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11 Dual-Task Interference and Elementary Mental Mechanisms

Harold Pashler

Human beings can perform an extraordinary variety of tasks involving coordinated perceptual, cognitive, and motor activity. In the psychological laboratory, people readily comply with even quite bizarre task instructions and successfully configure their mental machinery to produce arbitrary behaviors in response to the stimuli presented to them. Understanding how particular tasks are performed is often of theoretical and practical interest, but a scientifically deep understanding of human cognition and performance also requires uncovering essential constraints and mechanisms that underlie the extraordinary flexibility that we tend to take for granted.

This chapter summarizes recent work directed at revealing basic mental mechanisms by examining what happens when people attempt to perform more than one task concurrently. The goal of such “dual-task” research is one that has been useful in various fields: to reveal the basic components of a system and how they function together by examining how the system breaks down when it is overloaded in some way. Important facts about the overall structure and control of a complex system are often hidden when the system is functioning smoothly and little is demanded of it, but when it is challenged, important constraints may become evident.

Dual-task interference has been studied with a variety of different methods. The approach taken here starts with very basic (e.g., tachistoscopic and choice reaction time) tasks, studying performance on a trial-by-trial basis, adding additional components one by one, and focusing on the relative timing of particular stages of processing. This contrasts with much dual-task research of the past twenty years, which has often employed complex and temporally extended tasks, while assuming particular theoretical concepts (such as shared resources) in advance. I will argue that our results require postulation of several discrete attentional mechanisms. In general, our results tend to support some of the suggestions made by the investigators who first examined dual-task interference (notably Welford), while falsifying many hypotheses that have been advanced more recently.

11.1 DUAL-TASK INTERFERENCE

The simplest experimental situation that demands concurrent performance of two basic tasks is the *psychological refractory period* (PRP) paradigm. Here, two stimuli ($S1$ and $S2$) are presented, separated by some stimulus onset asynchrony (SOA), and the subject makes a separate speeded response to each ($R1$ and $R2$). Early investigators using manual responses to visual stimuli (e.g., Vince 1949) reported a marked slowing of the second response (the *PRP effect*) as the SOA decreased. In some cases, the slope of the function relating $R2$ latency to SOA was about minus one for short SOAs (Welford 1952).

Given the simplicity of the tasks employed, this interference is rather remarkable. It is also strikingly robust. Interference does not depend upon using two visual stimuli, as in the earliest studies. Davis (1959) found a PRP effect with a tone and a visual stimulus, for example. Nor does it depend upon requiring concurrent manual responses. For example, classic PRP functions have been observed with various manual and vocal response combinations (e.g., Pashler 1989, 1990), and even with manual and foot responses (Osman and Moore 1990).

Studies of divided attention that require the (unsped) report of brief visual displays have frequently observed better performance when the two stimuli are attributes of the same object (e.g., Duncan 1984). However, Clark Fagot and I have found that the classic PRP effect persists under these conditions. For example, in one experiment, we had subjects make a manual choice response to the identity of a character and name the color of the character aloud (the character— $S1$ —started out grey and then turned to the target color— $S2$ —after a variable SOA). In another experiment, subjects made a push-button response to the color of a character and named aloud its direction of motion (up vs. down). In both cases, the usual PRP effects were observed (Fagot and Pashler, in press).

It has been suggested that extensive practice with a consistent stimulus-response mapping allows performance to become independent of “attentional resources.” This conclusion is based mostly on studies in which subjects perform a visual search task at the same time as they maintain a memory load (Schneider and Shiffrin 1977). However, practice does not generally seem to eliminate the PRP effect, despite the use of completely consistent mappings throughout. For example, James Johnston and I required subjects to perform more than 10,000 trials of practice with a pair of overlapping choice tasks; the PRP effect remained (Johnston and Pashler 1984; see also Gottsdanker and Stelmach 1971). Common sense would suggest that maintaining a memory load may simply not require continuous mental operations, in which case the usual interpretation of the “automaticity” studies is not demanded by the data (see below).

While the PRP paradigm is an elegantly simple model for dual-task interference, it is artificial in requiring the subject to deal with only two punctate events. This requirement is rather rare outside the laboratory, where one task is typically performed for a while, and then another task intrudes more or

less unexpectedly. In principle, protracted performance might either increase interference (because of poor temporal warning) or decrease it (if performing a task for some time allows the processing machinery to organize itself so as to carry out the task autonomously). Johnston and I examined this question by having subjects perform a manual choice response to a tone either once or repeatedly, followed by a visual signal calling for a response with the other hand. The repeated first-task condition showed improved performance on that task, but the interference with the visual (second) task was actually *greater* than usual (Pashler and Johnston 1991). Extensive practice did not alter this, but providing an extra warning signal for the arrival of S2 mitigated the extra interference somewhat. Thus, so far we have found no reason to believe that the PRP effect is an artifact of performing two tasks in temporal isolation.

There is, however, at least one case in which the PRP effect seems to be largely eliminated. This occurs when one of the tasks involves a saccadic eye movement. Mark Carrier, Jim Hoffman, and I had subjects perform a manual response to a tone (high vs. low pitch) and, after a variable SOA, a saccadic eye movement cued by a visual stimulus (Pashler, Carrier, and Hoffman 1991). When the saccade task simply required subjects to move their eyes to a patch that appeared by itself on the left or right side of the screen, saccade latencies were not much affected by the SOA, and other indices of interference were virtually absent. The same was true when a red patch and a green patch were presented to either side of fixation, and subjects moved their eyes to the patch with a prespecified color. However, when a *central* color patch was presented, and subjects moved their eyes in one direction if it was red and in the other direction if it was green, the eye movement was clearly delayed by the first task. Clear-cut interference also occurred when the subject had to make a saccade toward the numerically higher of two large digits presented off fixation.

It appears, then, that under certain conditions, at least one response system (the oculomotor system) can be triggered to operate independently of other mental activities. This might be related to the fact that eye movements are mediated by several partially redundant brain systems. The response of shadowing verbal input may also be exempt from PRP-type interference (McLeod and Posner 1984). We are currently looking for other cases of interference-free behaviors (such as manual reaching), but even if there are several more of them, they would seem to represent the exception rather than the rule.

11.2 CAUSES OF DUAL-TASK INTERFERENCE

What causes the dual-task interference described so far? A wide range of theories have been proposed since the PRP effect was first observed. Early suggestions that the effect might stem simply from temporal uncertainty about the arrival of S2 were easily rejected. Instead, several workers proposed a "bottleneck" such that some stages of performance in each task require a common mechanism. According to this proposal, these stages in the second task cannot begin until the corresponding ones in the first task are complete.

This has the virtue of predicting in a straightforward way the minus one slopes noted above. Different researchers suggested different accounts of what stages constituted this bottleneck. A bottleneck in perceptual processing was considered (Broadbent 1958), while Welford (1952, 1980) suggested that a central mechanism was required to determine what response should be made (which he termed the “translation” mechanism).

Some early reviews favored Welford’s proposals (e.g., Smith 1967), but the evidence was not compelling, and in the following years, still further alternatives were advanced. These included the possibility of a bottleneck in the actual initiation or execution of responses (Keele 1973), or graded sharing of capacity between tasks (Kahneman 1973; McLeod 1977). The latter suggestion was motivated primarily by the observation that R1 as well as R2 was sometimes slowed in the dual-task situation. For reasons that are not entirely clear, the main focus of dual-task research turned to other procedures involving more continuous types of tasks. The consequence of this shift was that the dual-task situation most amenable to detailed analysis was relatively neglected for more than a decade.

11.3 RECENT ANALYSES OF DUAL-TASK INTERFERENCE

Chronometric Methods

In recent studies, we have focused on the PRP effect once again, using methods that enable the various candidate theories to be distinguished. One method we have used involves manipulating the duration of component stages of the second task (cf. Sternberg 1969) to test the predictions of bottleneck models.

Figure 11.1 illustrates the time course of dual task performance assuming a bottleneck in response selection. Various predictions can be derived from such a model. If an experimental factor is manipulated to retard stages of the

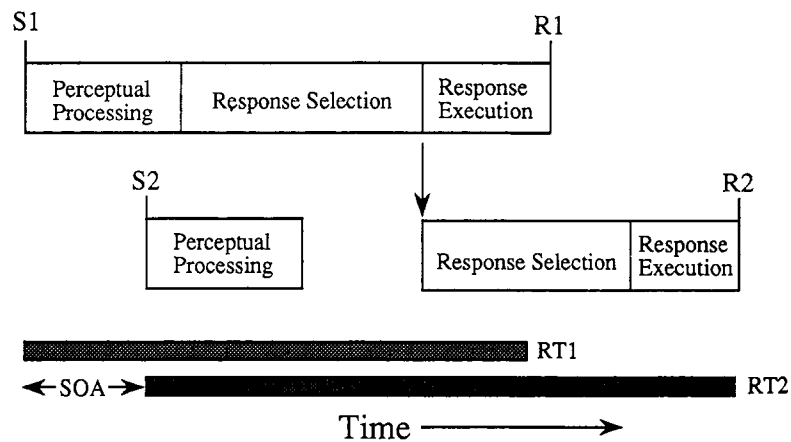


Figure 11.1 The response-selection queuing account for the psychological refractory effect.

second task *at* or *after* the bottleneck (i.e., response selection or execution), then this factor should slow the response correspondingly, whatever the SOA. Thus, at all SOAs, a 50-msec slowing of response selection in task 2 will increase RTs by 50 msec in both the single-task condition and the dual-task condition (whatever the SOA). On the other hand, if a stage of the second task located *before* the bottleneck (e.g., perceptual processing) is retarded, then some particularly diagnostic interactions are predicted. In the single-task condition, and at very long SOAs, the full slowing should be manifest in the R2 latency. However, when the SOAs are reduced, completion of the second task is increasingly likely to have to wait for the completion of the bottleneck stage of the *first* task, rather than for the completion of the stage of the second task that is slowed by the manipulation (fig. 11.1 shows just such a short SOA). For that reason, the effect of the manipulation should be progressively reduced as SOA is shortened.

It can be seen, then, that different bottleneck models make quite distinctive predictions about effects of S2 factors: (1) additive effects of dual-task slowing (i.e., dual-task short SOA vs. long SOA; or dual- vs. single-task) and factors affecting stages of task 2 *beyond* the bottleneck stage, and (2) *underadditive* interactions of SOA with factors affecting stages of task 2 *before* the bottleneck should be observed. By contrast, there is no particular reason to expect such a pattern if there is graded sharing of central capacity between tasks (e.g., Kahneman 1973; see Pashler 1984).

A number of PRP experiments have been analyzed in more or less this way over the years. Both Keele (1973) and Schweickert (1978) analyzed previously published PRP experiments that compared simple and choice RT2s, looking for signs of processing "slack." However, it appears that choice and simple RT do not differ merely in the duration of one particular single stage, rendering conclusions about dual-task interference from such analyses very uncertain (Sternberg 1969).

In the past several years, however, we have examined a wide range of task-2 factors that seem very likely to affect the duration of specific stages of processing, and the results have been quite consistent. When perceptual processing is slowed by reducing the intensity of a visual S2, the RT2 is increased less in the dual-task than in the single-task condition (Pashler 1984); furthermore, in the dual-task condition, intensity effects are reduced as SOA is shortened (Pashler and Johnston 1989). Similarly, display-size effects in a secondary visual search task are underadditive with dual-task slowing (Pashler 1984), and taper off with SOA (Pashler 1990). These effects indicate that a bottleneck exists beyond the perceptual processing which these manipulations retard. Manipulations that affect the speed of response selection generally have additive effects with dual-task slowing. For example, when the stimulus is repeated from trial to trial in a choice reaction-time experiment, response selection operates faster; this effect is *additive* with dual-task slowing, and with SOA (Pashler and Johnston 1989). Similarly, McCann and Johnston (1992) have found that the effect of S-R compatibility in a second task was also additive with SOA.

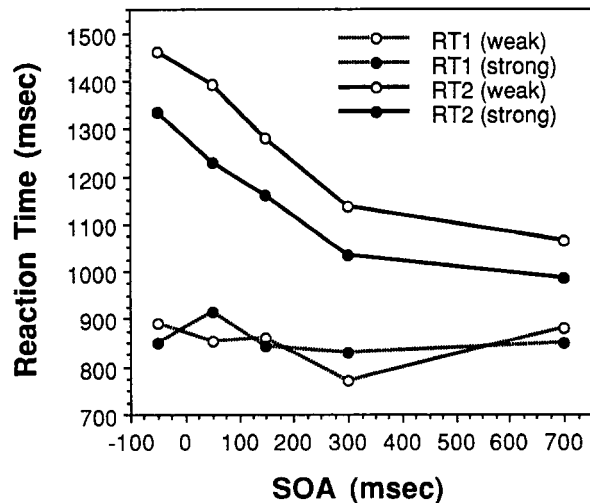


Figure 11.2 Dependency of RT2 on RT1. Graph shows mean RT2 as a function of the relative magnitude of RT1 on the corresponding trial (by quintile within the RT1 distribution for that SOA).

The results support a response-selection bottleneck. They also rule out the hypothesis that *producing* R2 is the first or only stage of processing that is delayed (as proposed by Keele 1973, and Norman and Shallice 1985). If no stage in task 2 before response production were delayed, then R2 latencies would not be affected by “cognitive” factors such as S-R compatibility at short SOAs. These findings also lend no support to capacity-sharing accounts either (see Pashler 1984 for a discussion).

Dual-Task Performance Dependencies

Further evidence for bottleneck models comes from analyzing the dependencies between R1 and R2 latencies. If processing required to produce R2 waits for completion of the major portion of the first task (where most of the variability in latency originates), then most trial-to-trial variance in R1 latency should propagate into the second task. Consistent with this, Welford (1967) noted positive correlations between response times in the two tasks. Positive correlations of this sort might be consistent with other possibilities, however, such as a positive dependency between the degree to which the subject has prepared each task in advance.

Bottleneck models predict a much more specific pattern of dependency between R2 and R1 latency, interacting with SOA. For our analyses, we generally divide the trials by quintiles, according to the relative speed of R1 within a condition. Figure 11.2 shows the mean R2 latency as a function of the relative R1 latency in a representative PRP experiment (similar to that described below and shown in fig. 11.3). At the long SOAs, there is little relationship (flat slope). As the SOA is reduced, R2 depends more positively upon R1 (upward tilt), and this dependency begins earlier and earlier in the R1

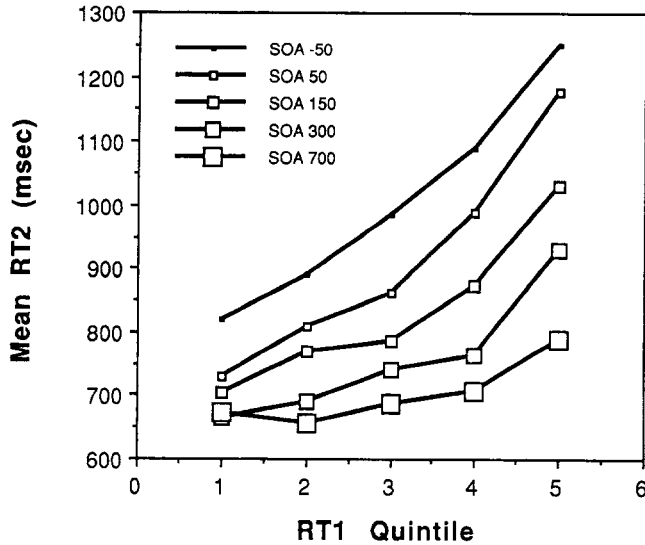


Figure 11.3 Effects of SOA and associative strength on RT1 and RT2 for speeded manual responses to a tone (R1) and speeded retrieval of a paired associate (R2). From Carrier and Pashler (1992).

distribution. Postponement of task-2 response selection predicts just this form of interaction between SOA and quintile. We have observed it repeatedly in PRP experiments with varying tasks, response modalities, and levels of practice (e.g., Pashler 1989, 1991; Pashler and Johnston 1991; Fagot and Pashler, in press).

Tachistoscopic Second Tasks

The evidence presented thus far supports a response-selection bottleneck and indicates that at least some perceptual processing in the second task proceeds unhindered by the first task. If this account is correct, certain additional predictions should also hold. For example, one should also find that the likelihood of completing perceptual processing of S2 within any given period of time after the onset of S2 should not be reduced when the two tasks overlap (i.e., at short SOAs) as opposed to when they do not overlap.

This prediction was tested by masking S2 and observing the accuracy of an *unspeeded* R2 (R1 was still speeded) as a function of SOA. Pashler (1989) reported several studies of this type. Subjects made a manual choice response to a tone, and after a variable SOA (50, 150, and 650 msec) a visual display was presented and then masked (display-mask interval was fixed in each block). To be sure that subjects had to complete perceptual processing before the mask in order to make an accurate response (rather than storing the contents of the display), the displays exceeded the span of immediate memory. In one experiment, the displays consisted of eight digits, and subjects named the highest of these digits; in another experiment, there were eight green and red O's and T's, and the subject decided whether a green T was present

(feature-conjunction search). Accuracy of performance on the second task was impaired by only a few percent as SOA decreased from 650 (longer than most R1s) to 50 msec.

However, when exactly the same pair of tasks was used and both responses were speeded (with S2 not masked), the usual PRP effect occurred, as did the usual pattern of dependencies between R1 and R2. So these results further support the existence of a bottleneck beyond perceptual recognition, at least for stimuli such as letters and digits (and arbitrary conjunctions of features as well). The full extent of stimulus analysis that can operate without the bottleneck mechanism remains to be determined.

What Counts as a Response?

Thus far, we have spoken of the selection of a particular response without defining what is selected. This leaves open a very interesting issue. Studies of bimanual coordination (e.g., Kelso, Southard, and Goodman 1979) indicate that movements of both arms are sometimes temporally synchronized, suggesting some form of coupled control. Can two actions be selected as a couplet without employing the bottleneck mechanism twice? To answer this question, Clark Fagot and I have examined situations in which two responses must be produced—one manual and one vocal—but both are *redundantly* signaled by the same stimulus (Fagot and Pashler, in press). For example, in one experiment, subjects named the color of a stimulus and made a manual response that also depended upon its color. In the dual-task condition, only the vocal response showed any slowing compared to a single-task control, and this slowing was very small (about 30 msec). Correlations between R1 and R2 latencies were extremely high. Together, these results suggest that a single mental operation selected a response *couplet*. By themselves, however, the data cannot rule out the possibility that manual and vocal responses were selected independently and simultaneously.

To analyze the time course of processing further, we introduced a manipulation that slowed the single-task manual response but had no effect on the single-task vocal response (namely, compatibility of stimulus position and manual response, or the *Simon effect*). In the dual-task condition, the Simon effect extended the vocal RTs, slowing them to about the same degree as the manual RTs. This clearly rules out independent response selections, and suggests that the response-selection mechanism underlying the bottleneck effect can be “set” to generate essentially arbitrary assemblages of motor behaviors as a single response. Further experimentation involving two response-selection manipulations also confirmed these conclusions.

11.4 EXTENT OF THE BOTTLENECK

The results discussed thus far have supported Welford’s early proposal that a bottleneck in selecting responses underlies the robust dual-task interference observed with pairs of sensorimotor tasks. The most natural interpretation of

the existence of such a bottleneck would be that the brain possesses only a single mechanism that must perform the relevant stages in each task. (Note that it would be functionally equivalent if the "mechanism" consisted of physically distinct systems or networks that mutually inhibited each other's operation.) To understand the general significance of this mechanism for human performance and cognition, we must determine whether it is involved only in the choice of *action* per se, or if it is in fact responsible for a wider range of cognitive operations.

This is plainly a very broad issue, and thus far we have only begun to scratch its surface. Mark Carrier and I started with the case of memory retrieval in cued recall. While this sort of memory retrieval is effortful and sensitive to nonspecific stressors like fatigue and intoxication, dual-task researchers have not had much to say about its possible reliance on general-purpose central mechanisms. Baddeley et al. (1984) claimed that memory retrieval does *not* rely on general "capacity," based on small effects of a concurrent task on memory-retrieval accuracy. Large effects on retrieval latency were observed, but they were attributed to response-related interference (although there was really no way of telling where the interference lay in these studies).

Carrier and I have approached this issue with two converging methods (Carrier and Pashler 1992). The first involves manipulating second-task stages in a PRP study, as described above. Subjects were pretrained on a set of paired associates, half of which were easy to learn (because of high prior association), and half of which were difficult. Subjects then performed a PRP procedure: here, the first task was the tone task with manual response, and the second task involved standard paired-associate retrieval (with vocal responses). Figure 11.3 shows the results: an additive effect of SOA and retrieval difficulty. As described above, such data indicate that the memory retrieval requires the same mechanism as the tone task; otherwise the effect of associative strength should have been "swallowed up" as SOA decreased.

Our second approach involved more time-consuming memory retrievals. Subjects attempted a relatively difficult cued semantic memory recall task (category-letter cue, e.g., "VEGETABLE A" yielding "asparagus"). In one condition, this task was performed alone for 30 sec. In another condition, the subject performed the usual tone task over and over (with essentially zero response-stimulus interval) for 10 sec after the category-letter cue was presented, and then continued the retrieval task by itself. During the 10 sec when the tone task was performed, rather little was accomplished on the memory retrieval. This was true even if the tone task did not begin until 1 sec after the retrieval cue. Thus, it appears that these semantic memory retrievals may require the same mechanism as that used for response selection in the tone task.

McCann and Johnston (1989) reported chronometric results indicating that certain *noncategorical* perceptual judgments with visual stimuli (e.g., line-length comparison) also exhibit the bottleneck limitation, based on additive effects of SOA and comparison difficulty. This is further evidence that the bottleneck does not only arise in the process of selecting motor actions per se.

11.5 VISUAL ATTENTION SHIFTS AND THE BOTTLENECK

Thus far, I have used the rather quaint term *bottleneck* to describe the cognitive processes subject to postponement in the PRP situation, while avoiding the term *attention*, which is notoriously laden with a variety of different meanings. Nonetheless, the results described do suggest that a surprisingly wide range of mental processes rely on a single general-purpose mechanism. Therefore, it seemed worth inquiring whether this central serial mechanism can be identified with what is most commonly referred to as attention.

The paradigmatic form of attention arises in the selection of sensory stimuli for further processing. It has long been known that people can voluntarily attend to just a particular subset of their sensory input, with the consequence that they have little awareness or memory of the remaining stimuli. In the case of vision, attention shifts can be triggered by a wide range of cues (e.g., von Wright 1968) and do not depend upon eye movements.

This raises the question of whether shifts in visual selective attention involve the bottleneck mechanism previously described. Posner et al. (1989) suggested that attention shifts require an "anterior attention system" (a concept rather close to the response-selection bottleneck) on the basis of experiments that combined shadowing with cued visual simple RT. Furthermore, Rizzolatti and Camarda (1987) claimed that control of motor movements and attention movements must involve the same neural system, based on patterns of associated symptoms observed in unilateral neglect patients. None of these results seemed conclusive, so the tachistoscopic second-task method described earlier was adapted to pursue the question (Pashler 1991). Subjects first performed the usual tone task with manual response, and after a variable SOA, a display of eight letters and a probe was presented; the probe indicated which letter should be attended to and reported. After a delay, the letters were masked. If the shift of attention to the probed letter was delayed by the tone task (as selection of a motor response would be), then task-2 errors should increase drastically as tone-display SOA is reduced. In fact, however, there was very little effect of SOA, even when the cueing was purely symbolic (an arrow in the center of the display pointing toward the cued letter). A control experiment provided direct evidence that a delay in the attention shift really would have produced a drastic increase in errors, because when the *probe* was delayed by 200 msec in a single-task condition, the error rate increased by more than 30 percent.

In summary, although a tone task reliably produced dramatic delays of speeded second-task responses, it did not delay a second-task attention shift more than a tiny amount. Thus, shifts of visual attention apparently do not involve the mechanism that underlies the bottleneck effects described earlier. More generally, one is forced to conclude that the form of attention responsible for selectivity in vision, and the form responsible for limitations in concurrent sensorimotor performance, are not the same. For this reason, it might be advisable to reserve the term attention for the former (if the term cannot be avoided altogether).

11.6 STORING INFORMATION IN VISUAL SHORT-TERM MEMORY

The technique used to separate selective attention from the central bottleneck can be extended to determine whether the bottleneck affects a variety of mental operations. Here we report some new empirical results that apply the technique to a previously unstudied mental operation: storing information in visual short-term memory (VSTM).

This is an important mental operation to examine in this context, because various intimate relationships between attention and short-term memory storage have been proposed over the years. For example, Shiffrin (1976) equated the limits on short-term storage with general attentional capacity. Baddeley, on the other hand, distinguished between a "central executive" and various "slave systems" used to store information in working memory. In principle, a central executive might play many different critical roles in short-term storage, retention, and retrieval. We focus on visual short-term storage because (1) the time during which visual stimuli are available can be carefully controlled, and (2) evidence concerning the identity and properties of visual short-term storage has been carefully analyzed at least for one particular kind of stimulus (used in the experiment reported here).

In particular, Phillips conducted a systematic investigation of VSTM, using short-term recognition of matrices composed of squares, stimuli that do not lend themselves to verbal description (summarized in Phillips 1983). A long series of elegant experiments provided converging evidence for a schematic memory (VSTM) that is not destroyed by masking, can maintain a spatiotopic representation of patterns, and clearly differs from both iconic memory and visual long-term memory. Phillips and Christie (1977) showed that nonvisual cognitive tasks lasting several seconds (e.g., adding auditorily presented digits) during the retention interval impair visual recognition performance quite substantially. To explain the latter result, they suggested that a central executive must intermittently refresh VSTM for optimal retention.

However, the Phillips experiments have not addressed whether *storing* information in VSTM requires intervention of this central executive. While memory for *unattended* stimuli is known to be very poor (e.g., Broadbent 1958), the preceding section indicates that visual selective attention, and the bottleneck mechanism investigated here, are quite distinct. Thus, storage in VSTM could well require appropriate deployment of visual attention even if it did not depend at all on the response-selection mechanism.

11.7 METHOD

Sixteen subjects from the UCSD subject pool participated for credit in a one-hour session. The experiment was controlled by IBM PC microcomputers, and stimuli were presented on NEC VGA monitors. The procedure is shown in figure 11.4. The first stimulus was a tone, which lasted 150 msec. Subjects

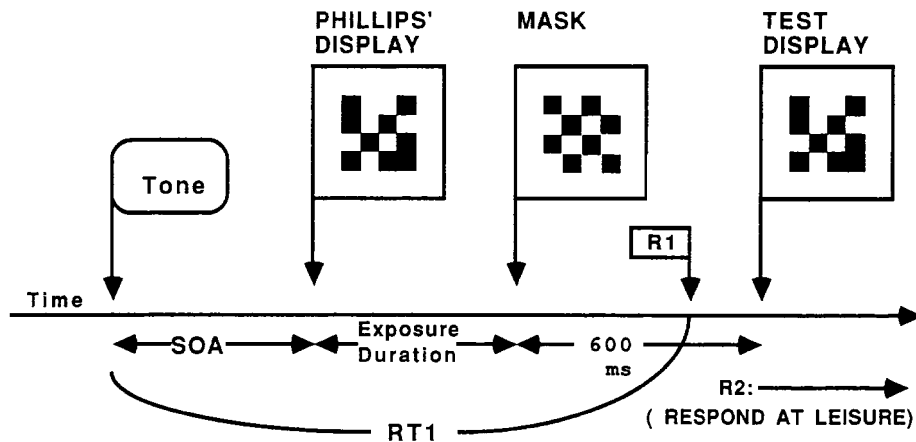


Figure 11.4 Procedure used on each trial in the VSTM experiment.

responded immediately by pressing the *z* key or the *x* key for tones of 300 hz or 900 hz, respectively. The speed of this response was strongly emphasized. After an SOA of 50, 150, or 650 msec, a visual stimulus was presented against a black background. The stimulus consisted of a random 4×4 matrix of squares (total width and length approximately 3.8 degree; squares were red or black with probability .5). The display was presented for either 100 msec or 300 msec. At the end of this interval, the display was masked with a 4×4 interleaved pattern, which lasted for 100 msec. After an interval of 500 msec, a test stimulus was presented. On half the trials, this stimulus was identical to the study pattern; otherwise, one square was randomly flipped from red to black or vice versa. The subject responded by pressing the period key for same, and slash key for different. The second response was *unspedeed*.

The session began with forty-eight practice trials, followed by ten blocks of forty-eight test trials. Within a given block, each combination of SOA, exposure duration, and response type (same/different) was represented equally often.

Results

Trials on which RT1 fell below 150 msec or exceeded 1000 msec were discarded. Figure 11.5 shows the results as a function of SOA. RT1s were faster for the 50- and 150-msec SOA (452 and 455 msec, respectively) than for the 650 SOAs (485 msec), $F(2, 30) = 9.1, p < .001$. RT1s were also slightly longer for the 300 msec exposure duration (467 msec) than for the 100 msec exposure duration (461 msec), $F(1, 15) = 4.6, p < .05$. Other effects and interactions were nonsignificant.

The key results concern accuracy of second-task responses. These were analyzed as a function of response type (same/different), SOA, exposure duration, and the relative speed of R1. Error rates were lower for 300-msec exposures (.130) than for 100-ms exposures (.260), $F(1, 15) = 87.5, p < .001$.

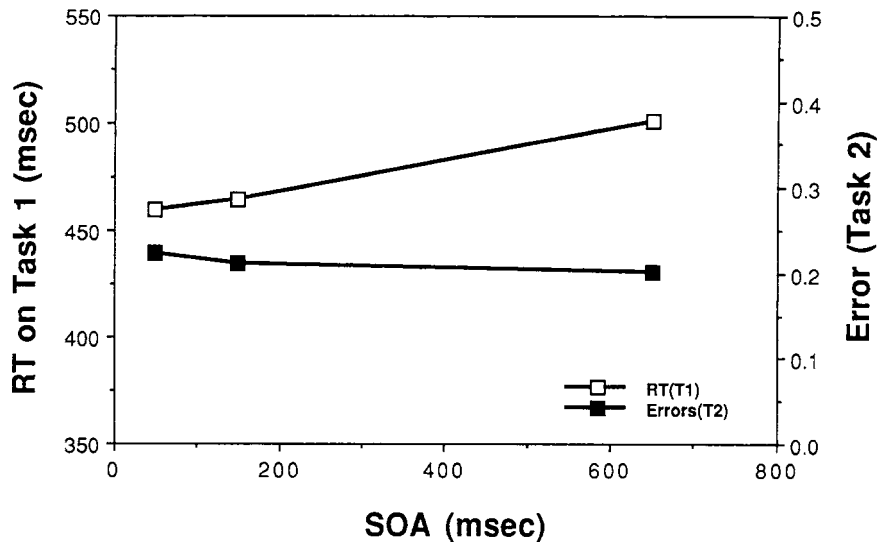


Figure 11.5 Mean RT for tone task (T1) and mean error rate for Phillips task (T2), as a function of SOA.

The error rates for SOAs of 50, 150, and 650 were .209, .190, and .186, respectively. This difference was not significant.

Thus, a 200-msec reduction in exposure duration increased error rates by 13 percent, whereas the SOA manipulation (contrasting extreme vs. minimal overlap with the first task) produced only a nonsignificant, approximately 2 percent difference. In many previous studies (e.g., Pashler 1989, 1991), the same tone task delayed *speeded* R2 responses by over 200 msec. Plainly, then, this first task was not delaying the storage of these patterns in visual STM nearly as much as it would delay selection of a second response. The effect of exposure duration also shows that the tiny effects of dual-task overlap do not reflect saturation of VSTM that could potentially introduce a sort of ceiling effect caused by the limited capacity of that memory system.

The R1 quintile effects (fig. 11.6) provide a check on this conclusion. If storage were delayed by task 1, then (increasingly at short SOAs) slow R1s should be associated with higher R2 error rates. For R1 quintiles 1–5, the R2 error rates were .178, .178, .191, .196, and .233. This modest correlation between performance on the two tasks was significant, $F(4, 60) = 3.6, p < .05$, but its relatively small size is not consistent with postponement of storage. Furthermore, the quintile effect was not larger for the short SOAs than for the long SOAs: the interaction between SOA and quintile was nonsignificant, $F(8, 120) = .21, p > .90$. The main effect of quintile probably stems from subjects being better prepared for both tasks on some trials compared to others. By contrast, the delay of response selection in a *speeded* second task produces a dramatic effect of quintile on R2 latency, interacting with SOA (compare fig. 11.2 with fig. 11.6).

(There was also an unexpected and, to the author, quite uninterpretable interaction between R1 quintile and exposure duration, $F(4, 60) = 3.6, p <$

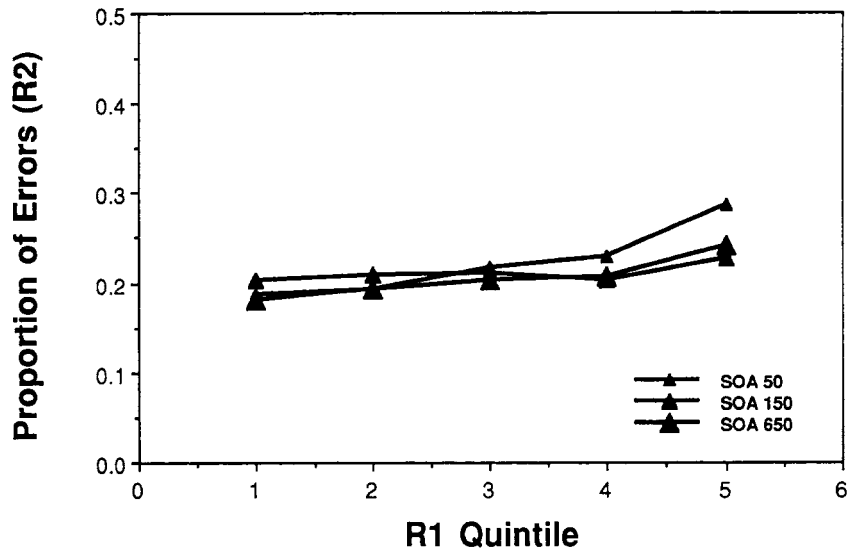


Figure 11.6 Mean error rate in the Phillips task (R2) as a function of the quintile in which RT1 belonged within its distribution.

.05. The interaction was nonmonotonic in character and mostly reflected a greater exposure-duration effect for quintile 2.)

Discussion

This experiment demonstrates that storage of information in visual short-term memory does not depend on the bottleneck mechanism associated with response selection, memory retrieval, and other mental operations. These results are especially interesting in light of Phillips and Christie's (1977) finding that adding auditory digits reduced the amount available from VSTM. Putting these conclusions together, it appears that the role of the bottleneck mechanism in visual short-term memory is probably restricted to intermittently refreshing fading temporary representations.

While of course we cannot generalize these conclusions to other forms of short-term storage with any confidence, they may apply there as well. If so, there would be clear implications for the many studies that have employed auditory memory loads to "deplete capacity." Perhaps subjects in such experiments did nothing whatsoever with the memory load while performing the punctate primary task. The effects of memory load may instead be attributable to interference with preparation for the primary tasks (see also Logan 1978).

In considering the generality of the results reported here, it is also worth noting that the present procedure required VSTM storage of information derived directly from perceptual input. However, this is not the only way that information can get into short-term storage: people are remarkably flexible in transferring information *between* different short-term stores (Broadbent 1989). The present results leave open the possibility that the bottleneck mechanism

may be necessary for *recoding* information into formats that do not match the sensory input.

11.8 CONCLUSIONS

The work reviewed here bears on various different approaches to dual-task interference that have arisen over the past twenty-five years or so. But it is not possible to discuss these approaches comprehensively here. However, we conclude with some brief comments about these other perspectives.

Capacity Sharing

The idea that dual-task performance commonly depends on a graded sharing of mental “resources” has been frequently suggested and—much more commonly—simply assumed. Yet, in the situation where performance can be studied in most detail (the PRP experiment), there is little evidence for this. It is true that slowing of R1 is sometimes observed, and this certainly might seem to suggest capacity sharing. However, when Johnston and I encouraged subjects to delay R1, the results showed clearly that subjects complied by withholding R1 until R2 was ready to be produced; the pattern of factor effects indicated that the response-selection bottleneck was still present (Pashler and Johnston 1989). When instructions do not clearly emphasize first-task speed, then this sort of “grouping” will probably occur on some trials, for some subjects, yielding moderate slowing of the mean RT1. It would be a mistake to infer from this slowing that capacity sharing must be occurring.

Another phenomenon generally taken to support capacity sharing occurs when subjects are instructed to vary their relative emphasis on two extended tasks (e.g., tracking and sentence comprehension). Typically, there is a tradeoff between performance in the two tasks. However, this trade-off could have many causes, some of which are consistent with an underlying bottleneck. For example, subjects may simply shift the proportion of *time* allocated to the two tasks by the bottleneck mechanism. Subjects may also vary the degree to which they prepare for the two tasks in advance; thus, the trade-off may occur over the several seconds *preceding* the trial, not during the trial.

Nonetheless, graded capacity sharing has been assumed much more often than it has been argued for, and not only by students of divided attention *per se*, but also by researchers exploring a great variety of mental processes (ranging even into clinical and developmental psychology). In particular, many investigators have used the Posner and Boies (1971) simple RT probe technique to “measure how much capacity” some particular mental process requires. As noted above, the assumption that there is actually a graded sharing of capacity between tasks is questionable to start with. Slowing in probe tasks may often reflect the same discrete queuing argued to underlie the PRP effect. In addition, very fast simple RTs seem to require a “hair-trigger” state of preparation, which is difficult to maintain while extraneous stimuli are

presented. Thus, even a to-be-ignored stimulus immediately preceding an imperative signal can produce a marked slowing of simple RTs (Davis 1959), which does not generally occur in choice tasks such as visual search (Pashler and Johnston 1989). For reasons such as these, supposed measurements of “capacity demands” should be viewed somewhat skeptically.

Various multiple-resource theories that have been considered in recent years (e.g., Wickens 1983) are also based on the assumption of graded allocation of resources. For the most part, these theories have been supported by rather coarse-grained observations (e.g., aggregated error over many seconds or minutes). Such measures cannot distinguish between different possible underlying sources of interference, including bottlenecks, capacity sharing, preparation effects, reliance on common memory stores, and so forth. This is not to deny that multiple resource theories may offer a useful way of describing human performance limitations for practical purposes. However, one would hope that a theory describing the detailed time course of dual-task interference will ultimately do a better job.

Multiple Processors and Task Similarity

Over the years, several investigators contested Welford’s original suggestion of a central bottleneck by pointing to cases where the use of very dissimilar response modalities seemed to reduce interference (e.g., McLeod 1978). Pashler (1990) reexamined this issue, comparing vocal-manual to manual-manual response combinations. In the usual PRP paradigm, clear-cut interference was observed with both combinations, with only slightly more interference for manual-manual combinations. However, when the experiment was modified so that the order of stimulus onset was not known to the subject before the trial (as in McLeod’s experiments), then the manual-manual combination showed much more interference than did the manual-vocal. This previously unnoticed interaction between knowledge of stimulus order and response modality seems to have led to the mistaken impression that response modality is the main determinant of task interference, which it is not. (The question of how to interpret this interaction was discussed by Pashler 1990).

Closely related to the multiprocessor idea is the proposal that the two cerebral hemispheres control or comprise separate pools of processing resources (e.g., Friedman and Polson 1981). The evidence for this view comes mostly from studies that use tasks like tapping, holding verbal memory loads, and other activities that may not demand constant central processing at all. For this reason, Shannon O’Brien and I have recently begun examining hemispheric factors in PRP experiments, using tasks that seem likely to depend relatively more upon one hemisphere than upon the other (e.g., responding with the left hand to a stimulus in the left hemifield, producing vocal responses, etc.). So far, we have found no sign that the PRP effect, or the R2/R1 dependencies, differ depending upon whether the same hemisphere or different hemispheres carry out the tasks. At the moment, this conclusion remains

tentative; if it holds up, it may have interesting implications about the neural basis for the central bottleneck.

Directions for Further Research

It might appear from the preceding discussion that the similarity of two tasks is claimed to have no effects on the interference they produce for each other. This is plainly false. Especially in tasks that last several seconds or more, similarity can greatly exacerbate interference. There are several reasons why this could happen that would be perfectly consistent with the theoretical claims made above. For example, if two tasks both depend upon short-term retention over the same time period, then if the material to be remembered in the two tasks is highly similar, performance may break down due to well-known interference effects in memory. The results of Hirst and Kalmar (1987) can be readily interpreted in this way. In addition, when one task involves stimuli that could potentially trigger responses in the other task, this may necessitate preparation of more complex and specific response-selection routines. Neither of these factors need contradict or supplant the fundamental bottleneck argued for above. At present, though, similarity effects in dual-task performance are not well understood.

Another important area for future research pertains to some provocative findings of situations where seemingly very demanding continuous tasks, each involving response selection and production, show virtually *no* interference (e.g., Allport, Antonis, and Reynolds 1972; Shaffer 1975). The lack of interference may simply be, as Broadbent (1982) noted, because continuous tasks offer previews of stimuli and involve long stimulus-response lags. For that reason, central mechanisms may switch between tasks, buffering stimuli at input and response sequences at output. Another possible factor is that the studies cited used shadowing as one of the tasks; as noted earlier, shadowing may simply bypass the usual dual-task limitations (McLeod and Posner 1984). Finally, the high degree of practice these subjects had in performing some of these activities might also be a factor.

At the moment, these interesting observations demand further, more systematic study. The conclusions described in this article stem from studies that have deliberately focused on very austere and simplified tasks. To develop these ideas further so that they can encompass more of the enormous range of human mentation and behavior remains an exciting challenge for the future.

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REFERENCES

- Allport, D. A., Antonis, B., and Reynolds, P. (1972). On the division of attention: A disproof of the single-channel hypothesis. *Quarterly Journal of Experimental Psychology*, 24, 225–235.
- Baddeley, A., Lewis, V., Eldridge, M., and Thomson, N. (1984). Attention and retrieval from long-term memory. *Journal of Experimental Psychology: General*, 113, 518–540.
- Bertelson, P. (1966). Central intermittency twenty years later. *Quarterly Journal of Experimental Psychology*, 18, 153–163.
- Broadbent, D. E. (1958). *Perception and Communication*. London: Pergamon Press.
- Broadbent, D. E. (1982). Task combination and the selective intake of information. *Acta Psychologica*, 50, 253–290.
- Broadbent, D. E. (1989). Lasting representations and temporary processes. In Roediger, H., and Craik, F. I. (eds.), *Varieties of Memory and Consciousness*, 211–228. Hillsdale, NJ: Erlbaum.
- Carrier, M., and Pashler, H. (1992). The attention demands of memory retrieval. Manuscript.
- Davis, R. (1959). The role of “attention” in the psychological refractory period. *Quarterly Journal of Experimental Psychology*, 11, 211–220.
- Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General*, 113, 501–517.
- Fagot, C., and Pashler, H. (N.d.). Making two responses to a single object: Exploring the central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*. In press.
- Friedman, A., and Polson, M. C. (1981). Hemispheres as independent resource systems: Limited-capacity processing and cerebral specialization. *Journal of Experimental Psychology: Human Perception and Performance*, 7, 1031–1058.
- Gottsdanker, R., and Stelmach, G. E. (1971). The persistence of psychological refractoriness. *Journal of Motor Behavior*, 3, 301–312.
- Hirst, W., and Kalmar, D. (1987). Characterizing attentional resources. *Journal of Experimental Psychology: General*, 116, 68–81.
- Johnston, J. C., and Pashler, H. E. (1984). Can two decision processes operate simultaneously? Paper presented at the annual meeting of the Psychonomics Society, Austin, Texas.
- Kahneman, D. (1973). *Attention and effort*. New York: Prentice Hall.
- Keele, S. W. (1973). *Attention and human performance*. Pacific Palisades, CA: Goodyear.
- Kelso, J. A. S., Southard, D. L., and Goodman, D. (1979). On the coordination of two handed movements. *Journal of Experimental Psychology: Human Perception & Performance*, 5, 229–238.
- Logan, G. D. (1978). Attention in character classification tasks: Evidence for the automaticity of component stages. *Journal of Experimental Psychology: General*, 107, 32–63.
- Logan, G. D., and Burkell, J. (1986). Dependence and independence in responding to double stimulation: A comparison of stop, change and dual-task paradigms. *Journal of Experimental Psychology: Human Perception & Performance*, 12, 549–563.
- McCann, R. S., and Johnston, J. C. (1989). The locus of processing bottlenecks in the overlapping tasks paradigm. Paper presented at the annual meeting of the Psychonomics Society, Atlanta, GA.
- McCann, R. S., and Johnston, J. C. (1992). The locus of the single-channel bottleneck in dual task interference. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 471–484.
- McLeod, P. (1977). Parallel processing and the psychological refractory period. *Acta Psychologica*, 41, 381–391.

- McLeod, P. (1978). Does probe RT measure central processing demand? *Quarterly Journal of Experimental Psychology*, 30, 83–89.
- McLeod, P., and Posner, M. I. (1984). Privileged loops from percept to act. In H. Bouma and D. G. Bouwhuis (eds.), *Attention and Performance X*. London: Lawrence Erlbaum Associates.
- Norman, D. A., and Shallice, T. (1985). Attention to action: Willed and automatic control of behavior. In R. J. Davidson, G. E. Schwartz, and D. Shapiro (eds.), *Consciousness and self-regulation*, Vol 4. New York: Plenum.
- Osman, A., and Moore, C. (1990). The effects of dual-task interference on movement related potentials. Paper presented at the Journal meeting of the Psychonomics Society, New Orleans, LA.
- Pashler, H. (1984). Processing stages in overlapping tasks: Evidence for a central bottleneck. *Journal of Experimental Psychology: Human Perception and Performance*, 10, 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*.
- Pashler, H. (1991). Shifting visual attention and selecting motor responses: Distinct attentional mechanisms. *Journal of Experimental Psychology. Human Perception and Performance*, 17, 1023–1040.
- Pashler, H., Carrier, M., and Hoffman, J. E. (N.d.). Saccadic eye movements and dual task interference. *Quarterly Journal of Experimental Psychology*. In press.
- Pashler, H., and 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., and Johnston, J. C. (1991). Continuous task performance and dual-task interference: Chronometric studies. Manuscript.
- Phillips, W. A. (1983). Short-term visual memory. *Phil. Trans. Royal Soc. London*, B302, 295–309.
- Phillips, W. A., and Christie, F. M. (1977). Interference with visualization. *Quarterly Journal of Experimental Psychology*, 29, 637–650.
- Posner, M. I., and Boies, S. J. (1971). Components Of attention. *Psychological Review*, 78, 391–408.
- Posner, M. I., Sandson, J., Dhawan, M., and Shulman, G. (1989). Is word recognition automatic? A cognitive-anatomical approach. *Journal of Cognitive Neuroscience*, 1, 50–60.
- Rizzolatti, G., and Camarda, R. (1987). Neural circuits for spatial attention and unilateral neglect. In M. Jeannerod (ed.), *Neurophysiological and Neuropsychological Aspects of Spatial Neglect*, 289–313. Paris: Elsevier.
- Schneider, W., and Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search and attention. *Psychological Review*, 84, 1–66.
- Schweickert, R. (1978). A critical path generalization of the additive factor method: Analysis of a Stroop task. *Journal of Mathematical Psychology*, 18, 105–139.
- Shaffer, L. H. (1975). Multiple attention in continuous verbal tasks. In P. M. A. Rabbitt and S. Dornic (eds.), *Attention and Performance V*, 157–167. New York: Academic Press.
- Shiffrin, R. M. (1976). Capacity limitations in information processing, attention and memory. In W. K. Estes (ed.), *Handbook of learning and cognitive processes: Attention and Memory*, Vol. 4, 177–236. Hillsdale, NJ: Erlbaum.

- Smith, M. C. (1967). Theories of the psychological refractory period. *Psychological Bulletin*, 67, 202–213.
- Sternberg, S. (1969). The discovery of processing stages: Extensions of Donders' method. In W. G. Koster (ed.), *Attention and Performance II*, 276–315. Amsterdam: North Holland.
- Vince, M. (1949). Rapid response sequences and the psychological refractory period. *British Journal of Psychology*, 40, 23–40.
- von Wright, J. M. (1968). Selection in immediate visual memory. *Quarterly Journal of Experimental Psychology*, 20, 62–68.
- Welford, A. T. (1952). The "psychological refractory period" and the timing of high speed performance—A review and a theory. *British Journal of Psychology*, 43, 2–19.
- Welford, A. T. (1967). Single-channel operation in the brain. *Acta Psychologica*, 27, 5–22.
- Welford, A. T. (1980). The single-channel hypothesis. In A. T. Welford (ed.), *Reaction Time*, 215–252. New York: Academic Press.
- Wickens, C. D. (1983). Processing resources in attention, dual task performance, and workload assessment. In R. Parasuraman and R. Davies (eds.), *Varieties of Attention*, 63–102. New York: Academic Press.

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