Motor limitation in dual-task processing

under ballistic movement conditions

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Abstract

The standard bottleneck model of the psychological refractory period (PRP) assumes that the selection of the second response is postponed until the first response has been selected. Accordingly, dual-task interference is attributed to a single central processing bottleneck involving decision and response selection but not the execution of the response itself. In order to critically examine the assumption that response execution is not part of this bottleneck, we systematically manipulated the temporal demand for executing the first response in a classical PRP paradigm. Contrary to the assumption of the standard bottleneck model, this manipulation affected the reaction time for Task 2. Specifically, reaction time of Task 2 increased with the execution time of Task 1. This carry-over effect from Task 1 to Task 2 provides evidence for the notion that response execution can be part of the processing bottleneck.

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When people carry out two tasks at the same time, task performance is usually worse than when people perform each of the two tasks in isolation. This dual-task interference has been an intriguing topic in psychology for a long time (e.g. Pashler, 1998; Woodworth, 1938). Recently, the mechanisms underlying this dual-task interference have received considerable attention not only in cognitive psychology but also in cognitive neuroscience (e.g., Jiang, Saxe & Kanwisher, 2004; Marois & Ivanoff, 2005). Most frequently, the psychological refractory period paradigm has been employed to investigate the causes of this interference, since this paradigm is particularly suited to resolve the temporal microstructure of dual-task interference (Kahneman, 1973; Logan & Gordon, 2001; Meyer & Kieras, 1997; Navon & Miller, 2002; Pashler & Johnston, 1989; Ruthruff, Pashler & Hazeltine, 2003; Tombu & Jolicœur, 2003).

The PRP paradigm requires participants to perform two successively yet temporally overlapping choice reaction time (RT) tasks. In each trial, two stimuli (S1 and S2) are presented in rapid succession, whereas each stimulus requires a separate response (R1 and R2). When the interval between S1 and S2 --- known as the stimulus onset asynchrony (SOA) --- is relatively long, participants simply perform both tasks one after the other, because processing of S1 can be finished before S2 onset. In this case, RT to S2 (RT2) is almost the same as when Task 2 is performed in isolation. However, when SOA is short, S1 is still processed while S2 is presented. In this

situation participants face the demand to process both tasks simultaneously and this produces a dramatic RT2 increase. This slowing of RT2 is commonly referred to as the PRP effect (Vince, 1949; Welford, 1952). In contrast to RT2, RT1 is usually not or only slightly affected by the SOA manipulation (for a review, see Pashler, 1994).

Various accounts of this PRP effect in terms of structural limitations (Pashler & Johnston, 1989), capacity limitations (Kahneman, 1973), or processing strategies (Logan & Gordon, 2001; Meyer & Kieras, 1997) have been proposed. Nevertheless, there is strong evidence that the effect emerges from a response-selection bottleneck stage, which is limited in its capacity to process more than one task at a time. Accordingly, response selection of R2 cannot begin until response selection of R1 has finished. This processing bottleneck may arise from a structural limitation of the central nervous system requiring serial processing of both tasks at the level of response selection (Luck, 1998; Pashler & Johnston, 1989). Serial processing at a level of response selection may also emerge from performance optimization within capacity-sharing models rather than from an insurmountable structural bottleneck (Miller, Ulrich & Rolke, in press). Irrespective of the nature of such a bottleneck, all models proceed from the assumption that dual-task interference is produced at a premotor level.

Several studies, however, suggest that the dual-task limitation may also include processes at a motor level. For example, Karlin and Kestenbaum (1968) asked participants to perform either a simple or a two-choice response task to the S2 stimulus. Contrary to the prediction of an additive effect of number of S2-R2 alternatives and SOA, the authors reported an underadditive

effect, that is, the difference between choice and simple RT increased with SOA. Based on this result and the assumption that number of S-R alternatives affects the duration of central stages (cf. Sanders, 1980), Keele (1973) argued that this underadditive effect reflects processing limitations at a post-decisional, most probably, response initiation stage. More specifically, Keele assumed that after R1 initiation some time has to cease before R2 can be performed.

This idea of a response initiation bottleneck was later incorporated by De Jong (1993), who successfully replicated Karlin and Kestenbaum's (1968) findings. He suggested a hybrid bottleneck model to account for PRP effects. This model extends the standard bottleneck model by including a further motor-related bottleneck. As in the standard model, only one response can be selected at any given time. In addition, due to the refractoriness of the motor system, R2 cannot be initiated immediately after activating R1.

The evidence for a motor bottleneck, however, is somewhat mixed. First, some authors challenged the interpretation by Karlin and Kestenbaum (1968), arguing that the underadditive effect of SOA and number of S-R alternatives reflects a differential anticipation effect in the simple RT task. Specifically, since in the simple RT task the response is known, participants may benefit from advance preparation in longer SOA conditions. In support of this idea, this underadditive interaction is only found when simple and two-choice tasks are compared. However, when response preparation is precluded as in choice tasks, SOA and number of S2-R2 alternatives produce an additive effect (Schubert, 1999; van Selst & Jolicœur, 1997). Additional support for the response anticipation account comes from an

electrophysiological study examining hand-specific motor activation (Sommer, Leuthold & Schubert, 2001). These authors found hand-specific motor activation to start before S2-onset in the simple but not in the choice condition when SOA was long. Thus, the underadditive effect reported by Karlin and Kestenbaum (1968) does not provide convincing evidence for the existence of a motor-related bottleneck.

Nevertheless, additional results by Sommer et al. (2001) bear on the possibility of such a late bottleneck. They reported electrophysiological evidence for a shortening of Task 2 motor processing time when SOA was long rather than short in the choice RT task. This particular result is consistent with the idea of a late bottleneck, because Task 1 motor processes should no longer occupy this bottleneck at the longest SOA. A more recent electrophysiological study by Sangals, Ross, and Sommer (2004) replicated this change in motor processing time with SOA. Additionally, their results suggested longer durations of motor processing for Task 2 when R2 was produced in close temporal proximity to R1. Although these electrophysiological findings are difficult to accommodate with the assumption of a central bottleneck, they do not provide putative evidence for a late motor bottleneck.

Here, we provide a more direct test for the existence of such a motor bottleneck by manipulating the duration of Task 1 motor processing. According to the standard bottleneck model, such manipulation should not influence Task 2 performance, because Task 1 manipulations affecting post-bottleneck processing should not carry over to Task 2. However, it is possible to extend the standard bottleneck model by assuming an additional motor-

related bottleneck. This extended version of the standard bottleneck model would entail such a carry-over effect (Figure 1). More specifically, an increase in Task 1 motor demands is expected to increase RT2 at short SOAs.

Surprisingly, to our knowledge only an unpublished study has attempted to examine whether the duration of Task 1 motor processing affects RT2 (Pashler & Christian, 1994). In four experiments, Pashler and Christian manipulated the duration for producing R1 to assess whether response production is part of the bottleneck process. For example, in Experiment 1 they manipulated the sequence length of R1. S1 was either the digit "1" or "5" and participants responded by saying "one" or "one two three four five". S2 was a tone of either 300 or 900 Hz, requiring a single keypress response with the middle or index finger of the right hand, respectively. As the authors intended, it took participants longer to complete the long than the short R1 sequence. In contrast to what the standard bottleneck model predicts, this sequence length effect propagated to some degree (i.e. 17-34%) onto RT2. Nevertheless, this rather small propagation effect clearly indicates that participants need not completely delay R2 until R1 has finished but can already produce R2 while R1 unfolds.

Interestingly, Pashler and Christian found a strong interference effect when both R1 and R2 were manual (Experiment 3b). More specifically, when participants were asked to produce successive finger taps (i.e. ring finger → middle finger → ring finger) with the left hand as R1, participants did not initiate R2 with the right hand before R1 was finished. Pashler and Christian, however, argue that difficulties in performing successive elements in such a response sequence may require central processes. For this reason, the

outcome of this experiment might be reconciled with the standard bottleneck model.

In their fourth and final experiment, Pashler and Christian (1994) employed a single movement task for R1. In this experiment, R1 was an aiming movement with one hand to a target stimulus appearing on a screen, whereas R2 was a vocal response. As implied by bottleneck models, RT2 should be correlated with RT1 but not with movement time of Task 1 (MT1). Although RT2 correlated positively with RT1, it was also slightly associated with MT1. This latter finding suggests that the initiation of R2 not only depends on the selection of R1 but also on the execution of R1. Because these inferences rest on correlation techniques, they are subject to various interpretations. For example, alertness may randomly fluctuate over trials and thus generate spurious correlation. More importantly, as suggested by the authors themselves, such aiming movements require visual control processes for guiding the hand to the target region (see Meyer, Smith, Kornblum, Abrams, & Wright, 1990). Thus, if central bottleneck processes encompass these control processes, one can reconcile this outcome with a single bottleneck process.

The present experiment provides a critical test of the assumption that bottleneck processes encompass response execution. It builds on Experiment 4 of Pashler and Christian (1994) but tries to omit the shortcoming of that study. In contrast to their experiment, we manipulated movement time experimentally. Specifically, to exclude contributions from control processes as incorporated in visual aiming movements, R1 required a guided ballistic manual movement along a track of either short or long distance (Figure 1,

lower panel). In order to initiate the ballistic movement phase of Task 1, the decision and the response selection phase for this task has to be completed. In addition, the movement phase of Task 1 can be performed without visual online control, hence, minimizing the possibility that central control processes are involved in the execution phase of R1.

Method

Participants. Twenty students from Tübingen University volunteered to participate in a 60-min experiment. Participants received course credits or payment (€7).

Stimuli and apparatus. Participants were tested in a sound-attenuated cabin with ambient lighting kept at a low level. S1 was a tone of either 1,000 or 1,075 Hz, presented via headphones. Its intensity was 70 dB(A) and its duration 60 ms. S2 was the letter O or X, presented in white (38 cd/m^2) on blue background (3.6 cd/m^2) on a monitor screen at a viewing distance of 60 cm. The height of each letter was 20 mm.

Responses were recorded with two separate response devices. The first device was designed to record continuous movements of R1 in the horizontal plane (Figure 1). It consisted of a metal platform where a slider with an attached handle (45 mm in diameter) could be moved along the 255-mm straight track. The start position was located 70 mm (185 mm) apart from the nearer (farther) end point of the track. A spring kept the slider in the start position and a force of about 14.0 N was required to move the slider towards each end point. At the start and end point, touch-sensitive keys were mounted, which recorded movement onset (RT1), i.e., when the slider began to be moved from its start position, and the time when the slider reached the

end point. The response device was located in front of the participant to the left of the midsaggital plane, with the track being oriented in parallel to this plane. Participants operated the slider with their left hand. In order to independently vary movement distance (70 versus 185 mm) and movement direction (forward versus backward) the response device was rotated in the horizontal plane by 180 degree. Continuous push or pull arm movements involved shoulder and elbow, and they were performed without visual guidance. A response panel was used for R2. Three response keys were mounted on this panel. These keys were horizontally arranged and separated by an inter-key distance of 30 mm, as measured from key centers.

Procedure and design. Participants were given written information about the forthcoming task and the S-R mapping. It was also emphasized to give priority to Task 1. Each trial began with the presentation of a blank screen for 1,000 ms. Then a fixation cross was displayed for 1,000 ms in the centre of the screen followed by the presentation of S1. After a variable SOA of 100, 250, or 900 ms, S2 was presented until R2 onset. Upon presentation of S1, participants were to immediately move the slider with their left hand to the target location indicated by tone pitch, whereas a right hand key press response with the index finger was demanded by the letter O, and with the middle finger by the letter X. In case of a wrong response, the message "Falsch" (incorrect) appeared shortly after R2 on the screen for 2,000 ms. After this message, or after R2 onset in the case of correct responses, a fixation cross was presented for 1,000 ms. Once the participant had moved the slider back to the start position, the next trial started.

The experiment consisted of two parts. Each part started with a practice block of 50 trials, which was followed by four experimental blocks consisting of two initial warm-up trials and 48 experimental trials. A short rest separated all blocks during which feedback about mean overall RT and overall error rate was provided on the display. Participants initiated the next block by pressing a key. The second part of the experiment was identical to the first part except that the response device was rotated by 180 degree. Half of the participants performed in the first part a short-distance push movement and a long-distance pull movement and in the second part a long-distance push movement and a short-distance pull movement. This arrangement was reversed for the other half of participants.

<u>Results and Discussion</u>

Participants made a total of 12.4% errors, including choice errors, misses, anticipations, and grouped responses. Responses faster than 150 ms or slower than 1,500 ms to S1 (0.6%) and S2 (3.9%) were excluded from further analysis as well as trials (0.6 %) where responses to S1 and S2 were grouped (i.e., RT2-RT1+SOA < 150 ms). RT1, RT2, and MT1 were only analysed when both tasks were correctly performed. A two-way ANOVA including the factors SOA (100, 250, 900 ms) and Distance (near, far) was performed on RT1, RT2, and MT1. In place of the usual $\underline{p}$-value, we report $\underline{p}_{rep}$ which estimates the probability of replicating an effect (Killeen, 2005).

<u>Task 1 performance</u>. Figure 2 depicts the results for RT1, MT1, and RT2. RT1 was slightly affected by SOA, $\underline{F}(2,38) = 7.3$, $\underline{p}_{rep}=.987$, $\eta^2=.28$, due to slower responses in the longest SOA condition as compared to both shorter SOA conditions, $\underline{F}s(1,19) > 5.3$, $\underline{p}_{rep}>.904$, $\eta^2>.22$. RT1 was also affected by

movement distance, $\underline{F}(1,19) = 27.5$, $\underline{p}_{rep}>.996$, $\eta^2=.59$, due to shorter RT1 for

the long (531 ms) than the short movement distance (562 ms). The latter

result clearly supports the idea that participants pre-program their movements

in a ballistic fashion. Accordingly, more muscle force is required to launch a

movement to a more distant goal (e.g. Schmidt, Zelaznik, Hawkins, Frank &

Quinn, 1979). More force, however, shortens RT1 since criterion force for

measuring RT is attained more rapidly (Ulrich & Wing, 1991). In agreement

with this conjecture, movement velocity associated with the long distance

movement was higher than for the short one (0.45 vs. 0.29 m/s).

As we expected, MT1 was longer when movement distance was long

(415 ms) than short (239 ms), $\underline{F}(1,19) = 436.6$, $\underline{p}_{rep}>.996$, $\eta^2=.96$. Also, MT1

slightly increased in the longest as compared to the two shorter SOA

conditions, resulting in an significant effect of SOA, $\underline{F}(2,38) = 11.4$, $\underline{p}_{rep}=.983$,

$\eta^2=.37$. Movement distance and SOA interacted, $\underline{F}(2,38) = 4.7$, $\underline{p}_{rep}>.913$,

$\eta^2=.20$, due to a larger distance effect (long minus short) in the longest SOA

condition (184 ms) than both shorter SOA conditions (173 and 172 ms,

respectively).

Task-2 performance. RT2 revealed a clear PRP effect, as documented

by a significant decrease in RT2 with increasing SOA, $\underline{F}(2,38) = 340.9$,

$\underline{p}_{rep}>.996$, $\eta^2=.95$. Participants clearly delayed the initiation of R2 when they

had to perform the long R1 movement, $\underline{F}(1,19) = 95.0$, $\underline{p}_{rep}>.996$, $\eta^2=.83$,

indicating longer RT2 for the long (736 ms) than the short movement distance

(653 ms). Most importantly, there was a significant interaction between SOA

and movement distance, $\underline{F}(2,38) = 23.7$, $\underline{p}_{rep}>.996$, $\eta^2=.56$. As can be seen in

Figure 2, this overadditive interaction was due to the smaller effect of

movement duration (long minus short) on RT2 for the longest SOA condition as compared to both shorter SOA conditions. Therefore, this pattern of results clearly shows that the distance effect on MT1 propagated onto RT2, to a large degree at the two short SOAs (67%) but only to a small degree at the long SOA (13%).

It is important to note that it was the effect of MT1 and not the effect of RT1 that propagated to RT2. That is, although RT1 was actually longer for short than for long R1 movements, both MT1 and RT2 showed the reversed pattern. This particular pattern of results suggests that the movement duration effect on RT2 is due to Task 1 processes that follow the initiation of R1. Therefore, these processes are associated with the execution of R1.

Conclusion

Contemporary explanations of the PRP effect proceed from a central bottleneck process that includes decision and response selection (Navon & Miller, 2002; Pashler & Johnston, 1989; Tombu & Jolicœur, 2003). Accordingly, dual-task interference should emerge before R1 is executed. We employed a standard PRP paradigm where the duration of R1 motor execution was manipulated by a guided ballistic manual movement of either short or long distance. The present results provide evidence against this view and suggest that the standard bottleneck model needs to be extended by a motor-related bottleneck (Figure 1, middle panel). Specifically, as predicted by this more general bottleneck model, R2 is delayed when motor execution demands for R1 increase. This finding is most easily accommodated by assuming that bottleneck processes involve response execution. It should be stressed that in contrast to Pashler and Christian's (1994) findings, the

present results cannot be attributed to movement corrections that draw on central resources. The absence of such corrections, for example, is strongly supported by the higher velocity for long than for short distance movements.

The present outcome indicates that the standard bottleneck model needs to be elaborated, at least, when the two tasks in a PRP paradigm involve more complex movement patterns rather than discrete movements (e.g. a single key press response) as in most PRP studies. There are at least two such elaborations conceivable. First, a complex R1 might be especially prone to response monitoring by central processes. As proposed by Welford (1952), central mechanisms may engage in proprioceptive feedback from R1 for a brief period. Only when this period is over, processing of the second task can proceed. This conjecture can account for the present data, if one assumes that the duration of this feedback period increases with the duration of the reaching movement. Although this subsidiary assumption seems plausible, further studies are required to address this possibility more directly.

Second, one may argue that the level of force demand interferes with cognitive processing (Loeb, 1886; Welch, 1898). A ballistic reaching movement to a far goal requires more initial muscle force than one to a close object and thus may require more of the available resources. Consequently, if response force production requires limited central resources, less of these resources should be available for performing Task 2 when participants need to reach for the far goal and this would slow down R2. Although, this is a somewhat speculative account, it is consistent with the present results.

In conclusion, the present study provides strong evidence for the notion that response execution creates an additional bottleneck, which follows the

central bottleneck. R2 in a PRP situation is delayed, as more time is required to execute R1, at least in dual-task experiments that require complex movement patterns. This result provides important new empirical evidence to constrain models on dual-task interference.

References

De Jong, R. (1993). Multiple bottlenecks in overlapping task performance.

Journal of Experimental Psychology: Human Perception and

Performance, 19, 965-980.

Jiang, Y., Saxe, R., & Kanwisher, N. (2004). Functional magnetic resonance

imaging provides new constraints on theories of the psychological

refractory period. Psychological Science, 15, 390-396.

Kahneman, D. (1973). Attention and effort. Englewood Cliffs, NJ: Prentice-

Hall.

Karlin, L., & Kestenbaum, R. (1968). 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. Pacific Palisades, CA:

Goodyear.

Killeen, P.R. (2005). An alternative to null-hypothesis significance tests.

Psychological Science, *16*, 345-353.

Loeb, J. (1886). Muskelthätigkeit als Maass psychischer Thätigkeit. Pflügers

Archiv für die gesamte Physiologie, 39, 592-597.

Logan, G.D., & Gordon, R.D. (2001). Executive control of visual attention in

dual-task situations. Psychological Review, 108, 393-434.

Luck, S.J. (1998). Sources of dual-task interference: Evidence from human

electrophysiology. Psychological Science, 9, 223-227.

Meyer, D.E., & Kieras, D.E. (1997). A computational theory of executive

cognitive processes and multiple-task performance: Part 2. Accounts of

psychological refractory-period phenomena. Psychological Review, 194, 749-791.

Meyer, D.E., Smith, J.E.K., Kornblum, S., Abrams, R.A., & Wright, C.E. (1990). Speed-accuracy tradeoffs in aimed movements: Towards a theory of rapid voluntary action. In M. Jeannerod (Ed.), Attention & Performance XIV (pp. 173-226). Hillsdale, N.J.: Erlbaum.

Miller, J., Ulrich, R., & Rolke, B. (in press). On the optimality of serial and parallel processing in the psychological refractory period paradigm: Effects of the distribution of stimulus onset asynchronies. Cognitive Psychology.

Marois, R., & Ivanoff, J. (2005). Capacity limits of information processing in the brain. Trends in Cognitive Sciences, 9, 296-305.

Navon, D., & Miller, J. (2002). Queuing or sharing? A critical evaluation of the single-bottleneck notion. Cognitive Psychology, 44, 193-251.

Pashler H. (1994). Dual-task interference in simple tasks: data and theory. Psychological Bulletin, 116, 220-244.

Pashler, H. (1998). The psychology of attention. Cambridge, MA: MIT Press.

Pashler, H., & Christian, C. (1994). Bottlenecks in planning and producing vocal, manual, and foot responses. UCSD Center for Human Information Processing Technical Report.

Pashler, H., & Johnston, J. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. Quarterly Journal of Experimental Psychology, 41A, 19-45.

Ruthruff, E., Pashler, H.E., & Hazeltine, E. (2003). Dual-task interference with equal task emphasis: graded capacity sharing or central postponement? <u>Perception & Psychophysics</u>, <u>65</u>, 801-816.

Sangals, J., Ross, L., & Sommer, W. (2004). Time pressure effects on information processing in overlapping tasks: evidence from the lateralized readiness potential. <u>Acta Psychologica</u>, <u>117</u>, 275-294.

Sanders, A. (1980). Stage analysis of reaction processes. In G. E. Stelmach & J. Requin (Eds.), <u>Tutorials of motor behavior</u> (pp. 331-354). New York: North-Holland.

Schmidt, R.A., Zelaznik, H., Hawkins, B., Frank, J.S., & Quinn, J.T. (1979). Motor-output variability: A theory fort he accuracy of rapid motor acts. <u>Psychological Review</u>, <u>86</u>, 415-451.

Schubert, T. (1999). Processing differences between simple and choice reactions affect bottleneck localization in overlapping tasks. <u>Journal of Experimental Psychology: Human, Perception, & Performance</u>, <u>25</u>, 1-18.

Sommer, W., Leuthold, H., & Schubert, T. (2001). Multiple bottlenecks in information processing? An electrophysiological examination. <u>Psychonomic Bulletin & Review</u>, <u>8</u>, 81-88.

Tombu, M., & Jolicœur, P. (2003). A central capacity sharing model of dual-task performance. <u>Journal of Experimental Psychology: Human Perception and Performance</u>, <u>29</u>, 3-18.

Ulrich, R., & Wing, A.M. (1991). A recruitment theory of force-time relations in the production of brief force pulses: The parallel force unit model. <u>Psychological Review</u>, <u>98</u>, 268-294.

Van Selst, M., & Jolicœur, P. (1997). Decision and response in dual-task interference. <u>Cognitive Psychology</u>, <u>33</u>, 266-307.

Vince, M. (1949). Rapid response sequences and the psychological refractory period. <u>British Journal of Psychology</u>, <u>40</u>, 23-40.

Welch, J.C. (1898). On the measurement of mental activity through muscular activity and the determination of a constant of attention. <u>American Journal of Physiology</u>, <u>1</u>, 283-306.

Welford, A.T. (1952). The "psychological refractory period" and the timing of high-speed performance – A review and a theory. <u>British Journal of Psychology</u>, <u>43</u>, 2-19.

Woodworth, R.S. (1938). <u>Experimental psychology</u>. New York: Henry Holt.

Acknowledgements

Figure captions

Figure 1. Predicted effects of Task 1 movement time manipulation on RT2.

Upper panel: No carry-over effect should be observed according to the central

bottleneck model. Middle panel: The central bottleneck model is extended by

assuming an additional motor bottleneck. This extended model predicts a

carry-over effect of Task 1 movement distance manipulation on RT2. (P1 and

P2: duration of perceptual processes of Task 1 and Task 2, respectively. C1

and C2: duration of central processes of Task 1 and Task 2, respectively. M1

and M2: duration of motor programming (blank) and movement execution

(hatched) for Task 1 and Task 2, respectively. S1 and S2: stimulus for Task 1

and Task 2, respectively. RT1 and RT2: reaction time for Task 1 and Task 2,

respectively). Lower panel: Response device for manipulating movement time

of Task 1. The current hand position indicates the home position from which

the long and the short distance movements have to be performed. For details,

see the method section.

Figure 2. RT1 (upper panel), MT1 (middle panel), and RT2 (lower panel) as a

function of stimulus onset asynchrony (SOA) and movement distance of R1.
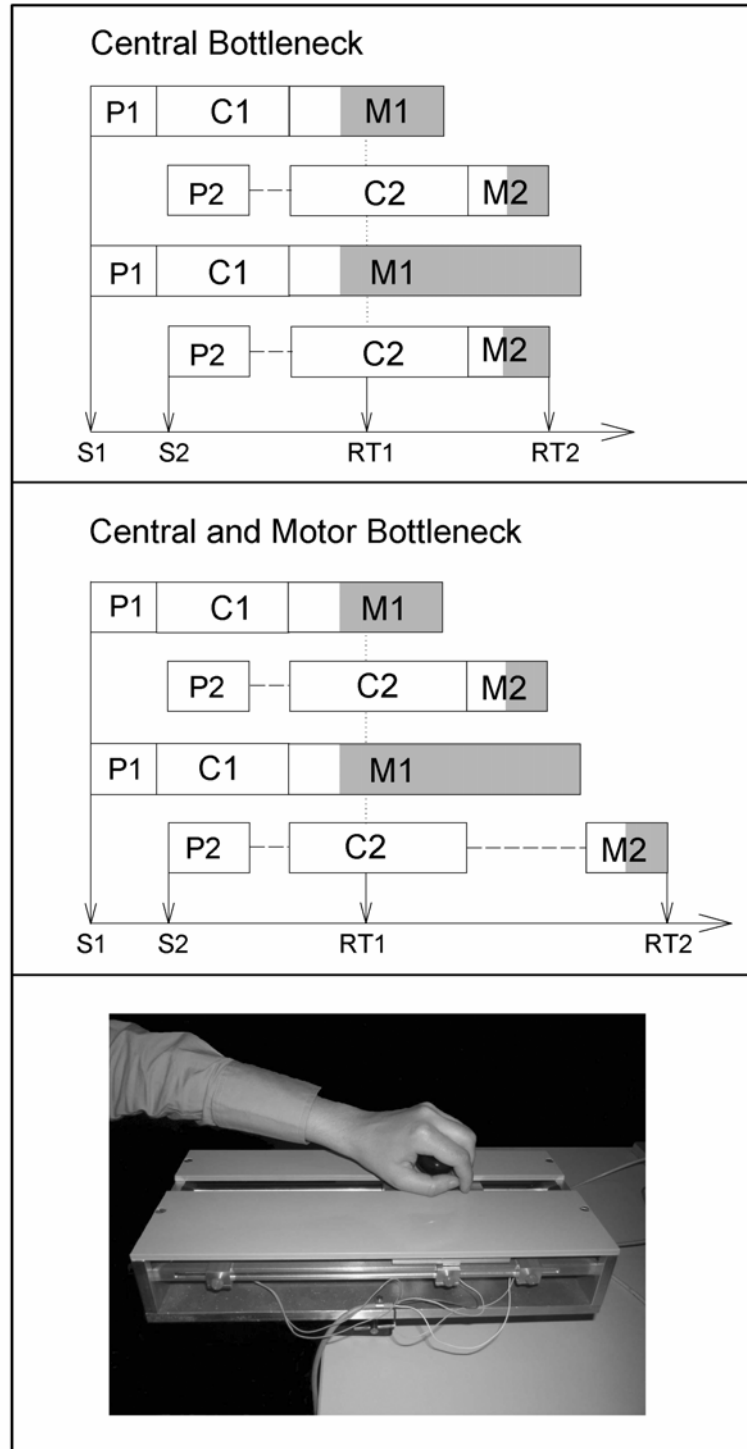
Figure 1

Figure 2