recently except that it was part of a two-bottleneck interpretation (De Jong, 1993; see also Pashler, 1994a, p. 229).

The interpretation presented in the present article goes beyond identifying response initiation as the locus of the bottleneck to propose a source of this limitation. We consider findings from research paradigms for which the relation to the PRP is not immediately obvious. The implication of these findings is that there must be a bottleneck that prevents concurrent programming of the timing of initiation of two responses. One of these paradigms is single-task simple RT. The findings indicate that a programming process occurs that requires more time for responses involving more complex timing and that this programming must be delayed until immediately prior to the response onset (Maslovat, Chua, Klapp, & Franks, 2016). The other type of finding is based on temporal coordination of action; this indicates that only one timing program can be active except under clearly specified special conditions (Jagacinski, Rizzi, Kim, Lavender, Speller, & Klapp, 2016). We argue that the processing restrictions underlying these two conclusions combine to create a bottleneck at response initiation. The logic can be regarded as inductive. Rather than representing predictions of the theory the conclusions from these research paradigms imply that a bottleneck must exist. Although earlier articles by the present authors suggested aspects of this interpretation (Klapp & Jagacinski, 2011, p. 452; Maslovat, et al., 2013, p. 36; Maslovat, et al., 2015, p. 482), the present analysis is the first complete presentation.

Processing is needed prior to initiation

Before analyzing the details of this interpretation, we consider evidence that, as our interpretation requires, processing of some type is needed to enable response initiation. This is consistent with a rather surprising limitation with respect to the power of the startle reflex to initiate an action. If there were no need for processing prior to response initiation, a startle might release a response involuntarily without any need for preliminary processing. A startle is known to trigger prepared responses at very short latency via a faster, less voluntary pathway (Valls-Sole, Rothwell, Goulart, Cossu, & Munoz, 1999; see Carlsen, Maslovat, & Franks, 2012; and Valls-Solé, Kumru, & Kofler, 2008 for reviews). However, Maslovat et al. (2013) found that, while a single key press could be triggered by a startling stimulus at a latency of only 96 ms when performed in isolation, this latency increased to 180 ms for short SOA dual-task trials. This finding of the PRP effect with a startling S2 stimulus is indicative of resistance to responding until after some processing has been completed. This processing is delayed by the PRP bottleneck. Perhaps startle speeds the release of the action but does not eliminate the need for programming of the (more rapid) timing of this release. Thus, RT2 is shortened overall by startle but nevertheless it is longer in dual-task compared to single-task conditions because of the PRP bottleneck.

Three properties required for a bottleneck

The findings regarding startle indicate that processing is needed just before response initiation and that this processing produces a bottleneck. A process can create a bottleneck at response initiation if the following three properties apply:

1. Occupies time. A bottleneck must involve a process that extends over an interval of time during which concurrent processing is blocked. Although triggering of response initiation might be regarded as a momentary event, findings from single-task RT studies indicate that programming the timing of response initiation is an inseparable aspect of response initiation and that this requires several milliseconds. The time required to complete this programming increases as a function of the complexity of timing. This processing can create a bottleneck.
2. Cannot occur at a time that would avoid a bottleneck. A process cannot create a bottleneck if it can be completed at a time when it would avoid conflicts. Data from the single-task simple RT studies indicate that programming of response timing is tied to response initiation in the sense that it can occur only during a brief window of time

just prior to response onset so that it does not have the flexibility needed to prevent encountering a bottleneck.

3. No parallel processing. A process can create a bottleneck only if parallel processing is not possible. Findings regarding central limitations in timing concurrent actions indicate that a no-parallel limitation usually applies for timing of response initiation. This limitation can be overcome under conditions that can be specified in detail.

Summary

Findings regarding the startle reflex indicate that processing is needed in conjunction with response initiation. A process will create a bottleneck at initiation if it meets three properties. It must require time to complete (Property 1), and it must be delayed to occur immediately prior to response initiation (Property 2). Thus, this processing becomes an inseparable aspect of response initiation. Concurrent processing must not be possible (Property 3). According to the data that we review below, programming the timing of response initiation meets these three properties needed to create a bottleneck. The next section involves Properties 1 and 2.

Single-task simple RT findings for Properties 1 and 2

Overview

It may seem surprising that interpretation of the dual-task PRP bottleneck involves results from simple RTs when only one task is involved. But these findings indicate important limitations in preparing to initiate a response that, although revealed with respect to a single response, must apply also to responding in the dual-task PRP and hesitation paradigms. The core finding of the studies to be considered in this section involves processing that requires longer to complete if the timing of the response is more complex. This processing must be delayed until immediately prior to initiation, during RT, even if all parameters of the response have been specified earlier as in the simple RT paradigm. Thus, these findings fit Properties 1 and 2. The results also confirm that response selection can be completed earlier in the trial and thus selection would not produce a bottleneck in versions of the PRP paradigm that involve simple RTs (Property 2 does not apply for response selection). Findings regarding Property 3 are considered later; these are based on a different approach that involves concurrent responses.

As a preliminary to describing the findings for single-task simple RT, we identify the level of analysis to which they

apply. An action is typically organized as a sequence of gestures or chunks (for reviews see Klapp, 2010 and Klapp & Jagacinski, 2011).¹ Control is hierarchical – ordering and sequencing of the chunks at the upper level and formation of individual chunks at the lower level. The analysis in this section concerns the upper level of control involving the ordering and timing of chunks.

Single-task simple RT

Evidence regarding properties 1 and 2 that are required to produce the PRP effect comes from single-task RT studies. For many years it has been known that, even if the response is cued in advance in a simple RT paradigm, simple RT increases as function of number of chunks involved. The pioneering experiment (Henry & Rogers, 1960) was intended to show that response sequences are organized in advance rather than controlled on-line by associative response chaining. Although this conclusion was supported, the authors (and many discussions of this study) failed to notice that the processing that was described might have been completed prior to, rather than during, simple RT because the relevant aspects of the response had been cued in advance (see Klapp, 2010 for a review). The fact that this pre-programming does not occur is critical for the present analysis.

Although the finding that simple RT increases as a function of the number of chunks in the response indicates that programming some aspect of the response must be delayed until the simple RT interval, these results do not enable specification of exactly what response attribute is limited in this way. A finding that extends this conclusion is based on a version of the simple RT paradigm in which the response is cued and then the participant “studies” the action during a foreperiod. The foreperiod ends when the participant indicates that he or she is ready to proceed with the rest of the trial. Both the foreperiod “study time” and simple RT increase as a function of the number of chunks in the response (Magnuson, Robin, & Wright, 2008). Apparently, some aspect of the response is programmed in the foreperiod, but programming of another aspect must be delayed until RT thereby causing simple RT to

¹ Some of the evidence in support of this claim is as follows: Pauses in action seem to mark the boundaries between chunks. Examples include pauses that occur when a pen is moved through a maze (Van Mier, Hulstijn, & Petersen, 1993) and when a cursor is moved to contact a target (Jagacinski, Repperger, Moran, Ward, & Glass, 1980) and during extended episodes of finger tapping (Rosenbaum, Kenny, & Derr, 1983). Transfer of pauses from training in which pauses were required to a new situation in which the pauses are optional indicates the robustness of the division of action sequences into chunks (Verwey, 1996, 2001). People spontaneously organize response sequences to include pauses (Verwey & Eikelboom, 2003); the exact pattern differs across participants but remains stable over time for each participant (Sakai, Kitaguchi, & Hikosaka, 2003). Findings regarding RT are different with respect to the sequence as in the present analysis and with respect to internal structure of individual chunks (Klapp, 2010; Maslovat et al., 2016).

increase as a function of the number of chunks. Our interpretation of the PRP effect is based on this second process.

Whereas the study time approach involves a participant-determined foreperiod duration, another demonstration of the distribution of programming between foreperiod and RT involved varying the duration of the foreperiod experimentally (Alouche, Sant'Anna, Biagioni, & Ribeiro-do-Valle, 2012). Simple RT increased strongly as a function of the number of chunks in the response if the foreperiod was short (300 ms), but this relation became weaker as the foreperiod was increased (1,000 or 2,000 ms). This finding suggests that programming both aspects of the response must occur during RT if the foreperiod is too short to allow any preprogramming. A longer foreperiod allows time for preprogramming one aspect of the response prior to RT thereby decreasing the strength of the relation between number of chunks and RT. However, even at the longest foreperiod, simple RT increased (less strongly) as a function of the number of chunks, thus indicating that programming another aspect of the response cannot be completed until just prior to its initiation, i.e., during RT.

In summary, the study time and variable foreperiod studies converge to indicate that processing is distributed between the foreperiod and simple RT. Which aspect of the response is programmed in each interval? One possibility is that selection of the response chunks can be completed during the foreperiod and programming the timing of initiation of the chunks cannot be processed in advance and thus must occur during simple RT (Klapp, 2010; Klapp & Jagacinski, 2011). Preliminary evidence in support of this idea was reported by Maslovat, Klapp, Jagacinski, and Franks (2014).

Recent findings are fully consistent with this hypothesis. In the single-task simple RT paradigm Maslovat et al. (2016) manipulated difficulty of selection and of timing independently for a sequence of three chunks (each a single key press). For selection the less difficult task involved using the same effector hand for all three chunks and the more difficult task involved different effectors (left vs. right hand) across the chunks. For timing the delays between chunk onsets were either isochronous (same delay in each case, less difficult) or non-isochronous (different delays, more difficult); the total duration was constant across these timing conditions. Increasing difficulty of response selection produced an increase in the participant-determined foreperiod “study time” between the precue and continuation of the trial. However, simple RT did not increase as a function of difficulty of response selection with the exception of a few participants for whom the self-determined foreperiod duration was very brief, suggesting that they may have elected to avoid selecting the response in advance of RT. Thus, the data suggest that the majority of the participants selected the sequence in the foreperiod rather than waiting until RT. Conversely, increasing the complexity of the timing of initiation of successive response chunks produced an increase in simple RT but not in foreperiod duration. This result indicates that programming timing of the

initiation of the response chunks must be delayed to occur during simple RT.

The conclusion that selection of the sequence of response elements can occur early in the trial, during the foreperiod, suggests that it might also be possible to select between alternative timing structures during the foreperiod even though programming the selected timing must be delayed until RT. This possibility has been confirmed by Maslovat, Chua, Klapp, and Franks (2017) using the response precue paradigm developed by Rosenbaum (1980). Participants performed a three key-press sequence and were provided with advance knowledge of the order of elements, of the timing structure, both of these (simple RT) or neither of these (choice RT). A critical result was that the timing precue shortened overall RT compared to choice RT even though the RT still depended on the complexity of the timing structure. The shortening of overall RT can be attributed to selection of the timing structure in advance of RT, and the effect of timing complexity on RT can be attributed to programming the implementation of the previously selected timing during RT. Another aspect of the findings is that RT was reduced (relative to choice RT) when only timing was precued and also when only the sequencing was precued. This result is consistent with independence of selection of these parameters – each can be selected independently of whether the other has also been selected (although programming of the selected timing must wait until just prior to the response).

Four implications of these results

- (a) Selection of the response (sequencing) and programming of the timing of response initiation can occur during different intervals, and each process can be performed without knowledge of the parameter involved in the other process, thereby indicating that these are independent processes.
- (b) Selection of the response sequence can occur during the foreperiod of the simple RT paradigm so that it does not need to occur immediately prior to response initiation where it might produce a bottleneck (Property 2 of a bottleneck does not apply to response selection).
- (c) Programming the timing of response initiation occurs over an interval of time that is longer if more complex timing is required (Property 1 of a bottleneck applies to timing).
- (d) Programming of timing of response initiation is restricted to a brief window immediately prior to response initiation so that this can produce a bottleneck (Property 2 of a bottleneck applies to timing).

These implications are consistent with the interpretation that the bottleneck that produces the PRP effect is attributable to programming of timing of response initiation but not to response selection. They indicate that the first two bottleneck properties apply to timing of response initiation and that the

second property does not apply to response selection. However, it remains to be shown that parallel processing for timing of initiation is typically impossible – that is the third property. The next section addresses this issue.

Limitation concerning timing of response initiation: Property 3

The third property is that a bottleneck must involve processes that cannot be carried out in parallel. This section provides evidence that parallel processing with respect to the timing of response initiation is typically not possible so that Property 3 applies. However, in special circumstances related to response isolation, parallel processing occurs so that property 3 is violated and the PRP effect is eliminated.

Limit to one time-frame for overt actions

In an early observation, Binet (1890) noted that arm movements of infants are tightly coupled temporally. A corresponding limit to one time-frame for adults attempting to perform rhythmic tapping using two hands was reported by Klapp (1979) and subsequently by Deutsch (1983); when participants attempted to tap independently timed rhythms with the right and left hands they were not successful in doing so. This limitation is not subtle as the reader can easily verify by first practicing fast tapping with the right hand alone and then practicing slow tapping with the left hand alone and finally attempting to produce these two rhythms concurrently. A formal study (Klapp, Nelson, & Jagacinski, 1998) demonstrated this difficulty of producing two independent rhythms concurrently after extensive part-task training on each of the rhythms separately.

This limit is attributed to a central program for action, not a peripheral constraint

This limit to a single time-frame for overt action is impressive but it could represent a peripheral rather than central restriction. The third, no parallel processing, property required for a PRP bottleneck is that the limitation must be central because the limit is assumed to arise before the actions start, i.e., during RT. Evidence considered next indicates that the limit that prevents generation of conflicting timed actions is central.

According to a central interpretation of the typical difficulty in producing conflicting rhythms concurrently it might be possible to overcome this problem if the central representation includes both actions so that these are integrated on a single programmed time-frame. In that mode only one program for timing is required. For example, consider the task of producing two rhythms, one with each hand, in which the right hand taps three times per interval while the left hand taps twice

during the same interval. As noted earlier, this is essentially impossible if the actions are represented as two independently timed conflicting rhythms. But these concurrent rhythms can be produced with ease if the task is trained as a single integrated action occurring on one temporal frame such that the responses are triggered in the repeating sequence: both-hands, right-hand, left-hand, right-hand (Klapp et al., 1998). Thus, there is no peripheral constraint preventing tapping at different rates across hands. Instead, there is a limit to only one central representation of the passage of time upon which multiple action triggers can be placed.

Strong additional evidence that bimanual rhythmic tapping, when successful, tends to be integrated on a single temporal framework is from patterns of covariance indicating that errors of timing for right and left hands are not independent as they would be if the actions were independently timed. Instead errors in timing of response initiations for one hand tend to propagate to the other hand (Jagacinski, Marshburn, Klapp, & Jones, 1988; Vorberg & Wing, 1996). This bias favoring an integrated single time-frame for rhythmic tapping even extends to skilled drummers, except in limited circumstances to be described in the next section (Jagacinski et al., 2016).

Training that promotes integration into a single centrally represented time-frame, as described above, is one way to enable concurrent production of actions with conflicting timing. Another way is by use of stimuli that can guide the actions externally without reliance on a central code thereby bypassing any central limitation. For example, Rosenbaum, Dawson, and Challis (2006) showed that, although drawing a circle with one hand and a square with the other hand is typically very difficult, the same motor actions can be produced by blindfolded participants who track the two patterns tactually. This result demonstrates that it is possible to generate conflicting patterns with the right and left hands. This task can be difficult because of limits in central processing; the difficulty is removed if the task is guided externally.

Conclusions

The typical difficulty in generating concurrent actions with differing temporal patterns is not attributable to a peripheral restriction but instead is of central origin as expected if it is not possible to concurrently program two or more central temporal codes. This conclusion shows that timing of response initiation meets the third property for the PRP bottleneck.

Streaming: an exception to the no parallel limitation for timing of responses

As noted earlier, the PRP effect can be avoided by isolation when both stimulus-response bonds are strong. Isolation can also occur if the single time-base limitation described in the

preceding section is eliminated thereby permitting independently timed actions. This can happen if perceptual and motor events become structured into two isolated and independent streams. The perceptual aspect of streaming has its historical origins in a Gestalt grouping principle described next in relation to contemporary studies.

Streaming of perceptual events

Streaming is the perceived fissioning of a sequence of perceptual events into multiple sub-sequences. Temporal order is still perceived within each sub-sequence, but not between sub-sequences. Streaming is more likely to occur for events that are more distinct and that occur at a faster rate. For example, in auditory perception an alternating sequence of high and low notes occurring at slow rates of presentation will be perceived as a single sequence including all notes. However, perception of the sequence will fission into two groups with high notes in one stream and low notes in a separate stream at fast rates of presentation if the notes are sufficiently different in pitch (Bregman, 1990; Jones & Yee, 1993). Similarly, in visual perception a sequence of light flashes that progresses horizontally from left to right and alternates between high and low vertical positions will be perceived as the apparent up/down movement of a single object if the flashes occur at a moderate rate. At faster speeds and wider vertical separation the observer will see apparent motions of two objects, one moving horizontally at the high vertical position and the other moving horizontally at the low vertical position (phi phenomenon).

The necessary conditions to achieve perceptual streaming can be described in terms of a velocity:

$$V = d/t$$

in which t is the time between successive events, and d is the perceived distance between these events. As applied to the perceptual illusions described above, when this velocity, V , is increased beyond a threshold, perception switches from integrated (under a single temporal organization) to streamed (under multiple parallel temporal organizations). This is analogous to a limitation in the speed of moving attention. If transitions of attention across distance d would require a velocity exceeding the threshold, the transitions are not possible and the perceived pattern becomes segregated across this space. Streaming is supported further if the velocity within each stream is less than the threshold so that movement occurs within each stream. In the historical formulation the velocity threshold for streaming is a gestalt grouping principle known as Korte's Third Law (see Klapp & Jagacinski, 2011). Because of the velocity threshold, streaming is more likely at faster rates (shorter t) and if the distance, d , is longer. In visual perception d is a measure of perceived spatial separation; events at a large separation tend to break apart to form

separate streams. Similarly, in auditory perception, d is a measure of perceived pitch distance, so high notes tend to break apart from low notes if the perceived difference in pitch is large. The Korte velocity that is needed to reach threshold and enable streaming may differ across observers and over time for a single observer. Thus, the result of any experiment reflects averaging.

Streaming of motor events

Although streaming is a clearly established (but perhaps rather obscure) perceptual phenomenon, it would be relevant to the PRP effect only if it applies also for motor action. This generalization from perception to motor control fits the principle that control of motor action is closely related to perception (e.g., see Klapp & Jagacinski, 2011; Mechsner, Kerzel, Knoblich, & Prinz, 2001). And, indeed, streaming has been reported for very fast bimanual tapping (Jagacinski et al., 2016; Krampe, Kleigl, Mayr, Engbert, & Vorberg, 2000). That result corresponds to the perceptual principle that a high Korte velocity (short t) is associated with streaming in vision and in audition. Also consistent with the Korte principle is the finding that motor streaming is more likely for rhythmic actions of more distinct effectors (hand and foot) than for similar effectors (hand and hand); the hand foot combination is interpreted as a larger distance (d) in the Korte velocity (Jagacinski et al., 2016). Because streaming represents a violation of the third (no-parallel) property, actions that are streamed could avoid the PRP bottleneck. Findings fitting this prediction are reviewed next.

The PRP effect is weakened when the two responses differ in modality

Consistent with this analysis, several studies reported that use of different response modalities (large d) reduces the PRP effect. McLeod (1977) examined interference between a continuous manual task guided by a visual stimulus when this was attempted concurrently with a two-choice tone identification task involving either manual or vocal responses. He reported that "The probability of response production on the continuous task was affected by the production of manual responses but not by the production of vocal responses" (Abstract p. 651). Pashler (1990) found slightly longer PRP duration for manual responses paired with another manual response than for vocal responses paired with a manual response when the order of the tasks was predictable, and a much larger difference comparing these modality conditions when the order of these tasks was unpredictable (as in McLeod, 1977). DeJong (1993, p. 270, Exp. 2) reported that response similarity (hand-hand vs. hand-foot) determined potency of the bottleneck, with longer PRP duration for hand-hand. Specifically, making two responses, one with fingers of the right hand and the other

with fingers of the left hand, produced longer PRP duration than the combination of fingers of right hand paired with left versus right foot.

Studies by Maslovat and his colleagues in an investigation of another topic used only mixed modality, vocal and manual, and thus do not provide a comparison of mixed versus same modality within the same experiment. However, consistent with the notion that the PRP effect is present but weakened with differing modalities, Maslovat et al. (2013) reported a slope for RT2 as a function of SOA of $-.49$ rather than -1 , as would be predicted based on Fig. 1 and Maslovat et al. (2015) reported a slope of $-.69$. Other studies indicate no PRP effect if modalities are mixed. Halvorson and Hazeltine (2015) found no PRP effect if S1 was auditory and R1 was vocal when this task was paired with another task with visual S2 and manual R2. Pashler, Carrier and Hoffman (1993) reported limited or no “typical” PRP effect for manual R1 paired with saccadic eye movement for R2.

The bottom line is, when modalities of responding differ between the two responses, the PRP effect is reduced and sometimes even eliminated. This is not predicted by the response selection interpretation of the PRP bottleneck because use of different response modalities for R1 and R2 would not reduce the difficulty of response selection for either response. However, this effect is consistent with a bottleneck in programming response timing because a difference in modalities can increase motor streaming, which in turn would promote independent and parallel timing of response initiation, thereby reducing or eliminating the PRP.²

A role of practice in streaming and in elimination of the PRP effect

For reasons that are not fully understood a high level of practice often facilitates motor streaming (Jagacinski et al., 2016; Krampe et al., 2000). If streaming eliminates the PRP effect, practice should play a similar role in the PRP paradigm. Consistent with this possibility, the PRP effect is sometimes eliminated completely after extensive practice (Hazeltine,

Teague, & Ivry, 2002; Schumacher, Seymour, Glass, Fencsik, Lauber, Kieras, & Meyer, 2001).

Conclusion

Isolation of the responses violates Property 3 and thereby can eliminate the PRP effect. Two mechanisms that can achieve isolation are (1) very strong relations between stimuli and responses as discussed in an earlier section and (2) perceptual motor streaming that is enhanced if the responses are more distinct and if the time between responses is shorter as discussed in this section.

Review and extension of the theoretical analysis

The PRP effect is attributable to a bottleneck that delays processing for a second response until processing related to a first response has been completed. The bottleneck does not include overt responding. Further evidence indicates that neither stimulus perception nor response selection produces this bottleneck.

Findings from paradigms other than the PRP demonstrate that programming the timing of response initiation meets the three properties that are needed to produce a bottleneck: (1) This programming takes time, which increases with the complexity of response onset timing. (2) The programming cannot occur early in the trial and thereby avoid a bottleneck but instead it must be delayed until immediately prior to response initiation. (3) It is not possible to program two timing frameworks simultaneously except under special circumstances that can produce isolation by streaming.

This logic is inductive in the sense that these three conclusions from previously reported findings indicate that there must be a bottleneck in programming the timing of response initiation. This bottleneck can cause the PRP effect. Although our goal is to develop an interpretation of the PRP effect that is based on these findings and that also fits other existing results, new predictions can be derived. One approach is to examine ways in which the limitations imposed by one or more of the above principles can be eliminated.

An example of this approach extends a finding that perceptual streaming can be enhanced or reduced by immediate prior exposure. In auditory perception the tendency for a set of tones to stream builds up over time. The listener initially regards all tones as coming from the same source, but this grouping is overcome over time so that the listener comes to perceive the tones as if they come from different sources (Bregman, 1978). This buildup of streaming can be “reset” by a sudden change in the stimuli so that the streaming is eliminated (Roberts, Glasberg, & Moore, 2008). In motor performance, streaming can eliminate the PRP effect because

² Interpretation of the occurrence of independent non-interfering actions in terms of streaming has some interesting similarities and differences with respect to the multiple resource theory of task interference (Navon & Gopher, 1979; Wickens, 1984). Both of these analyses are directed toward explaining why greater dissimilarity leads to less multi-task interference and they lead to similar predictions regarding the modalities of the two responses. According to resource theory interference is reduced when these modalities differ because distinct resources are employed. However, this theory has been criticized because a claim of different resources merely restates a result of more independence while offering no additional predictions (Navon, 1984). The present theory involves a different metaphor that is grounded in the perceptual phenomenon of streaming. Korte’s velocity threshold is the dynamic condition for multiple parallel attentional foci to emerge in both perception and motor action. In both metaphors deriving precise predictions is difficult. For resource theory the problem involves circularity; for the Korte interpretation the problem is in measurement of the size of a difference in response modalities.

property 3 does not apply. Therefore, extension of the finding regarding auditory streaming implies that the PRP effect should diminish over time and then return in the presence of a sudden change in the stimulus environment. This prediction remains to be tested.

A two-bottleneck theory is questionable

A two-bottleneck hypothesis involving both response selection and an aspect of response initiation was proposed by DeJong (1993). This possibility is consistent with his finding (Experiment 1) from a GO versus NO-GO paradigm in which the PRP duration is longer if S1 signals GO rather than NO-GO with respect to R1 although there is a short PRP duration for NO-GO trials. It could be argued from this finding that both bottlenecks, one due to selection and one to initiation, apply for GO trials, but only selection (of whether to respond or not) applies to NO-GO trials. However, this finding is also easily handled by a one-bottleneck timing interpretation of the PRP effect as follows: For GO trials a strong PRP effect occurs due to the timing bottleneck. For NO-GO trials there is no initiation of R1, thus no response timing bottleneck and no PRP as it is traditionally thought of. However, response inhibition with respect to R1 occurs on NO-GO trials, and this inhibition could generalize to R2 thereby increasing RT2. Thus, this finding from the GO NO-GO paradigm can be interpreted without assuming two bottlenecks. A bottleneck involving response selection is problematic because, as discussed above, this violates the properties needed to produce a bottleneck.

Somewhat longer PRP duration if the complexity of the first response is increased

Pashler and Christian (1994) showed that increasing the number of elements in the first response (R1) caused a large increase in its duration but only a comparatively small, yet significant, increase in RT2. As discussed earlier, this is one source of evidence that response execution is not a critical factor in the bottleneck because this would predict a much larger increase in RT2. Although these authors favored an explanation for the small increase in RT2 that involved a response selection bottleneck but only on a disproportionately small number of trials, a timing bottleneck may instead cause the longer RT2. Increasing the number of response elements in R1 would increase the duration of programming the timing of these initiations (Maslovat et al., 2016) and thereby increase RT1 (Fig. 1A). This increase would be reflected in the delay interval and thus in RT2 (Fig. 1D). The increase in RT2 being smaller than the increase in R1 duration indicates that

response execution is not part of the PRP bottleneck (Pashler & Christian, 1994). Instead, according to the present theory, the small increase in RT2 when the number of elements in R1 is increased can be attributed to increased time to programming timing of initiation of R1 when this involves more elements. This programming lengthens the bottleneck, thereby delaying processing of R2.

Interference between concurrent tasks is not limited to that produced by a bottleneck

The present analysis has focused on the PRP and hesitation effects that represent an absolute bottleneck in processing. However, it is important to note that not all difficulties associated with performing concurrent tasks can be attributed to a processing bottleneck. This section considers findings suggesting that performance can degrade for dual-task compared to single-task situations even in situations that do not produce an absolute bottleneck.

Results based on a novel paradigm, Prioritized Processing (Miller & Durst, 2015; Mittlestandt & Miller, 2017) can be considered from this perspective. In this paradigm only one response is required, although two successive stimuli are presented. On most trials responding is required to the stimulus for a primary task with no response for the other, background task. A response to the background task is required only when the stimulus for the primary task indicates NO-GO. A remarkable finding is that, if the first task is identified as primary, the RT for this task in the Prioritized Processing (one response) paradigm was much shorter than RT1 in a corresponding PRP paradigm (two responses). Because the presence of a bottleneck would not slow the initial RT in either situation; the longer RT1 in the dual-task PRP paradigm is not due to a bottleneck and may instead be attributed to distracted attention because of an overhead cost in top down control when two tasks rather than one must be managed. This suggests that at least two types of interference from concurrent tasks can occur, one due to a bottleneck that increases RT2 in the PRP paradigm and another due to distracted attention which increases RT1.

Another finding that is consistent with two types of dual-task interference, one due to a bottleneck and one not, involved manual tracking accompanied by a second task in which two auditory stimuli appeared in succession. A secondary key press response was required only to the second of these stimuli; whether this response was required or not depended on whether the two stimuli did or did not match in pitch (GO for same pitch vs. NO-GO for different pitch or vice versa). Hesitations in tracking occurred only after the second stimulus and then only if the key press was required. This finding is expected if hesitations are due to a bottleneck that blocks concurrent preparations for response initiation. However, tracking performance was reduced without

hesitations during the period between stimuli even if no key press was required (Netick & Klapp, 1994, Experiment 3). This degradation in performance cannot be attributed to a bottleneck involving concurrent responses because only one response, tracking, is involved at the time that performance is degraded. Thus, these findings, like those from the Prioritized Processing paradigm, suggest that there are two mechanisms of dual-task interference – a bottleneck leading to hesitations when two responses were involved and distracted attention due to managing the possibility of two responses even if only one was actually required.

In typical real-world situations it is also likely that only part of the interference between concurrent tasks is due to a bottleneck. The PRP effect and hesitations are both attributed to an absolute bottleneck. Both are brief in duration (in the order of one-third of a second). For example, interference resembling the PRP effect occurs due to producing another motor action, even speech articulation, while driving (Levy, Pashler, & Boer, 2006). However, in many situations degradation in driving performance extends over a longer interval and is not clearly tied to making a secondary motor response so that this is not due to a bottleneck in responding. Instead, this degradation may be due to distraction of attention (Strayer, Drews, & Johnston, 2003).

As discussed next, these two types of interference, absolute bottleneck and distracted attention, may map onto subcortical and cortical processing respectively.

Subcortical and cortical processing

The presence of an absolute PRP bottleneck in human information processing is surprising because the brain is regarded as complex and massively parallel in organization. Perhaps functions that are processed in the cortex can occur in parallel and do not encounter a bottleneck even though distracted attention can degrade performance in less drastic ways. The bottleneck may lie in subcortical structures. In particular, programming the timing of response initiation, which encounters the PRP bottleneck, may be a subcortical function for which limitations occur that are not present in cortical processing.

Consistent with this hypothesis, evidence considered here indicates that the PRP bottleneck is not with respect to the cortical functions of perception or response selection. Perception of form is a cortical function except for preliminary processing in the retina and lateral geniculate nucleus. Neural evidence for cortical involvement in response selection has been provided by a number of event-related brain potential techniques (see Leuthold, Sommer, & Ulrich, 2004 for a review). For example, when provided with advance information about which limb will be used to make a movement, lateralized cortical activation associated with the side of the response can be observed, indicative of selection of the

appropriate muscle group for the required movement (Leuthold, Sommer, & Ulrich, 1996).³ Thus, both perception and response selection can be attributed primarily to cortical processing which may not be impacted by an absolute bottleneck and thus are not the cause of the PRP. Nevertheless, in dual-task settings these cortical processes may be subject to distraction by divided attention.

Here we have argued that, rather than due to perception or to selection (both cortical functions), the PRP effect is produced by a bottleneck in programming the timing of response initiation. Control of temporal intervals is a function of subcortical regions primarily involving the cerebellum rather than the cortex (Ivry & Keele, 1989). Thus, the PRP effect may be due to a subcortical limitation. The hypothesis that the PRP is not of cortical origin could explain why attempts to isolate control of the two tasks in a PRP paradigm into different cerebral hemispheres have not succeeded in elimination or reduction of the PRP effect (Pashler & O'Brien, 1993) and why a robust PRP effect has been reported for “split brain” patients after callosotomy (Ivry, Franz, Kingstone, & Johnston, 1998; Pashler, Luck, Hillyard, O'Brien, & Gazzaniga, 1994) when a standard PRP paradigm was used.⁴

Limited sub-cortical working memory may produce the PRP effect

This interpretation that subcortical processing, but not cortical processing, is impacted by the PRP bottleneck implies that subcortical processing is limited in ways that cortical processing is not. How might we characterize this limit? In the single-task simple RT studies considered earlier in this

³ Although response selection may be a cortical function, that does not mean that it is necessarily non-automatic or immune from non-conscious influences. Instead response selection can be primed associatively without awareness of the priming stimulus (for a review of evidence on this point see Klapp, 2015).

⁴ The results for a split-brain participant were very different with a modified paradigm (not the PRP) in which both tasks were presented simultaneously and neither was given priority (Hazeltine, Weinstein, & Ivry, 2008). The split-brain participant showed substantially reduced dual-task cost in this procedure compared to that observed in the PRP paradigm. These authors proposed that this difference across paradigms may represent a difference in strategy. An alternative interpretation follows from the theoretical framework that we propose. With the modified procedure the responses tended to occur simultaneously. If the robust delay in the second response typically found with the PRP paradigm is due to a bottleneck that prevents simultaneous programming of two onset times (as we propose), this dual-task cost would not occur on those trials for which the responses are initiated simultaneously because only one timing must be programmed even though two responses are required. That would explain the reduced dual-task cost in the simultaneous task for the split-brain participant. But why does a cost remain for control participants in this modified paradigm? For the control participants this dual-task interference was mediated by the compatibility between the two responses; this compatibility effect was minimal for the split-brain participant. Thus, the interference observed for the control participants may involve conflict in response codes; this conflict does not occur for the split-brain participant because of isolation of response codes across hemispheres.

analysis, evidence indicates that response selection (cortical processing) occurred early in the trial (during the foreperiod). For selection early in the trial to be effective, the choice of which action goal is to be achieved must be retained in working memory until later in the trial when the response is required. By contrast, these single-task simple RT studies also indicate that programming the timing of response initiation (subcortical processing) cannot be completed until immediately prior to the action so that this must occur during simple RT. Perhaps the reason that a program for timing cannot also be generated in advance and then retained is that there is insufficient or no subcortical working memory that could retain the neural coding needed to implement timing. Thus, whereas timing can be selected in advance, the previously selected timing can be programmed only just prior to the response (Maslovat et al., 2017). This restriction (property 2) is a necessary condition for a bottleneck to occur.

A tale of three limitations

In this article we considered the following three surprisingly robust limitations in human performance:

1. One aspect of preparing for (programming) motor action cannot be completed until just prior to the start of the action, i.e., during RT. This conclusion follows from findings regarding single-task simple RT first reported by Henry and Rogers (1960). Recent results enable specification of the aspect of programming that is limited in this way. It is now clear that it is programming of the timing of response onsets that can occur only immediately prior to response initiation (Klapp, 2010; Maslovat et al., 2016).
2. Rhythmic bimanual actions are typically locked to a single time-frame (Binet, 1890; Klapp, 1979). This has been shown to be due to restrictions with respect to the central representation of timing rather than to peripheral factors (Klapp et al., 1998). This restriction can be bypassed by streaming under some conditions (Jagacinski et al., 2016).
3. The PRP effect, first described by Telford (1931), is a stubborn restriction that prevents concurrent processing for multiple actions. It is the topic of the present analysis.

It may be fair to say that no one would have anticipated any of these limitations *a priori* and yet each has been firmly established within its independent tradition of empirical research. Our analysis goes beyond describing these limitations individually to suggest that the first two combine to produce the third, the PRP bottleneck. Furthermore, according to this analysis all three limitations are related to response timing.

The cerebellum may play only an indirect and limited role in memory related to selection of sequences (Spencer & Ivry, 2009) and, as discussed above, there may be no cerebellar working memory for the coding that implements timing. Thus, even though timing is programmed in the cerebellum, this structure may be unable to support retention of the program that it forms. As noted earlier, this lack of working memory can explain why advance programming of timing is not possible in the simple RT paradigm (first of the three limitations). Restricted memory with respect to timing may contribute to the tendency to use only one temporal frame (second limitation). If the PRP effect (third limitation) is produced by the other two limitations in combination as we propose, restricted working memory for timing could be the unifying principle behind all three limitations. Whether this proposal regarding working memory is on the right track or not, the presence of a robust limit with respect to response timing warrants further exploration.

Appendix A

If perception of S2 can be performed in parallel with RT1 (Fig. 1C), an interaction can occur between the duration of perception of S2 and SOA. The source of this interaction is described in Fig. 3 which is an expanded version of Fig. 2. As perception of S2 becomes more difficult and therefore takes longer, the horizontal line moves upward (because RT_{ref} includes the time needed to perceive S2) and the inflection point at which the slope transitions from -1 to 0 moves to the left (shorter SOA) as shown in Fig. 3. Thus when RT2 is measured for difficult (long duration) and easy (short duration) perception of S2 at two different SOA's, an underadditive interaction is predicted only if the two measured SOA's bracket at least one of the two inflection points. That is, for these values of SOA the influence of increasing perceptual difficulty for S2 is weaker for the shorter SOA. This conclusion, that this interaction occurs only if the SOA's bracket an inflection point, may not be generally recognized.

The pattern depicted in Fig. 3 can be derived from Fig. 1C. RT2 is greater than RT_{2ref} by the amount of slack in the sequence of RT2 events. When SOA is short, increases in SOA shorten RT2 and the amount of slack and generate the slope of -1 on the left side of Fig. 3. When SOA is long enough that there is no remaining slack, then $RT2 = RT_{2ref}$. Any further increases in SOA do not reduce RT2 (the slope equals 0 on the right side of Fig. 3). The change in slope from -1 to 0 occurs at a shorter SOA when perception of S2 is longer. In other words, the inflection point is farther to the left and RT_{2ref} is higher.

Fig. 3 If stimulus 2 (S2) perception can occur in parallel with reaction time to task 1 (RT1) as in Fig. 1C, then variations in the duration of S2 perception (long — — —, short —————) and SOA produce an interactive pattern for reaction time to respond to task 2 (RT2)

References

- Alouche, S. R., Sant'Anna, G. N., Biagioni, G., & Ribeiro-do-Valle, L. E. (2012). Influence of cueing on the preparation and execution of untrained and trained complex motor responses. *Brazilian Journal of Medical and Biological Research*, 45(5), 425–435.
- Binet, A. (1890). Recherches sur le mouvement de quelques jeunes enfants [Investigation concerning the movement of several young children] *Revue Philosophique*, 29, 297–309.
- Bratzke, D., Rolke, B., & Ulrich, R. (2009). The source of execution-related dual-task interference: Motor bottleneck or response monitoring? *Journal of Experimental Psychology: Human Perception and Performance*, 35(5), 1413–1426.
- Bregman, A. S. (1978). Auditory streaming is cumulative. *Journal of Experimental Psychology: Human Perception and Performance*, 4, 380–387.
- Bregman, A. S. (1990). *Auditory scene analysis*. Cambridge, MA: MIT Press.
- Carlsen, A. N., Maslovat, D., & Franks, I. M. (2012). Preparation for voluntary movement in healthy and clinical populations: Evidence from startle. *Clinical Neurophysiology*, 123(1), 21–33.
- Carrier, L. M., & Pashler, H. (1995). Attentional limits in memory retrieval. *Journal of Experimental Psychology: Learning Memory and Cognition*, 21, 1339–1348.
- Cliff, R. C. (1973). Attention sharing in the performance of a dynamic dual task *IEEE Transactions on Systems, Man, and Cybernetics*, SMC-3, 241–248.
- Craik, K. H. W. (1947). Theory of human operator in control systems: I; The operator as an engineering system. *British Journal of Psychology*, 38, 56–61.
- De Jong, R. (1993). Multiple bottlenecks in overlapping task performance. *Journal of Experimental Psychology: Human Perception and Performance*, 19(5), 965–980.
- Deutsch, D. (1983). The generation of two isochronous sequences in parallel. *Perception & Psychophysics*, 34(4), 331–337.
- Donders, F. C. (1868/1969). Over de snelheid van psychische processen [On the speed of mental processes]. In W. G. Koster (Ed.), *Attention and performance II. Acta Psychologica* (Vol. 30, pp. 412–431).
- Fagot, C., & Pashler, H. (1992). Making two responses to a single object: Implications for the central attentional bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 1058–1079.
- Fitts, P. M., & Seeger, C. M. (1953) S-R compatibility: Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology*, 46, 199–210.
- Green, C., Johnston, J. C., & Ruthruff, E. (2011). Attentional limits in memory retrieval – Revisited. *Journal of Experimental Psychology: Human Perception and Performance*, 37, 1083–1098.
- Greenwald, A. G. (1970). Sensory feedback mechanisms in performance control: With special reference to the ideomotor mechanism. *Psychological Review*, 77(2), 73–99.
- Greenwald, A. G. (2003). On doing two things at once: III. Confirmation of perfect timesharing when simultaneous tasks are ideomotor compatible. *Journal of Experimental Psychology: Human Perception and Performance*, 29(5), 859–868.
- Greenwald, A. G., & Shulman, H. G. (1973). On doing two things at once. II. Elimination of the psychological refractory period effect. *Journal of Experimental Psychology*, 101(1), 70–76.
- Halvorson, K. M., Ebner, H., & Hazeltine, E. (2013). Investigating perfect timesharing: The relationship between IM-compatible tasks and dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, 39(2), 413–432.
- Halvorson, K. M., & Hazeltine, E. (2015). Do small dual-task costs reflect ideomotor compatibility or the absence of crosstalk? *Psychonomic Bulletin and Review*, 22(5), 1403–1409.
- Hazeltine, E., Teague, D., & Ivry, R. B. (2002). Simultaneous dual-task performance reveals parallel response selection after practice. *Journal of Experimental Psychology: Human Perception and Performance*, 28(3), 527–545.
- Hazeltine, E., Weinstein, A., & Ivry, R. B. (2008) Parallel response selection after callosotomy. *Journal of Cognitive Neuroscience*, 20(3), 526–54.
- Henry, F., & Rogers, D. (1960). Increased response latency for complicated movements and a "memory drum" theory of neuromotor reaction. *Research Quarterly of the American Association for Health, Physical Education, and Recreation*, 31(3), 448–458.

- Hick, W.E. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology*, 4, 11–26.
- Hommel, B., & Eglau, B. (2002). Control of stimulus-response translation in dual-task performance. *Psychological Research*, 66(4), 260–273.
- Ivry, R. B., Franz, E.A., Kingstone, A. & Johnston, J.C. (1998) The PRP effect following callosotomy: Uncoupling of lateralized response codes. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 463–480
- Ivry, R. B., & Keele, S. W. (1989). Timing functions of the cerebellum. *Journal of Cognitive Neuroscience*, 1(2), 136–152.
- Jagacinski, R. J., Marshburn, E., Klapp, S. T., & Jones, M. R. (1988). Tests of parallel versus integrated structure in polyrhythmic tapping. *Journal of Motor Behavior*, 20(4), 416–442.
- Jagacinski, R. J., Reppeger, D. W., Moran, M. S., Ward, S. L., & Glass, B. (1980). Fitts' law and the microstructure of rapid discrete movements. *Journal of Experimental Psychology: Human Perception and Performance*, 6, 309–320.
- Jagacinski, R. J., Rizzi, E., Kim, T. H., Lavender, S. A., Speller, L. F., & Klapp, S. T. (2016). Parallel streams versus integrated timing in multilimb pattern generation: A test of Korte's Third Law. *Journal of Experimental Psychology: Human Perception and Performance* 42, 1703–1715. DOI: <https://doi.org/10.1037/xhp0000263>
- James, W. (1890). *Principles of psychology*, Vol. 2. New York, NY: Holt.
- Janczyk, M. (2016). Sequential modulation of backward crosstalk and task-shielding in dual-tasking. *Journal of Experimental Psychology: Human Perception and Performance*, 42(5), 631–647.
- Jones, M. R., & Yee, W. (1993). Attending to auditory events: The role of temporal organization. In S. McAdams & E. Reigand (Eds.), *Cognitive aspects of human audition* (pp. 69–112). New York, NY: Oxford University Press.
- Kantowitz, H., & Knight, J. L., Jr. (1976). Testing tapping timesharing, II: Auditory secondary task. *Acta Psychologica*, 40(5), 343–362.
- Karlin, L., & Kestenbaum, R. (1968). The effects of number of alternatives on the psychological refractory period. *Quarterly Journal of Experimental Psychology*, 20, 167–178.
- Keele, S. W. (1973). *Attention and human performance*. Palisades, CA: Goodyear.
- Klapp, S. T. (1979). Doing two things at once: The role of temporal compatibility. *Memory and Cognition*, 7, 375–381.
- Klapp, S. T. (2010). Comments on the classic Henry and Rogers (1960) paper on its 50th anniversary: Resolving the issue of simple versus choice reaction time. *Research Quarterly for Exercise and Sport*, 81(1), 108–112.
- Klapp, S. T. (2015). One version of direct response priming requires automatization of the relevant associations but not awareness of the prime. *Consciousness and Cognition*, 34, 163–175.
- Klapp, S. T., & Jagacinski, R. J. (2011). Gestalt principles in the control of motor action. *Psychological Bulletin*, 137(3), 443–462.
- Klapp, S. T., Kelly, P. A., & Netick, A. (1987). Hesitations in continuous tracking induced by a concurrent discrete task. *Human Factors*, 29(3), 327–337.
- Klapp, S. T., Nelson, J. M., & Jagacinski, R. J. (1998). Can people tap concurrent bimanual rhythms independently? *Journal of Motor Behavior*, 30(4), 301–322.
- Klapp, S. T., Porter-Graham, K. A., & Hoifield, A. R. (1991). The relation of perception and motor action: Ideomotor compatibility and interference in divided attention. *Journal of Motor Behavior*, 23(3), 155–162.
- Krampe, R. T., Kliegl, R., Mayr, U., Engbert, R., & Vorberg, D. (2000). The fast and the slow of skilled bimanual rhythm production: Parallel versus integrated timing. *Journal of Experimental Psychology: Human Perception and Performance*, 26(1), 206–233.
- Leuthold, H., Sommer, W., & Ulrich, R. (1996). Partial advance information and response preparation: Inferences from the lateralized readiness potential. *Journal of Experimental Psychology: General*, 125(3), 307–323.
- Leuthold, H., Sommer, W., & Ulrich, R. (2004). Preparing for action: Inferences from CNV and LRP. *Journal of Psychophysiology*, 18, 77–88.
- Levy, J., & Pashler, H. (2008). Task prioritisation in multitasking during driving: Opportunity to abort a concurrent task does not insulate braking responses from dual-task slowing. *Applied Cognitive Psychology*, 22(4), 507–525.
- Levy, J., Pashler, H., & Boer, E. (2006). Central interference in driving: Is there any stopping the psychological refractory period? *Psychological Science*, 17(3), 228–235.
- Lien, M. C., McCann, R. S., Ruthruff, E., & Proctor, R. W. (2005). Confirming and disconfirming theories about ideomotor compatibility in dual-task performance: A reply to Greenwald (2005). *Journal of Experimental Psychology: Human Perception and Performance*, 31(1), 226–229.
- Lien, M. C., & Proctor, R. W. (2002). Stimulus-response compatibility and psychological refractory period effects: Implications for response selection. *Psychonomic Bulletin and Review*, 9(2), 212–238.
- Logan, G. D., & Delheimer, J.A. (2001) Parallel memory retrieval in dual-task situations II. Episodic memory *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 27, 668–685
- Logan, G. D. & Schulkind, M.D. (2000) Parallel memory retrieval in dual-task situations I semantic memory. *Journal of Experimental Psychology: Human Perception and Performance*, 26, 1072–1090.
- Lu, Chen-Hui & Proctor, R.W. (1995) The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin & Review*, 2(2) 174–207
- MacLeod, C.M. (1991) Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, 109(2), 163–203.
- Magnuson, C. E., Robin, D. A., & Wright, D. L. (2008). Motor programming when sequencing multiple elements of the same duration. *Journal of Motor Behavior*, 40(6), 532–544.
- Maslovat, D., Chua, R., Carlsen, A. N., May, C., Forgaard, C. J., & Franks, I. M. (2015). A startling acoustic stimulus interferes with upcoming motor preparation: Evidence for a startle refractory period. *Acta Psychologica*, 158, 36–42.
- Maslovat, D., Chua, R., Klapp, S. T., & Franks, I. M. (2016). Independent planning of timing and sequencing for complex motor movements. *Journal of Experimental Psychology: Human Perception and Performance*, 42, 1158–1172.
- Maslovat, D., Chua, R., Klapp, S.T., & Franks, I.M. (2017) Preparation of timing structure involves two independent sub-processes. *Psychological Research* <https://doi.org/10.1007/s00426-017-0877-3>
- Maslovat, D., Chua, R., Spencer, H. C., Forgaard, C. J., Carlsen, A. N., & Franks, I. M. (2013) Evidence for a response preparation bottleneck during dual-task performance: Effect of a startling acoustic stimulus on the psychological refractory period. *Acta Psychologica*, 144(3), 481–487.
- Maslovat, D., Klapp, S. T., Jagacinski, R. J., & Franks, I. M. (2014). Control of response timing occurs during the simple reaction time interval but on-line for choice reaction time. *Journal of Experimental Psychology: Human Perception and Performance*, 40(5), 2005–2021.
- McCann, R. S., & Johnston, J. C. (1992). Locus of the single-channel bottleneck in dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 471–484.
- McGurk, H. & MacDonald, J. (1976) Hearing lips and seeing voices. *Nature*, 264, 746–748
- McLeod, P. (1977). A dual task response modality effect: Support for multiprocessor models of attention. *Quarterly Journal of Experimental Psychology*, 29, 651–667.
- McLeod, P., & Posner, M. I. (1984). Privileged loops from percept to act. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and performance*

- X: *Control of language processes* (pp. 55–66). Hillsdale, NJ: Erlbaum.
- Mechner, F., Kerzel, D., Knoblich, G., & Prinz, W. (2001) Perceptual basis of bimanual coordination. *Nature*, 414, 69–73.
- Miller, J. & Durst, M. (2015) A comparison of the psychological refractory and prioritized processing paradigms: Can the response-selection bottleneck model explain them both? *Journal of Experimental Psychology: Human Perception and Performance*, 41, 1420–1441.
- Mittlestadt, V. & Miller, J. (2017) Separating limits on preparation versus online processing in multitasking paradigms: Evidence for resource models. *Journal of Experimental Psychology: Human Perception and Performance* 43, 89–102.
- Navon, D. (1984). Resources – A theoretical soup stone? *Psychological Review*, 91, 216–234.
- Navon, D., & Gopher, D. (1979) On the economy of the human-processing system. *Psychological Review*, 86, 214–255.
- Netick, A., & Klapp, S. T. (1994). Hesitations in manual tracking: A single-channel limit in response programming. *Journal of Experimental Psychology: Human Perception and Performance*, 20(4), 766–782.
- Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, 10(3), 358–377.
- Pashler, H. (1989). Dissociations and dependencies between speed and accuracy: Evidence for a two-component theory of divided attention in simple tasks. *Cognitive Psychology*, 21, 469–514.
- Pashler, H. (1990). Do response modality effects support multiprocessor models of divided attention? *Journal of Experimental Psychology: Human Perception and Performance*, 16(4), 826–842.
- Pashler, H. (1993). Doing two things at the same time. *American Scientist*, 81, 48–55.
- Pashler, H. (1994a). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, 116(2), 220–244.
- Pashler, H. (1994b). Graded capacity-sharing in dual-task interference? *Journal of Experimental Psychology: Human Perception and Performance*, 20(2), 330–342.
- Pashler, H. (1998). *The psychology of attention*. Cambridge, MA: MIT Press.
- Pashler, H., Carrier, M., & Hoffman, J. (1993) Saccadic eye movements and dual-task interference. *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology*, 46(1), 51–82.
- Pashler, H., & Christian, C. (1994) Bottlenecks in planning and producing manual, vocal and foot responses. Unpublished manuscript, University of California, San Diego. Summarized in Pashler (1998, p. 283).
- Pashler, H., & Johnston, J. C. (1989) Interference between temporally overlapping tasks: Chronometric evidence for central postponement with or without response grouping. *Quarterly Journal of Experimental Psychology*, 41A, 19–45.
- Pashler, H., Luck, S.J., Hillyard, G.R., O'Brien, S., & Gazzaniga, M.S. (1994) Sequential operation of the disconnected cerebral hemispheres in “split-brain” patients. *Neuroreport*, 5, 2381–2384.
- Pashler, H., & O'Brien, S. (1993). Dual-task interference and the cerebral hemispheres. *Journal of Experimental Psychology: Human Perception and Performance*, 19(2), 315–330.
- Roberts, B., Glasberg, B.R., & Moore, B.C.J. (2008). Effects of the build-up and resetting of auditory stream segregation on temporal discrimination. *Journal of Experimental Psychology: Human Perception and Performance*, 34, 992–1006.
- Rosenbaum, D. A. (1980). Human movement initiation: Specification of arm, direction, and extent. *Journal of Experimental Psychology: General*, 109 (4), 333–474.
- Rosenbaum, D. A., Dawson, M., & Challis, J. H. (2006) Haptic tracking permits bimanual independence. *Journal of Experimental Psychology: Human Perception and Performance*, 32, 1266–1275.
- Rosenbaum, D. A., Kenny, S. B., & Derr, M. A. (1983). Hierarchical control of rapid movement sequences. *Journal of Experimental Psychology: Human Perception and Performance*, 9(1), 86–102.
- Ruthruff, E., Johnston, J. C., & Remington, R. W. (2009) How strategic is the central bottleneck: Can it be overcome by trying harder? *Journal of Experimental Psychology: Human Perception and Performance*, 35(5), 1368–1384.
- Ruthruff, E., Pashler, H. E., & Hazeltine, E. (2003). Dual-task interference with equal task emphasis: Graded capacity sharing or central postponement? *Perception and Psychophysics*, 65(5), 801–816.
- Sakai, K., Kitaguchi, K., & Hikosaka, O. (2003). Chunking during human visuomotor sequence learning. *Experimental Brain Research*, 152(2), 229–242.
- Sanders, A.F. & Lamers, J.M. (2002) The Eriksen flanker effect revisited. *Acta Psychologica*, 109, 41–56.
- Schumacher, E. H., Lauber, E. J., Glass, J.M., Zurbriggen, E.L., Gmeindl, L., Kieras, D., & Meyer, D.E. (1999). Concurrent response-selection processes in dual-task performance: Evidence for adaptive executive control of task scheduling. *Journal of Experimental Psychology: Human Perception and Performance*, 25, 791–814.
- Schumacher, E. H., Seymour, T. L., Glass, J. M., Fencsik, D. E., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (2001). Virtually perfect time sharing in dual-task performance: Uncorking the central cognitive bottleneck. *Psychological Science*, 12(2), 101–108.
- Schweickert, R. & Fisher, D. L. (1987) Stochastic network models. In G. Salvendy (Ed.) *Handbook of human factors* (pp. 1177–1211) New York: Wiley.
- Smith, M. C. (1967) Theories of the psychological refractory period. *Psychological Bulletin*, 67, 202–221.
- Spencer, R.M. & Ivry, R. (2009) Sequence learning is preserved in individual with cerebellar degeneration when the movements are directly coded. *Journal of Cognitive Neuroscience*, 21 (7), 1302–1310.
- Strayer, D.L., Drews, F.A., & Johnston, W.A. (2003) Cell phone-induced failures of visual attention during simulated driving. *Journal of Experimental Psychology: Applied*, 9, 23–32.
- Telford, C. W. (1931) The refractory phase of voluntary and associative responses. *Journal of Experimental Psychology*, 14, 1–36.
- Tombu, M., & Jolicoeur, P. (2003) A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, 29(1), 3–18.
- Valls-Solé, J., Kumru, H., & Kofler, M. (2008) Interaction between startle and voluntary reactions in humans. *Experimental Brain Research*, 187(4), 497–507.
- Valls-Solé, J., Rothwell, J. C., Goulart, F., Cossu, G., & Munoz, E. (1999). Patterned ballistic movements triggered by a startle in healthy humans. *Journal of Physiology*, 516.3, 931–938.
- van Mier, H., Hulstijn, W., & Petersen, S. (1993) Changes in motor planning during the acquisition of movement patterns in a continuous task. *Acta Psychologica*, 8, 291–312.
- Verwey, W. B. (1996) Buffer loading and chunking in sequential key-pressing. *Journal of Experimental Psychology: Human Perception and Performance*, 22, 544–562.
- Verwey, W. B. (2001) Concatenating familiar movement sequences: The versatile cognitive processor. *Acta Psychologica*, 106(1–2), 69–95.
- Verwey, W. B., & Eikelboom, T. (2003) Evidence for lasting sequence segmentation in the discrete sequence-production task. *Journal of Motor Behavior*, 35(2), 171–181.
- Vorberg, D., & Wing, A. M. (1996) Modeling variability and dependence in timing. In S. Keele & H. Heuer (Eds.), *Handbook of perception and action, Vol 2* (pp. 181–262). New York: Academic Press.
- Welford, A. T. (1952) The “psychological refractory period” and the timing of high speed performance - A review and theory. *British Journal of Psychology*, 43, 2–19.
- Wickens, C. D. (1984) Processing resources in attention. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention* (pp. 63–102). Orlando, FL: Academic Press.