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Dual-Task Interference in Simple Tasks: Data and Theory

Harold Pashler

People often have trouble performing 2 relatively simple tasks concurrently. The causes of this interference and its implications for the nature of attentional limitations have been controversial for 40 years, but recent experimental findings are beginning to provide some answers. Studies of the psychological refractory period effect indicate a stubborn bottleneck encompassing the process of choosing actions and probably memory retrieval generally, together with certain other cognitive operations. Other limitations associated with task preparation, sensory-perceptual processes, and timing can generate additional and distinct forms of interference. These conclusions challenge widely accepted ideas about attentional resources and probe reaction time methodologies. They also suggest new ways of thinking about continuous dual-task performance, effects of extraneous stimulation (e.g.. stop signals), and automaticity. Implications for higher mental processes are discussed.

For more than 100 years, psychologists have been interested in people's ability (or inability) to perform two or more activities concurrently. One reason these limitations provoke curiosity is simply that people wonder what is humanly possible. This question has obvious significance for practical problems such as designing interfaces to prevent operators from becoming overloaded or predicting what a pilot can do in an emergency. There is also an important scientific reason to try to understand dual-task performance limitations: Overloading a system is often one of the best ways to figure out what the parts of the system are and how these parts function together. For this reason, studying dual-task interference provides an important window on basic questions about the functional architecture of the brain. For certain of these questions—such as whether human cognitive architecture includes a central processor—dual-task studies may provide the only avenue of study.

Ordinarily, people are not aware of having much difficulty performing different activities at the same time unless the tasks are either physically incompatible (e.g., typing and drinking coffee) or intellectually demanding (e.g.. conversing and adding up the check in a restaurant). Casual observation of people's behavior outside the laboratory seems to support this impression: People apparently have conversations at the same time they are driving, read magazines while they run exercise bicycles, chew gum while they walk, and so forth. It might seem, therefore, that one would have to look at rather exceptional activities to find much dual-task interference. Laboratory studies show just the opposite, however: Many pairs of tasks interfere with each other quite drastically, even though they are neither intellectually challenging nor physically incompatible.

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Correspondence concerning this article should be addressed to Harold Pashler. Department of Psychology 0109, University of California at San Diego. La Jolla, California 92093. Electronic mail may be sent to hpashler@ucsd.edu.

Researchers studying dual-task performance in the laboratory have investigated tasks that differ greatly in complexity, ranging all the way from simple reaction time (RT; "Press a button when the tone sounds") to such complex "real-world" activities as taking dictation and answering questions. The present article focuses on studies at the simpler end of this continuum. Most of the tasks discussed here involve a fairly straightforward stimulus-response (S-R) mapping, and they usually take less than a second for someone to carry out. The relative simplicity of these tasks allows one to test more precise hypotheses about the causes of dual-task interference than would be possible with more elaborate or time-consuming tasks. The ultimate goal of such research, however, is to illuminate complex kinds of mental activity as well as simple laboratory tasks, and this article concludes by exploring some possible implications for a broader range of behavior.

This review is organized into five main sections. The first provides a brief overview of some possible ways in which performing one task could interfere with performing another. The second section focuses on a form of dual-task interference that is particularly amenable to dissection with behavioral measures: the so-called psychological refractory period (PRP) effect. The PRP effect is the slowing that almost invariably occurs when a person tries to perform two speeded tasks at approximately the same time. The evidence described in this section makes a fairly-strong case that two factors work together to produce PRP effects in essentially every PRP task (a "central bottleneck" and a preparatory limitation), whereas other factors contribute only under very special circumstances (e.g.. manual-control limitations arising when two finger responses must be made nearly simultaneously). The remaining sections of the article consider a much broader range of empirical and theoretical issues in light of the conclusions derived from PRP studies. The third section discusses six other kinds of dual-task situations that have been studied quite extensively but differ from the PRP situation in that they do not involve two punctate speeded tasks. Several of these topics are discussed in some detail, including probe RT tasks, concurrent memory loads, and concurrent tapping. Two other topics are discussed in less detail: concurrent perceptual discriminations and concurrent continuous task performance. These are large fields of study that cannot be reviewed comprehensively here: instead, the focus is on how the central bottleneck implicated by the PRP studies relates to the performance limitations observed in these two areas of research. The fourth section discusses the behavioral effects of extraneous stimuli that do not require separate responses but, instead, modulate the response to a primary stimulus (e.g., a stimulus that signals one to abort one's response). These phenomena do not fall under the rubric of dual-task performance proper, but they have important implications for theories of the causes of dual-task interference. The fifth section examines some broader theoretical issues, including the nature of the central bottleneck and two concepts widely used in discussing information processing generally: attention and automaticity. It is argued that although these two concepts illuminate some aspects of cognition and experience, they often obscure the most important factors that determine performance. The article concludes with the question of how dual-task limitations in simple tasks may be relevant to understanding human behavior beyond the domain of simple laboratory tasks.

Theoretical Approaches to Dual-Task Interference

Why would people have trouble doing two tasks at the same time? A great variety of possible answers have been proposed at one time or another in the dual-task literature. Three of the most influential classes of explanations are capacity sharing, bottlenecks (task switching), and cross talk. Before turning to data, it is worth sketching these approaches.

Capacity Sharing

Probably the most widely accepted way to think about dual-task interference is to assume that people share processing capacity (or mental resources) among tasks. More than one task is performed at any given moment; thus, there is less capacity for each individual task, and performance is impaired. This view seems to fit ordinary experience quite well: People apparently carry out several different activities at once quite routinely until one or more of these activities becomes difficult. When that happens, more effort is required, and performance on one or both may be degraded. Generally speaking, people seem to have a fair amount of control over how they distribute their finite resources among different tasks; they can, for instance, choose to give more emphasis to driving than to conversation when they encounter busy traffic. Some capacity theorists have suggested that a single mental resource can account for performance limitations (Kahneman, 1973), whereas others have argued for multiple resources (Navon & Gopher, 1979; Wickens, 1980). If scarce mental resources—whether unitary or not—are allocated in a graded fashion, then the tools of economics may be useful in analyzing human performance limitations (such as utility functions relating performance to amount of capacity allocated; Navon & Gopher, 1979; Norman & Bobrow, 1975).

Bottleneck (Task-Switching) Models

An alternative—and in some ways simpler—idea is that parallel processing may be impossible for certain mental operations. Some operations may simply require a single mechanism to be dedicated to them for some period of time. When two tasks need the mechanism at the same time, a bottleneck results, and one or both tasks will be delayed or otherwise impaired. Bottleneck models were first proposed in connection with the dual-task interference observed with pairs of punctate tasks (the PRP paradigm), but bottlenecks could also account for interference found in apparently continuous tasks if each task had to compete for (intermittent) access to the bottleneck mechanism. Just as with resource limitations, there could be a single bottleneck or multiple bottlenecks associated with different stages of processing or different types of mental operations.

Cross-Talk Models

Yet another possibility is that interference might be critically dependent not on what sort of operation is to be carried out but on the content of the information actually being processed: what sensory inputs are present, what responses are being produced, what thoughts the person is having. In principle, it could be easier to perform two tasks concurrently when they involve similar inputs if this meant that the same set of processing machinery could be "turned on" and used for both. However, theorists have usually favored the opposite possibility, that it is more difficult to perform two tasks when they involve similar information (e.g., see Paulhan, cited in James, 1890). Engineers use the concept of cross talk to refer to content-dependent degradation of communications channels, and Kinsbourne (1981) has suggested that cross talk may be a useful metaphor for understanding dual-task interference in human beings. Along similar lines, Navon and Miller (1987) suggested that dual-task interference may be caused by what they termed *outcome conflict.* in which one task "produces outputs, throughputs, or side effects that are harmful to the processing of the [other task]" (p. 435).

Testing Dual-Task Models

It is an empirical question which of these ideas best explains the interference people encounter in doing various kinds of tasks concurrently. The ideas are not necessarily mutually exclusive. For one thing, different accounts might be valid for different kinds of tasks. For example, if two concurrent tasks would unacceptably disrupt each other through cross talk if performed concurrently, the tasks might be executed sequentially as a matter of strategy. Similarly, if it is possible to share capacity in a graded fashion, capacity might nonetheless be allocated in a discrete fashion on some occasions. In both of these examples, there would be a bottleneck, but it would be strategic rather than essential and unmodifiable (i.e., structural).

The question, then, is where best to start in trying to test these different kinds of explanations empirically. This article argues that the key to distinguishing between different possible underlying mechanisms of interference is to analyze the time course of mental operations as they unfold over short periods of time. This is best accomplished with one of the simplest and longest-studied features of dual-task performance: the PRP effect.

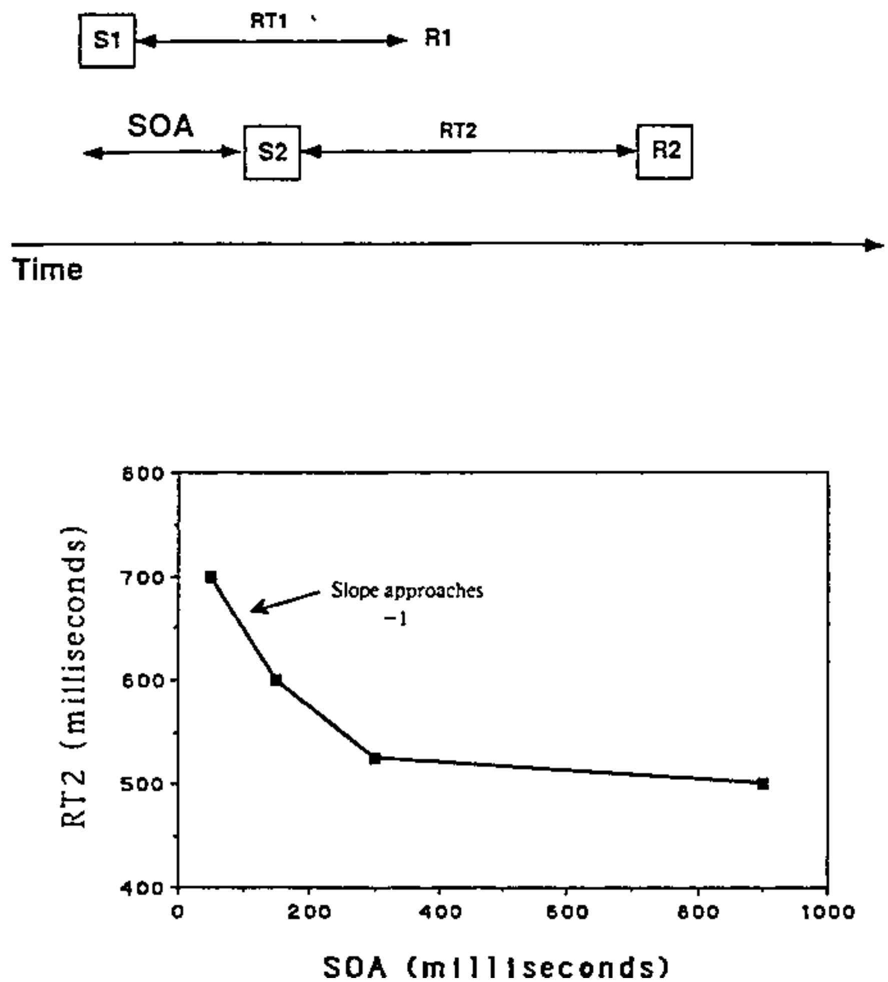

Figure 1. The psychological refractory period effect. Top panel: The first stimulus (S1) precedes the second stimulus (S2), and reaction times (RTs) are recorded to each. Bottom panel: typical pattern whereby the second reaction (R2) is slowed as the interval between the tasks is reduced. The slope approaches -1, indicating that (on average) the second response cannot be produced until a certain lime after S1. R1 = first response; SOA = stimulus onset asynchrony.

Interference in Two Speeded Tasks: The PRP Task

The Ubiquitous PRP Effect

Telford (1931) apparently was the first to demonstrate that when people respond to each of two successive stimuli, the response to the second stimulus often becomes slower when the interval between the stimuli is reduced. Telford termed this slowing the psychological refractory period on analogy to the refractory period of neurons. Although many people have noted that the analogy is far from perfect,[1] the term has stuck nonetheless. In a typical PRP experiment, two stimuli are presented (S1 and S2. separated by a stimulus onset asynchrony [SOA]). The person makes a response to each stimulus (R1 and R2, respectively). As shown in Figure 1. the time between S2 and R2 (denoted RT2) becomes progressively greater as the SOA is shortened, whereas the time between S1 and R1 (RT1) is often relatively unaffected by SOA (although on other occasions it too may be increased, as is discussed later). Often the slope approaches — 1, implying that reducing the SOA further simply increases RT2 correspondingly.

Slowing such as that shown in Figure 1 has been observed in a great variety of different tasks, including simple RT (as in Telford's studies) and choice RT (e.g., Creamer, 1963) tasks. Most of the earliest PRP experiments involved two manual responses, sometimes with the same finger and sometimes with different fingers (e.g., Vince. 1949). However, recent work shows that a PRP effect can be found even when pairs of tasks use very-diverse kinds of responses. Examples include manual and eye-movement responses (Pashler, Carrier, & Hoffman, 1993), man-

[1] When a neuron that has just produced an action potential is stimulated, it will fail to respond unless the stimulation is very intense: normal stimulation does not produce a delayed response, as in the PRP effect.

ual and vocal responses (Pashler, 1990), manual and foot responses (Osman & Moore, 1993), and vocal and foot responses (Pashler & Christian, 1994). Although some combinations remain to be tried, the effect appears to be robust across a wide range of effectors.

Almost all PRP studies have used auditory or visual stimuli, or both, but at least one has used tactile stimulation. Brebner (1977) stimulated one finger on each of the subject's hands with an upward movement of a key driven by a solenoid: subjects responded by depressing the same key, and a substantial PRP effect was observed. The PRP effect is readily observed even when S1 and S2 use different input modalities. For example, Creamer (1963) and Borger (1963), who were the first to observe PRP effects with choice reaction tasks, combined a visual with an auditory stimulus. There is no clear evidence that R2 slowing is greater when S1 and S2 are in the same modality, although this is hard to assess because variations in modality are usually confounded with changes in stimulus-response compatibility.[2]

Over the past 40 years or so, a number of different explanations for the PRP effect have been proposed (Smith, 1967b). Some correspond directly to the three overall classes of dual-task models sketched earlier.

Temporal Uncertainty

Before considering how different theories of dual-task interference might account for the PRP effect, one needs to be sure that the PRP effect actually represents dual-task interference. Several early investigators suggested that subjects' uncertainty about when S2 will appear delays R2. However, this cannot account for the PRP effect observed in choice tasks for the following reasons. First, slowing of RT2 is regularly observed even when there is no temporal unpredictability because the SOA is held constant over a whole block of trials (e.g., Bertelson, 1967; Broadbent & Gregory, 1967). In Bertelson's study, for example, two lights were illuminated, each adjacent to a key that the subject pressed (one with each hand). Substantial slowing of R2 was found, and the slowing was only slightly larger when the order varied randomly from trial to trial. Second, when S1 is presented but no response is required (with SOAs still varying from trial to trial), there is very little slowing of the response to S2 (e.g., Pashler & Johnston, 1989).[3] The reader may notice that other results discussed in the following sections also confirm that temporal uncertainty cannot be the cause of the PRP effect with choice tasks.

When the second task involves simple RT tasks, on the other hand, the points just made probably do not apply. Temporal uncertainty has large effects on simple RT (Klemmer, 1957), and the slowing of the response to S2 is sometimes the same regardless of whether any response is required to S1 (Davis, 1959; Koster & van Schuur, 1973). Thus, temporal uncertainty may play a special role in simple RT (which is perhaps unsurprising given the nature of that task).

Bottleneck Theories

It is evident, then, that the PRP effect in choice tasks reflects genuine dual-task interference. What mechanism produces this interference? The effect naturally suggests the possible existence of a processing bottleneck, and bottlenecks were first proposed in connection with this effect. Stating that some mental process *a* represents a bottleneck simply means that when process *a* occurs in one task, process *a* cannot occur in any other task at the same time. Assuming that the first task generally lays first claim to the bottleneck mechanism, one would therefore expect to find delays in the second (but not the first) task.[4] The most obvious reason for a processing bottleneck in process *a* would be that the mind contains only a single "device" that is capable of carrying out process *a.* Of course, such a device need not be localized in one particular region of the brain; it could be widely distributed anatomically. Alternatively, process *a* in Task 1 might be carried out in one location while process *a* in Task 2 was carried out in another; the bottleneck could result from an active process of mutual inhibition. (These possibilities illustrate the fact that performance studies can reveal fundamental properties of brain function that cannot, in principle, be delineated with imaging of brain function or studying effects of brain damage.)

Before turning to tests of bottleneck theories, it is essential to be wary of some common confusions about bottlenecks. First, a bottleneck is not equivalent to a point in processing at which voluntary control can operate. Unfortunately, these two issues—broadly speaking, issues of dual-task performance and issues of selective attention—have been conflated in many textbooks. A person may be capable of voluntarily preventing irrelevant stimuli from being recognized perceptually (early selection) even if there is no perceptual bottleneck that would prevent the person from recognizing more than one stimulus at a time, should the person desire to attend to these stimuli. Thus, the fact that dual-task performance is subject to a bottleneck in process *a* does not mean that this operation is the first or only point at which information flow can be gated in selective attention tasks.

Second, a single bottleneck might encompass processes that could—for other purposes—be subdivided into different component stages of processing. In his classic chapter on the additive factors method, Sternberg (1969) described a way of distinguishing successive stages of processing on the basis of selective effects of different variables on RTs. Three stages might be successive in Sternberg's sense, yet all could constitute a single bottleneck. In that case, none of the three stages could operate in one task while any other stage from the set was operating in another task.

Third, the case just described needs to be distinguished from the possibility of different processing bottlenecks located in different stages of processing. For example, if S1 and S2 each

[2] As noted later, when the two tasks involve difficult perceptual discriminations, a different source of interference arises that does depend on whether the stimuli are in the same modality and that is more evident in accuracy than speed.

[3] Davis (1962) observed some slowing of the response to S2 in a choice RT task in which S1 did not require any response. However, the effect was small and may partly reflect the fact that the two stimuli were highly confusable.

[4] This applies only to the PRP situation; obviously, a bottleneck can slow both responses in a dual-task experiment in which the order of the two tasks is not controlled.

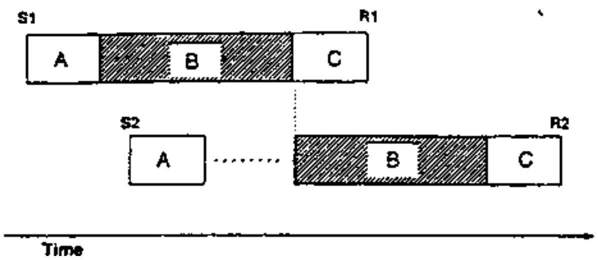

Figure 2. A central bottleneck model: The shaded portion of Task 2 cannot begin until the corresponding portion of Task 1 is complete. Other stages can operate in parallel, however. S = stimulus; R = response.

individually constituted a bottleneck, this would mean that Stage S1 of one task could not operate at the same time as Stage S1 of another task, and Stage S2 of one task could not operate at the same time as Stage S2 of another task (but Stage S1 in one task might overlap Stage S2 in another).

Testing Bottleneck Models

These preliminaries aside, the basic question is how behavioral measures can reveal whether the PRP effect reflects a bottleneck in a particular stage and. if so, whether one can identify what that stage might be. Fortunately, bottleneck theories make very distinctive predictions for the results of PRP experiments in which the duration of different stages of each task is manipulated. Suppose there is a bottleneck in a particular central stage, as shown in Figure 2. Four useful principles follow from this model, making it highly testable. These principles are illustrated in the four panels of Figure 3. Each panel shows what happens when a particular stage of one of the tasks is made more time-consuming by means of some sort of manipulation (e.g.. reducing the intensity of a stimulus or changing the stimulus-response mapping). Panels 1-4 correspond to Principles 1-4 described subsequently. (In each instance. Figure 3 illustrates the case in which the SOA is short enough that the critical [shaded] stages of one task actually postpone the critical stages of the other task.)

Principle 1. If one makes a stage of Task 1 up to or including the bottleneck stage take longer, this slows both RT1 and RT2 to the same degree. One might say that the slowing in the first task is propagated from the first task onto the second task. (Of course, if the SOA were long enough, this propagation should not occur.) Everyone is familiar with this principle in another context: If one enters a bank right behind another customer and there is only one teller on duty, the teller represents a bottleneck. Principle 1 holds that if the first customer dawdles while talking with the teller, both customers will be delayed, and to the same extent.

Principle 2. If stages of Task 1 after the bottleneck are slowed, this increases RT1 but does not increase RT2. because Task 2 is not directly waiting for these stages. (If the first customer dawdles in counting his or her money after leaving the teller's window, the second customer will not be delayed.)

Principle 3. This principle makes the most interesting predictions. If one slows stages of Task 2 before the bottleneck by a certain amount, RT2 will not be increased correspondingly. The reason is that (at short SOAs) the second task is not directly waiting for the completion of stages in Task 2 before Stage B but for completion of critical stages in Task 2. (While the teller is working with the first customer, the second customer can fill out his or her deposit slips more slowly without spending any extra time in the bank.)

Principle 4. Manipulating the duration of stages at or after the bottleneck in Task 2 to a given extent will have no effect on RT1 and will slow RT2 to exactly the same extent, regardless of the SOA. (A customer spending 3 extra minutes talking with the teller has no effect on preceding customers; however, it always causes the customer in question to spend 3 extra minutes in the bank.)

It is possible to derive still more fine-grained quantitative predictions from this kind of model (for pioneering work along these lines, see Schweickert, 1978, 1993). However, more detailed predictions may not be so readily applied if various extraneous "nuisance" factors (discussed later) contribute a portion of the observed dual-task slowing. Principles 1-4 generate predictions of effects and interactions that are large and distinctive, thereby allowing one to test hypotheses even when there may be additional minor slowing caused by extraneous factors. Furthermore, these predictions are essentially independent of the shape of the underlying distributions.

There are now a fairly large number of published studies that provide tests of bottleneck models using these four principles. The results described subsequently come from typical PRP experiments that have avoided using difficult perceptual discriminations in the same sensory modality. The results strongly imply the existence of a stubborn bottleneck in response selection (first hinted at by Craik, 1947, and advocated by Welford, 1952, 1980) and certain other central cognitive operations while rejecting bottlenecks in other stages.

Evidence for Response Selection Bottleneck

Assuming that there is a bottleneck in response selection. Principle 1 holds that increasing the duration of response selection (or preceding stages) in Task 1 should increase RT2 as well as RT1 when the SOA is short. Karlin and Kestenbaum (1968) and Smith (1969) confirmed this prediction when they manipulated the number of alternatives[5] in a choice RT task, as did Hawkins. Church, and de Lemos (1978. Experiment 1) using stimulus probability.[6] (Broadbent and Gregory [1967]) found a slightly greater effect of S1 probability on Task 2 relative to Task 1, however.)

According to Principle 2, if there is a bottleneck in response selection, then increasing the time taken to produce the already-selected R1 will not increase RT2. Pashler and Christian (1994) varied the complexity of the Task 1 response. In one case, subjects had to produce either a single keypress or a sequence of

[5] Varying the number of alternatives is likely to increase preparatory demands (see later discussion) and is therefore not an ideal variable for such studies.

[6] Probability probably affects both identification and response selection (Sternberg, 1969).

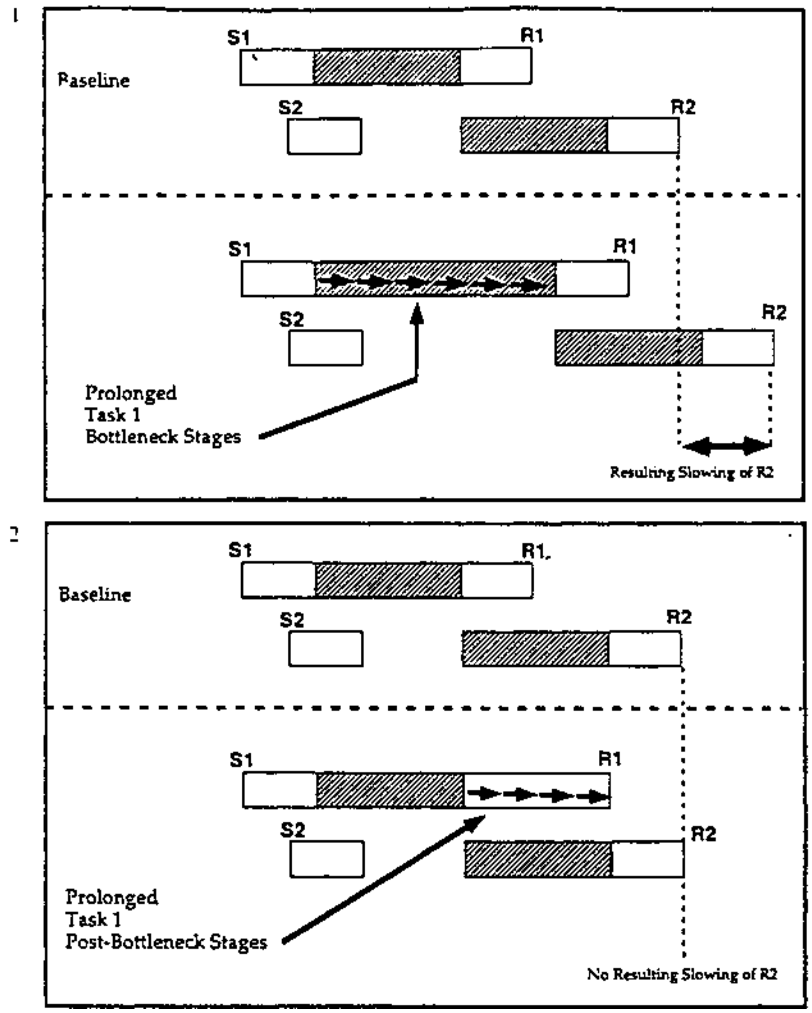

Figure 3. Predictions of a central bottleneck (in shaded stage) for experiments in which a particular stage of one or another task (the stage with superimposed arrows) is prolonged by an experimental variable. Panel 1: Prolonging the bottleneck stage in Task 1 delays both the first response (R1) and the second response (R2) correspondingly. Panel 2: Prolonging the postbottleneck stage in Task 1 does not delay R2. Panel 3: Prolonging the prebottleneck stage in Task 2 does not delay either R1 or R2. Panel 4: Prolonging the Task 2 bottleneck stage adds a constant to R2 (no effect on R1). S = stimulus. (Figure 3 continued on following page.)

three keypresses depending on the identity of S1. Subjects produced the first keypress in Task 1 at approximately the same time regardless of whether the response involved one keypress or three. Naturally, however, it took them longer to complete three, about 489 ms longer in one experiment. The key question was how much of this slowing would "propagate" to produce slowing of the (vocal) RT2 as well. The answer: only 64 ms. This shows that actually producing the sequence (including whatever central and peripheral motor control processes may be operating through the time of the last keypress) did not hold up the second task. On the other hand, the 64-ms slowing—although small in relation to effects on RT1—suggests that a response selection account may not be the whole story. Possibly, response production may normally work in a manner autonomous of the bottleneck, but on a few trials corrections may be necessary, reoccupying the bottleneck machinery.

The most distinctive predictions made by a response selection bottleneck theory follow from Principle 3, which implies that increasing the time for perceptual processing of S2 should have smaller effects in the dual-task condition when the SOA becomes short. Several experiments manipulating stimulus intensity have confirmed this prediction (De Jong, in press; Pashler, 1984; Pashler & Johnston, 1989). Because there is still uncertainty about how far into the system effects of intensity operate (Miller, 1979), this might be consistent with a bottleneck that encompasses not only response selection but the later stages of perception (e.g., object recognition) as well. (Other results discussed later provide some evidence against this possibility, however.)

According to Principle 4, a response selection bottleneck predicts that increasing the duration of response selection in the second task should have a constant effect on RT2, regardless of SOA. Many studies have confirmed this result.

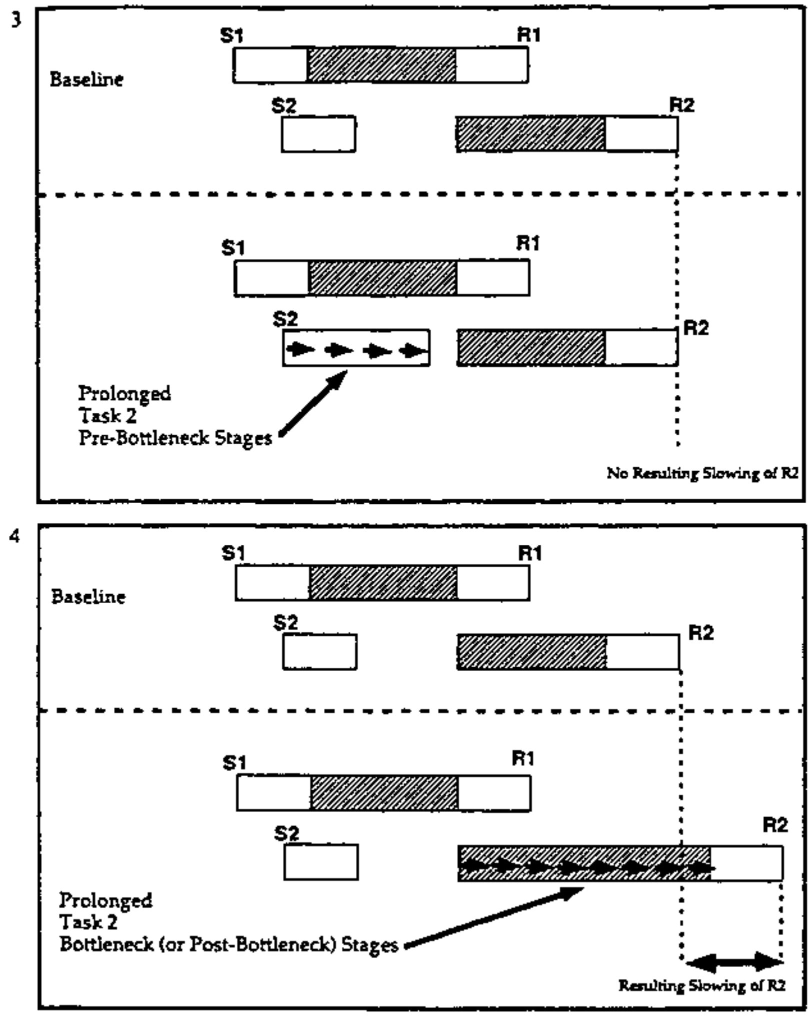

Figure 3. *(continued)*

Pashler and Johnston (1989) found that the effects of stimulus repetition were additive with SOA (i.e., when S2 on trial *n* was identical to S2 on trial *n* - 1, RT2 was faster, but to the same degree at short and long SOAs). In relatively unpracticed choice RT tasks with easily recognizable stimuli, repetition primarily affects the time required to select a response (Pashler & Baylis, 1991).

Pashler (1989) had subjects perform a second task involving naming the highest digit in a display of digits (Experiment 4) or making a button push response indicating its identity (Experiment 3). Naturally, response selection is easier in the vocal task, and RT2 was more than 100 ms quicker in that task. The SOA effect was very similar in the two tasks, however.

McCann and Johnston (1992) used a second task requiring subjects to press one of two response keys depending on the identity of a visual stimulus. In the compatible condition, the stimuli (shapes of increasing size) were mapped onto an array of response keys in an orderly fashion: in the incompatible condition, the mapping was shuffled. In the incompatible condition. RT2 was about 60 ms slower than in the compatible condition. This effect was additive with SOA (see Figure 4). Other cases of additivity have been reported by Pashler (1984, Experiments 1 and 2; target presence-absence). Fagot and Pashler (1992, Experiment 7; Stroop effect), and Hawkins et al. (1978; number of stimuli per response[7]).

Recent results show that the bottleneck encompasses more time-consuming memory retrievals as well as selection of responses in easy choice RT tasks. Carrier and Pashler (in press) performed a PRP experiment in which cued recall of the second element of a prememorized set of paired associates was the second task. RTs for the cued recall were slower when the pairs had

[7] In the difficult Task 2 mapping, three digits were mapped onto each of two buttons: in the easy condition, one digit was mapped. No reduction of the effect at short SOAs was observed in the first experiment: the second experiment showed a reduction after practice when one stimulus was auditory and the other was visual. Particularly with practice, subjects may categorize the stimuli in two groups, and this factor may affect categorization time rather than response selection time.

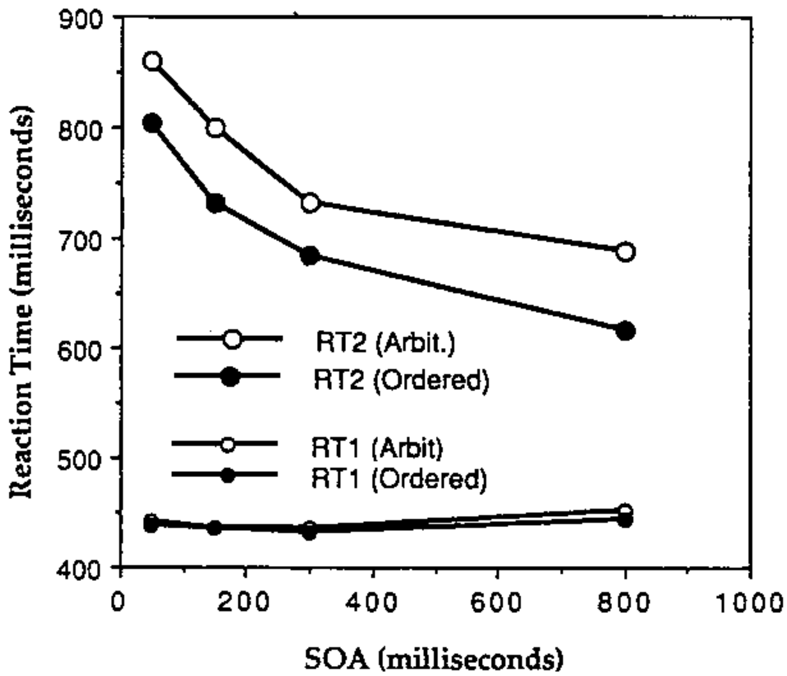

Figure 4. Additive effects of second-task stimulus-response compatibility and stimulus onset asynchrony (SOA) on reaction times (RTs) in a psychological refractory period experiment. In the ordered condition, the size of the boxes is mapped onto buttons in an orderly fashion, whereas in the arbitrary (Arbit.) condition, the mapping is not orderly. The upper two lines show Reaction Time 2, whereas the lower lines show Reaction Time 1. From "Locus of the Single-Channel Bottleneck in Dual-Task Interference" by R. S. McCann and J. C. Johnston, 1992, *Journal of Experimental Psychology: Human Perception and Performance, 18,* p. 477. Copyright 1992 by the American Psychological Association.

been studied less frequently; this effect was additive with SOA, showing that memory lookup was delayed by the first task.

RT Variability

So far I have discussed the mean RTs in PRP studies, but the response selection bottleneck model explains some features of trial-to-trial variability in RT1 and RT2 as well. According to the model, random variability in the time taken by stages of Task 1 up to the bottleneck must increase RT2 as well as RT1, thereby producing a strong correlation between RT1 and RT2 (at short SOAs). Correlations have, in fact, been high (e.g., Gottsdanker & Way, 1966; Pashler & Johnston, 1989; Welford, 1967). To look at the nature of this correlation in more detail, it is useful to divide up the trials at a given SOA into bins depending on the relative speed of R1 and then plot the average RT2 against the average RT1 within each of these bins (Pashler, 1989). The results of a typical analysis of this sort—in which the RT1s are divided into five bins (quintiles)—are shown in Figure 5. The fact that the correlation becomes stronger as the SOA becomes shorter fits the predictions of a bottleneck nicely.

The data reviewed so far seem to leave little doubt about the existence of a bottleneck encompassing at least the process of response selection in choice RT tasks and certain other central cognitive operations, including memory retrieval. (Again, these conclusions pertain to stimuli in different sensory modalities and tasks that have been subject to modest amounts of practice.)

Evidence Against Perceptual Bottlenecks

The fact that RT2 is slowed at all when S1 and S2 are presented in different sensory modalities makes it seem rather unlikely that perceptual processes could be part of the central bottleneck in the PRP situation. Furthermore, the reduced effects of visual stimulus intensity in the second task of a PRP situation (noted earlier) show that the stages slowed by intensity are not delayed by the first task, whereas subsequent stages are, in fact, delayed.

There is additional evidence against a perceptual bottleneck theory of the PRP effect. The high correlations between RT1 and RT2 noted earlier imply that most of the variability in RT1 occurs before the processes constituting a bottleneck are completed. The reason is that variability after the bottleneck would have to weaken the RT1-RT2 correlations, because this would represent noise present in RT1 but not RT2. It is unlikely that most of the variance in choice RT latencies could be generated by perceptual operations, so high correlations would be hard to account for if perception was the only bottleneck.[8]

More direct evidence against a perceptual bottleneck comes from recent studies examining accuracy in difficult but un-

[8] Compare, for example, the RT variance reported by Grice and Canham (1990) for a go-no-go task (about 625 ms^2) and for a comparable two-choice task (about 4,500 ms^2).

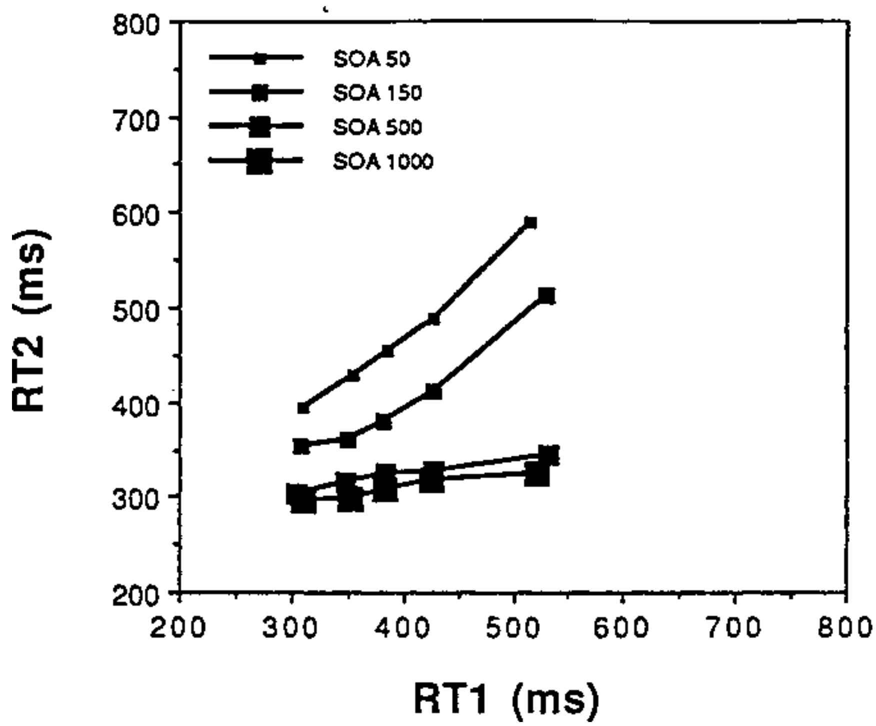

Figure 5. Reaction time (RT) for the second task as a function of the relative speed of the first response on the corresponding trial (by quintile) in a typical study. The results show a pronounced dependency that becomes stronger as stimulus onset asynchrony (SOA) is reduced. From "Dual-Task Interference and the Cerebral Hemispheres" by H. Pashler and S. O'Brien, 1993. *Journal of Experimental Psychology: Human Perception and Performance, 19,* p. 327. Copyright 1992 by the American Psychological Association.

speeded perceptual tasks performed concurrently with speeded choice RT tasks. In one such experiment, subjects made a button push response to a tone (S1) and determined whether a green *T* was present in a display of green *O*s and red *T*s briefly exposed and followed by a mask (requiring an unspeeded response). Accuracy in the visual search task was almost as good when the two tasks overlapped as when the tone and the array were separated by a long SOA (Pashler, 1989). If the visual processing in Task 2 (the processes that are terminated by the mask) had to wait for response selection in Task 1, then Task 2 accuracy could hardly fail to suffer severe interference at short SOAs (the condition under which overt responses to RT2 would suffer the greatest delays in the PRP situation).

Together, these results argue that people can recognize familiar visual stimuli and carry out visual search at the same time they are selecting a response in another task. Therefore, these operations cannot be part of the central bottleneck. The same appears to be true for storing unfamiliar visual patterns in visual STM (Pashler, 1993). However, some recent PRP studies imply that certain "cognitively demanding" kinds of perceptual operations may be part of the bottleneck. McCann and Johnston (1989) concluded that the process of comparing the width of two boxes very close in width was subject to bottleneck-induced delays (following Principle 4). Likewise, Ruthruff, Miller, and Lachmann (1994) concluded that "mental rotation" performed to determine whether a character was a mirror image or normal was subject to delays by a first task (angular disorientation of the character was additive with SOA). (Outside the scope of PRP tasks, too, there are signs that central mechanisms may be needed for more "cognitive" perceptual tasks; for example, Reisberg [1983] found that a counting task slowed the rate at which people could find alternate organizations of ambiguous figures.) Thus, it appears that although finding a preselected target or recognizing a familiar stimulus does not depend on the central bottleneck, carrying out more ad hoc manipulations of perceptual input—such as forming, manipulating, or comparing images—may often depend on it.

Evidence Against Response Production Bottleneck

Over the years, many investigators have suggested that the PRP effect is caused by motoric rather than cognitive limitations. For example, Keele (1973), Norman and Shallice (1985), and Logan and Burkell (1986) all argued for a bottleneck in the initiation or production of responses. One reason this view is tempting is because of the tendency—formerly common in human performance research—to divide processing into perception and response, overlooking the intervening cognitive stages of response selection. The hypothesis of a bottleneck located exclusively in initialing or executing responses makes a distinctive prediction following Principle 3: When an experimental manipulation increases the duration of stages in the second task before response initiation (e.g.. the time to determine what the response will be), R2 should not be slowed as much when the SOA becomes short. As described earlier, many experiments have found just the opposite: Response selection difficulty factors (such as compatibility and number of alternatives) generally add a constant to RT2, regardless of the SOA.

This does not necessarily mean that response production can never constitute a bottleneck. Consider what happens when subjects are required to produce a sequence of keypress responses with one hand (in response to S1) and a single keypress response with the other hand (in response to S2). Rather than R2 being produced while the R1 sequence is under way, R2 is almost always delayed until the last keypress in the R1 sequence is finished (Pashler & Christian, 1994). The results suggest that production of an ongoing sequence of manual keypress responses constitutes a bottleneck for the production of a response with the other hand (or, as it happens, foot). It might appear that bottlenecks are now proliferating, but this finger-and-foot response-execution bottleneck is unlikely to play a role in any of the "usual" PRP designs, even those tasks that involve two separate finger responses (see De Jong, in press, for further discussion). This is because in the ordinary designs the (single) keypress that constitutes R1 would usually be finished well before R2 could potentially be selected and ready to execute. Therefore, it is probably only when R1 involves extended sequences, as in the Pashler and Christian studies, that the inability to produce truly simultaneous finger responses would make any difference. Thus, available data show that there is a general bottleneck in response selection (regardless of input or output modality) and potential specific (i.e., effector-dependent) bottlenecks in response execution that are elicited only under special circumstances. The latter are unlikely to play much role in the more common laboratory tasks. (Of course, they may be important outside the laboratory as when, for example, a musician executes sequences of complex finger movements.) I turn now to two phenomena that have special relevance to assessing possible conflicts in response production: PRP effects in simple and "go-no-go" RT tasks.

PRP in simple RT. The earliest studies of dual-task interference in speeded tasks combined simple RT tasks to which the subject responded with the same effector (Telford, 1931). Later studies used two simple RT tasks with different fingers (e.g., Welford, 1952). All of these studies found slowing at short SOAs. If there is a bottleneck exclusively in selection of responses, and if simple RT does not require selection of the response—as Donders (1969) hypothesized—then it is not clear why this interference should exist.

There are several possible explanations. The first is an account raised earlier: The central bottleneck may encompass both selection and initiation (setting the response in motion but not supervising its execution). If initiation takes roughly the same time for short and long response sequences, this would be consistent with the results reviewed in the preceding section. A PRP effect when simple RT is the second task may reflect this bottleneck in initiation.

There is, however, evidence to suggest that simple RT may differ from choice RT more radically than Donders (1969) hypothesized. As noted earlier, simple RT is highly sensitive to temporal uncertainty (Klemmer, 1957). Davis (1959) combined two manual simple RT tasks with SOAs ranging from 50 to 500 ms (randomly intermixed). In some blocks, the stimuli were both visual; in other blocks, one stimulus was visual and the other was auditory. A substantial slowing of R2 occurred in both cases. Most relevant for present purposes, Davis also found a slowing of the response to S2 that occurred even when S1 did not require a response. As mentioned earlier, delays in choice RT seem negligible when no response is made to S1 (Pashler & Johnston, 1989; see Footnote 3). Frith and Done (1986) also noted that distraction slows simple RT more than choice RT. If simple RT were only a subset of choice RT, this should not happen. Thus, PRP effects observed in simple RT seem fundamentally different from those found in choice RT tasks. For this reason, studies that have varied the number of alternatives in choice tasks over the range between one and two must be interpreted with great caution (e.g., Karlin & Kestenbaum, 1968; Schweickert, 1978); evidently, this manipulation does not simply change the duration of a particular stage or insert a single stage, as Donders hypothesized.[9]

PRP in go-no-go tasks. A natural strategy for determining the role that response production plays in the PRP effect is to use a so-called go-no-go task (e.g., "Press the key if an *A* appears; otherwise, do not respond") as Task 1 and a choice task as Task 2. This was tried by several investigators in the 1960s (Bertelson & Tisseyre, 1969; Smith, 1967a). The result was that RT2 was slowed after the no-go stimulus on Task 1 as well as after the go stimulus, although the slowing was greater after the go stimulus. However, both studies showed striking variability between subjects, with some subjects showing comparable slowing in the two conditions and some showing virtually no slowing after no-go trials. (The experiment involved multiple sessions for each subject, and these individual differences proved reliable.) When one considers the range of processing strategies that might potentially be applied in a go-no-go task, this heterogeneity may not be so surprising. Logically speaking, the no-go stimulus need not be processed any more extensively than a distractor in a search task, and people can sometimes reject distractors at the same time they carry out an unrelated task (Pashler, 1989). At the other extreme, subjects might "preactivate" the go response and then, on the no-go trials, select an inhibitory response. Bertelson and Tisseyre (1969) constructed a task to make this strategy impossible: using two different go stimuli, each with a separate response, along with two no-go stimuli. The variability between subjects remained, although the authors were impressed with how much slower RT2s were after go responses.

It is also interesting that a choice response is delayed by a go response in the standard go-no-go paradigm because, in line with Donders's (1969) analysis, one might think that a single go response would not have to be selected at all. Together with the observations about simple RT discussed earlier, this evidence suggests that initiating, as well as choosing, responses is subject to the same central bottleneck.

[9] Karlin and Kestenbaum (1968) found an underadditive interaction between SOA and simple versus choice RT that was confirmed by Hawkins, Church, and de Lemos (1978). Keele (1973) used this result to argue that response-initiation delays were the sole cause of the PRP effect, which is inconsistent with the evidence described earlier.

From the PRP findings described thus far, one is left with the impression that dual-task interference in choice tasks is easier to understand than dual-task interference in the more primitive of Donders's (1969) tasks (simple and go-no-go). Because choice tasks seem to offer a better model for a range of interesting human behaviors, it probably makes sense to concentrate on them.[10] For the moment, the most that can be concluded from studies of the simpler tasks is that simply initiating a preplanned response may require the same bottleneck mechanism that is needed for choosing responses from among a set of several possibilities.

Capacity-Sharing Models of the PRP

As described earlier, many writers have assumed that dual-task interference should be explained in terms of allocation of one or more forms of processing capacity. This intuitively natural idea was specifically applied to the PRP task by Kahneman (1973) and McLeod (1977b), who suggested that processing capacity was divided among two tasks in a flexible and graded fashion: a little more to one task, a little less to the other. McLeod assumed that capacity was generally allocated to the first task until S2 appeared; thereafter, the two tasks shared capacity until R1 was produced, at which time the second task proceeded with full capacity.[11]

The evidence for a central processing bottleneck in the PRP task discussed in the preceding sections does not completely rule out the possibility of capacity sharing. In just about all PRP studies (beginning with Creamer, 1963), emphasis has been placed on producing R1 as quickly as possible (R2 is also to be produced quickly, but not at the cost of delaying R1). Even if graded capacity sharing were possible, instructions to give R1 priority might lead people to allocate all available capacity to Task 1 until it was complete and then allocate full capacity to Task 2. Therefore, there might appear to be a structural bottleneck even if there is none.

The obvious solution is to omit any requirement for rapid responses on Task 1. In some cases, this has been done and the results still favor a bottleneck (Carrier & Pashler, in press; Ruthruff, Miller, & Lachmann, 1994). When subjects are free to respond as they choose, however, some will "group" their responses, producing R1 and R2 in a fixed pattern (not necessarily simultaneous), with extremely little variability in the interresponse interval (the time between occurrence of R1 and R2). Grouping is especially common when the SOA is fixed in a block of trials. The existence of response grouping does not contradict the bottleneck model: Pashler and Johnston (1989) manipulated the duration of second-task processing stages with subjects who were encouraged to group their responses and concluded that the mental operations proceeded as shown in Figure 6.[12] Here responses are selected sequentially and then the two responses are jointly executed.

Given these complexities, clear-cut evidence against the possibility of capacity sharing is hard to come by. The evidence for a response selection bottleneck might be accounted for by a modified capacity-sharing theory postulating that processing capacity is required for response selection and that people often choose to allocate this capacity in an all-or-none fashion. Can such an account be rejected? The particular theory proposed by McLeod (1977b; which assumes that each task consumes a fixed total amount of capacity; see Footnote 11) predicts that increases in the difficulty of the first task will have greater effects on RT1 in the dual-task situation than in the single-task situation. The data described earlier reject this theory (Pashler, 1984). However, capacity-sharing models need not have the analytically tractable characteristics that McLeod included in his model, so these data are not fatal to capacity-sharing models in general.

To properly test graded capacity sharing in general, one needs to provide incentives to share capacity in a graded fashion and then look for evidence of sharing. Pashler (1994a) had subjects perform two choice RT tasks with stimuli separated by intervals of -1,000, -500, 0, 500, and 1000 ms.[13] The instructions called for equal capacity to be allocated to the two tasks. If capacity sharing is possible, one would expect that in the zero SOA condition some people would share capacity roughly equally among the two tasks, carrying them out concurrently (albeit more slowly than normal). If there is a structural bottleneck, on the other hand, subjects should have no choice but to carry out central stages of one task before the other, producing a bimodal distribution of responses. In fact, subjects fell into two groups. Some clearly grouped their responses (indicated by interresponse intervals near zero with extremely low variability). Most subjects, however, showed the bimodal pattern of responding predicted by a structural bottleneck.

Of course, a single study cannot rule out the possibility of graded capacity sharing in general.[14] The possibility can only be weakened as cases accumulate in which capacity sharing might have been expected to show up but does not. As the matter stands however, there is no evidence in the PRP task that specifically favors capacity sharing, even when attempts have been made to elicit it. (What is commonly taken to be evidence for capacity sharing obtained outside the scope of PRP studies is discussed later.)

[10] This recommendation was first offered by Bertelson (1966).

[11] McLeod's model further assumed that each task consumed a fixed total amount of capacity; that is, two comparable tasks would take twice as long to perform simultaneously (each getting half the capacity per unit time) as either would take by itself. This assumption is rather arbitrary, but it makes the model very tractable. It then yields the rather unintuitive prediction that for any given SOA, R2 is completed at the same time regardless of the proportion of capacity allocated to the two tasks during the S2-R1 interval (because the second task is completed when the total capacity required by both tasks is complete, which cannot depend on the division of capacity). Thus, McLeod's version of capacity sharing does not entail any actual trade off between Task 1 and Task 2.

[12] When each task involves simple RT and the two stimuli appear close together in time, a different form of grouping seems to occur (Welford, 1952) in which the two responses are selected as a unit. This makes different predictions from selecting them individually and emitting them as a unit (Fagot & Pashler, 1992; Pashler & Johnston. 1989).

[13] The purpose of including a range of SOAs was to discourage grouping, and this strategy was partly successful; explicitly discouraging grouping would have undermined the purpose of the experiment.

[14] In particular, it would be good to see that the result holds with tasks using different response modalities and more difficult response selection requirements.

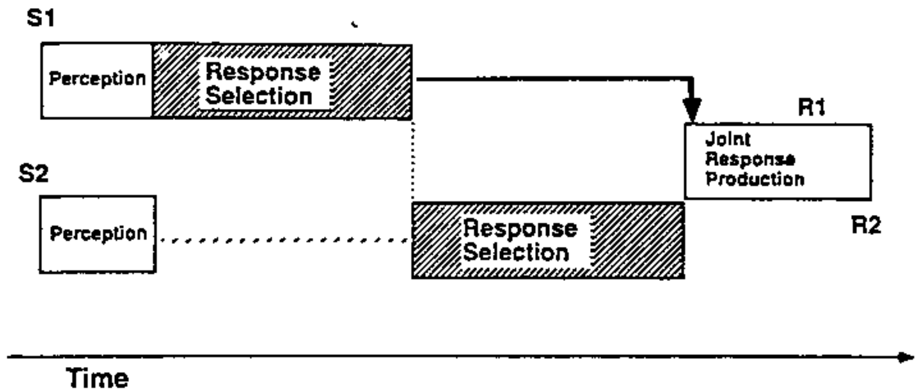

Figure 6. Hypothetical sequence of processing stages when subjects group responses: Selection of both responses is sequential, and it precedes joint production of the two responses. S = stimulus; R = response.

Task Preparation in the PRP

Another important but much neglected aspect of dual-task performance is task preparation. In a typical laboratory study of human performance, an "imperative stimulus" is presented on each trial, and the subject makes a response to each one that, logically speaking, depends on both the imperative stimulus and the instructions given to the subject at the beginning of the experiment. Researchers typically focus on the mental events that occur between the imperative stimulus and the response. However, it is obvious that important mental events must occur before the stimulus itself is presented.

What role does preparation play in dual-task interference? The simplest and most extreme view would be that the response selection bottleneck is itself caused by a preparatory limitation. Maybe it is impossible to prepare the response selection machinery to handle the S-R mappings for both tasks. Therefore, the first mapping is prepared, R1 is selected, and then the machinery must be "reprogrammed" before R2 can be selected. If this scenario is correct, then response selection should no longer constitute a bottleneck when two (or more) tasks involve the same mapping (but different stimuli). Pashler (1994b) investigated this question by using a serial RT task in which the mapping of letters to keypress responses remained the same while the subject responded to a "run" of 10 different stimuli. Sometimes subjects were not allowed to preview stimuli (i.e., stimulus $n + 1$ was not visible until the subject had responded to stimulus n). In another condition, preview was provided: Stimulus $n + 1$ was available even before the subject responded to stimulus n. Potentially, this could allow overlap of processing, just as in the PRP task; the question is how much overlap. Preview sped up the rate of responding (something first observed by Cattell, 1886), implying that some overlap was occurring. Several difficulty factors were manipulated, targeted to slow either response selection or perception stages. When response selection was slowed for the 10 stimuli, the time between responses within a run increased to the same extent, regardless of preview. On the other hand, when perceptual processing was slowed, the rate of responding was affected only when preview was not present. With preview, the perceptual slowing was "swallowed up." The results can be summarized by stating that response selection (but not perception) was always rate limiting for serial performance even when people could preview stimuli ahead of those to which they had responded, indicating (by the same reasoning as Principles 3 and 4) that only one response could be selected at a time even though the mapping remained unchanged. Figure 7 shows a sequence of processing stages with and without preview that accounts for the results very naturally; with preview, perceptual factors cease to be rate limiting, whereas response selection (shaded) remains so.

Because the bottleneck in selecting responses remains present even when the S-R mapping stays constant, the bottleneck cannot be caused by an inability to keep two different mappings prepared. Rather, a bottleneck seems to be caused by an inability to actually carry out the selection of two responses at the same time. Some very interesting early results of Jersild (1927), however, suggest that there is one special case in which people cannot keep two task mappings prepared at once, namely when each mapping takes the same set of stimuli onto different responses. An example would be reading a number aloud versus adding six to a number and pronouncing the sum. Jersild found that when people alternated between two such tasks, they took hundreds of extra milliseconds per task (in comparison with performing the same task over and over). One can probably conclude, therefore, that people can keep two task mappings in mind in the ordinary PRP task in which different stimuli are mapped onto different responses (i.e., tasks in which the mapping is a function) but they cannot do so in Jersild's situation (in which the mapping is not a function).

Even though people can normally prepare two mappings at the same time, doing so nevertheless seems to have some cost, contributing additional slowing beyond that attributable to the central bottleneck. This extra slowing presumably affects RT1 as well as RT2. One reason to believe that this is the case is that even when the SOA is rather long, both RT1 and RT2 are invariably slower than they would be in a single-task condition in which only one task has to be prepared.

This preparatory limit provides a plausible explanation for an observation that has puzzled PRP investigators for some

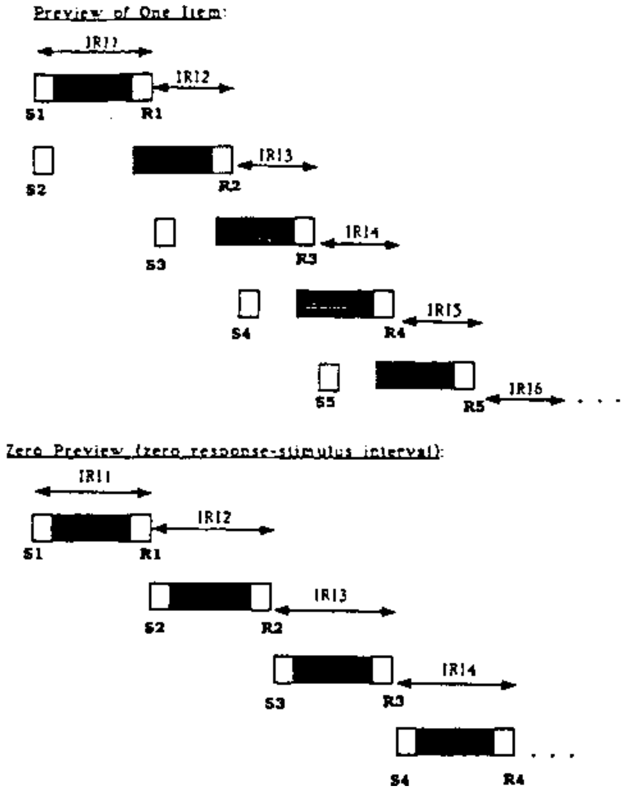

Figure 7. Processing stages in serial performance with preview: The shaded region depicts response selection. This stage becomes rate limiting when preview is provided (top panel): all stages are rate limiting without preview (bottom panel). S = stimulus; R = response. From "Overlapping Mental Operations in Serial Performance with Preview" by H. Pashler, 1994. *Quarterly Journal of Experimental Psychology, 47a.* p. 161. Copyright 1994 by the Experimental Psychology Society. Reprinted by permission.

time: R2 is often slowed (in comparison with a single-task control) even when S2 is presented after R1 has occurred. Welford (1952) explained this observation by hypothesizing that the central bottleneck mechanism took time out to monitor feedback from the execution of the response. However, this seems unlikely with responses such as keypresses, given that requiring more keypresses in the first task response produces little additional slowing of the second task (Pashler & Christian, 1994). Dual-task performance is likely to be slower than single-task "control" performance simply because the dual-task situation requires preparing the mappings for both tasks.

Preparation seems to depend on the amount to be prepared, and preparatory state probably changes rather slowly. Dixon (1981) found that subjects took hundreds of milliseconds to use cues about upcoming S-R alternatives. Logan and Zbrodoff (1982) cued subjects about the optimal strategy to use in a choice RT task and found that it required 400 to 600 ms for maximal benefits of the cue to be achieved. Consistent with these findings is the fact that—in the PRP situation—a gradual decline in RT2 is often observed out to very long SOAs of more than 1 s. This suggests that subjects slowly improve their state of preparation for the second task after they complete the first task.

This preparatory limitation is likely to affect performance in single- as well as dual-task experiments. Consider, for example, a choice RT task arbitrarily mapping individual stimuli onto responses. As the number of stimulus-response (S-R) alternatives increases, so too does the RT (Hick, 1952). This increase depends on the number of alternatives for which the subject must prepare rather than the number of different alternatives to which the person has been exposed during the current block of trials (Dixon, 1981). Together, these observations imply that when people must prepare different response selection "links" simultaneously, they cannot prepare them as fully and, consequently, they perform the tasks more slowly (an idea first suggested by Gottsdanker, 1980). This still leaves open the details of how poor preparation affects execution of a task, that is, what stages are affected and how (e.g., whether they are slowed or whether their onset may be delayed). Experiments involving concurrent memory loads—discussed later—provide some clues.

The fact that some dual-task slowing comes from limitations in preparing rather than executing the tasks also has important methodological implications. The first is that single-task performance may often be an inappropriate baseline against which to assess dual-task interference. As McLeod (1977a) first noted, it is more useful to compare performance at short SOAs and longer SOAs—still short enough to prevent much preparation from being accomplished—when the goal is to determine which mental events can operate at the same time.

A second implication is that one must use caution in interpreting effects of variables that change the amount of preparation a subject must carry out. For example, increasing the number of alternatives in Task 2 might affect RTs in Task 1 by impairing preparation of that task. In that case, the factor should slow Task 1 even when the SOA is long enough that the first task is completed before S2 has even been presented.[15] For this reason, variables that can be manipulated in mixed-list designs (e.g.. intensity and compatibility) are probably more suitable for research of this kind.

In summary, the inability to select two responses at the same time (the central bottleneck) is not the only cause of dual-task slowing. Another is a preparatory limitation. The bottleneck itself is not likely to be caused by an absolute inability to prepare two mappings at the same time, but dual-task slowing is probably increased by the fact that tasks are prepared less effectively when other tasks must be prepared at the same time. Preparatory states probably change rather slowly. Experiments designed to answer the question What mental operations cannot be carried out at the same time? must be carefully designed if

[15] An even more extreme case would be that of experiments comparing the same versus different S-R mappings in Task 1 and Task 2 (e.g., Duncan. 1979, Experiment 2). It seems reasonable that it would be easier to prepare to use the same mapping twice than to use completely unrelated mappings in two tasks. This does not mean that the two tasks are not actually carried out separately and sequentially.

they are to avoid confusing delays due to bottlenecks with slowing due to impaired preparation.

The Variety of Dual-Task Situations

So far, the focus of this review has been on the PRP situation, in which a person tries to choose and execute two responses as rapidly as possible. Under these conditions, it has been shown that interference arises chiefly because of a bottleneck in response selection (and certain other cognitive operations) and secondarily because of a limited ability to prepare multiple task mappings. These forms of dual-task limitations seem to account for the main PRP phenomena quite satisfactorily. However, dual-task performance has been studied in many contexts aside from the PRP task. This section considers some of the most commonly studied dual-task situations from the theoretical perspective developed in the preceding section. Initially, four situations involving simple tasks are considered in some detail (although not exhaustively): probe RT tasks, concurrent memory load effects, motor production tasks, and perceptual judgment tasks combined with speeded tasks. Then two other kinds of dual-task performance are discussed more selectively: perceptual judgment tasks combined with other tasks of the same kind and continuous dual-task performance. There is a vast literature on these two issues that cannot be reviewed here, but an effort is made to show how the conclusions reached from PRP studies may illuminate the main phenomena observed in both domains.

Probe RT Tasks

Many investigators have looked at dual-task interference in simple tasks using what is sometimes called the "probe RT method." One of the first and best-known probe RT studies was reported by Posner and Boies (1971). As their primary task, subjects had to determine whether two successively presented letters were identical by making a rapid button push response shortly after the second letter appeared. (The two letters are referred to here as "sample" and "test" letters.) On half of the trials, a tone sounded at some point during the trial, and the subject responded to the tone by pressing a key with the other hand as rapidly as possible. The instructions stressed rapid performance of the letter matching task as the primary task, however.

Posner and Boies (1971) assumed that the speed of the response to the probe would provide an index of the amount of spare capacity left unoccupied by the primary task. As shown in Figure 8, probe RTs were not much elevated when the probe was presented within a short time of the presentation of the sample letter. Therefore, the authors concluded that the perception of the sample letter could not have used up more than a very small amount of capacity. RTs to probes were elevated beginning after the presentation of the sample letter and at approximately the time the test letter was presented. Posner and Boies (1971) concluded that although encoding of the test letter did not require central capacity, "generation of distinctive features for testing" during the interval between the letters and the "response phase" of the matching task did require capacity (p. 407).

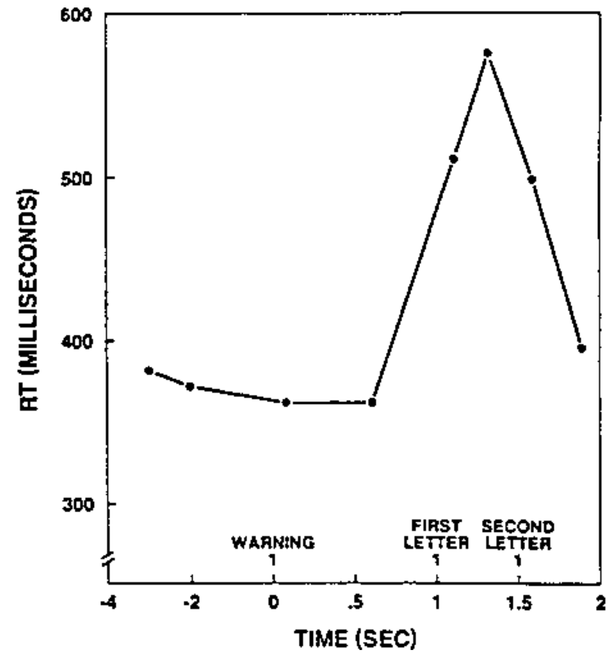

Figure 8. Reaction times (RTs) to respond to a probe that occurs at some time during a letter matching task. (Time refers to occurrence of probe with respect to letters.) From "Components of Attention" by M. Posner and S. Boies, 1971, *Psychological Review: 78,* p. 402. Copyright 1971 by the American Psychological Association.

The PRP results described earlier point up various problems with these inferences. First, the idea of shared capacity—which is assumed rather than tested in probe RT studies—is itself questionable. Second, the probe method usually involves simple RT, so the peculiar sensitivities of that task, especially to temporal uncertainty, could masquerade as capacity limits. Third, the task allows fairly long periods of "empty time," so people might be able to alter their preparation for the probe task, which would again be mistaken for a change in capacity allocation. In spite of all these problems, the conclusions reached by Posner and Boies (1971) are not that different from the conclusions reached earlier from PRP experiments involving choice tasks (although the concept of response phase would seem to include both choosing and carrying out responses, activities that, according to the PRP studies, play quite different roles in dual-task performance).

Subsequent studies using the probe RT method have challenged Posner and Boies's (1971) conclusions, however. Instead of presenting the sample letter for a full half second of view, Comstock (1973) presented it briefly, followed by a mask (100-ms SOA), and found that this produced an abrupt increase in probe RTs when the probe was presented 100 ms after the letter. This is not necessarily inconsistent with Posner and Boies's conclusion that encoding did not require central capacity because, when they expect a mask, people might begin "generation of test features" immediately.

The possible capacity demands of perceptual processing were also addressed in a recent probe RT study reported by Thompson (1987). In her study, the primary task involved visual search rather than matching. Subjects searched an array either for a single feature or for a conjunction of features (their primary task). They did not have to make any immediate response to the array; they simply had to remember it and, after 2 s, choose a pair of target alternatives. RTs to probes presented at the time of the display or 50 ms after it were elevated to a relatively small degree. However, given that simple RT is elevated by a previous stimulus that does not require any response (Davis, 1959), the results do not make any strong case for central demands of the search process itself (less surprisingly, when a visual search task does require an immediate response, probe RT is elevated; Logan, 1978a).

In summary, probe RT is substantially elevated when the probe is presented at approximately the time response selection in the primary task is likely to be under way. Actually producing a manual reaching response also delays concurrent manual probe RTs much more than it delays concurrent vocal probe RTs (McLeod, 1980). The latter observation is quite compatible with the potential for conflicts in simultaneous manual movements noted earlier. So far, then, there is no incompatibility between the results of the probe studies and the conclusions derived from PRP studies. In fact, there is every reason to suspect that many probe RT results reflect the same bottleneck as the PRP effect: the reason this was not apparent was that, in the probe studies, the experimenter had no control over the order of responding, and the data were not analyzed for signs of a bottleneck (e.g., looking at the relation between RTs for the two responses).

Memory Loads as Concurrent Tasks

Many studies have required subjects to hold on to a memory load as they perform some speeded task. Sometimes the purpose of such studies has been to explore the nature of short-term memory (Baddeley. 1986). Other experiments, however, have been carried out to determine whether particular mental processes require processing capacity, and these studies have relied on the assumption that filling short-term memory depletes this capacity. So long as the memory load is well below the memory span, people's ability to retain the memory load is usually unaffected by the concurrent task. People are slower at carrying out that task while they are holding on to the load, however. This slowing is typically very modest and, interestingly, additive with most factors affecting the duration of different stages, including perceptual processing (Egeth, Pomerantz, & Schwartz, 1977; Logan, 1978b). This implies that the memory load cannot be delaying central processing stages; otherwise, an underadditive interaction with perceptual slowing would be expected (Principle 3).

As Logan (1978b) and Egeth, Pomerantz, and Schwartz (1977) pointed out, if one believed that tasks required a fixed amount of capacity and memory loads depleted capacity, then overadditive interactions should have been expected. Thus, the effects of concurrent memory loads provide no basis for assuming that a load depletes the processing capacity necessary for performing RT tasks. What does a memory load do. then? One plausible account would be that holding on to a memory load neither uses up processing resources nor occupies any single-channel machinery. Rather, as Logan (1978b) suggested, it may simply cause the S-R mapping for the RT task to be more poorly prepared. This might happen because rehearsing the memory load before the beginning of the speeded task prevents rehearsal of the S-R mapping for that task or because both the speeded task instructions and the memory load compete for limited short-term memory storage capacity. In any case, the result may be that the processing stages that depend most critically on preparation[16] then operate more slowly, without any stages actually being delayed as they are in the PRP situation. Logan (1979) did find interactions of memory load with number of alternatives; as he noted, this is consistent with a preparation account because the number of alternatives determines the amount to be prepared.

Production of Predictable Motor Responses

Many investigators have examined concurrent tasks that require people to produce a sequence of motor responses with no response uncertainty. Repetitive finger tapping is an example. Several interesting results have emerged. First, tapping has almost no effect on speeded tasks involving responses in a different response modality (e.g., voice) or on cognitive operations generally. (The reader can easily verify this last point informally by tapping rapidly while counting backward by 7s from, say, 488.) Although statistically significant effects have sometimes been found (e.g., Kee, Hellige, &, Bathhurst, 1983), they are extremely small in comparison with PRP effects. Baddeley (1986) and his colleagues found similar results when they combined concurrent articulation (e.g., saying *the* over and over) with tasks involving decision making and reasoning; concurrent articulation usually produced statistically significant but very small performance decrements. A second finding is that producing a rhythmic pattern of finger movements interferes dramatically with production of other sequences having harmonically unrelated rhythms (Klapp, 1979). Third, tapping also interferes with people's ability to perceive the rhythm in a sequence of unrelated sounds (Klapp et al., 1985). The finding that tasks like tapping interfere little with tasks that require response selection but use different response systems fits very well with the conclusion from PRP studies that execution of motor responses is not part of the central bottleneck. On the other hand, the difficulty people have in tapping out harmonically incompatible rhythms with the two hands shows that finger tapping is by no means a completely "automatic" behavior. Although tapping does not involve the central bottleneck, it apparently involves the same timing machinery as that required to perceive rhythms, for example. Ivry and Keele (1989) suggested that this machinery may consist of a single programmable interval timer located in the cerebellum.

[16] From the perspective of the additive factors methodology (Sternberg, 1969). this account would cause one to wonder why memory loads did not interact with more of the factors Logan manipulated. One possible explanation is that interactions due to a common stage locus may sometimes be smaller and thus harder to detect than interactions produced by postponement of a stage, which are likely to be quite drastic (e.g., "complete" underadditivity).

Unspeeded Perceptual Judgments Combined With Speeded Tasks

A few researchers have examined the accuracy with which a perceptual judgment (involving no speed pressure) can be performed concurrently with a speeded task. The hypothesis of a postperceptual bottleneck makes a clear prediction: Although the speeded task should occupy the central bottleneck, perceptual analysis should be able to occur simultaneously with no decrement. (Performance in one or both tasks might still be impaired as a result of the preparatory limit noted earlier, however.) Blake and Fox (1969) had subjects make a speeded detection response to the onset of a tone; at some point between 0 and 200 ms after the onset of the tone, one of three letters was exposed very briefly. After making a simple RT response, the subjects took their time and reported the identity of the letter, the exposure duration of the letter was adjusted so that the letter could be accurately reported approximately 66% of the time. There was no dual-task interference whatsoever. The same results were found when the stimulus for the first task was visual: a set of circles flanking the center of the display.

Because an unmasked letter generates iconic persistence, the reason that there was no interference might have been that subjects were able to postpone identifying the letter until after they had completed the detection task (thereby concealing the interference). To get around this problem, Pashler (1989) had subjects carry out a speeded choice response to a tone of one of two possible pitches and perform an unspeeded visual search task that involved a display of characters followed by a mask. In the dual-task condition, the SOAs ranged from 50 ms (maximal overlap) to 650 ms (almost no overlap). Second-task accuracy was minimally affected by SOA, and the speed of any given tone response did not predict the accuracy of the corresponding visual response. As noted earlier, the results support the view that visual search proceeds independently of the central processing in the tone task. Recently, however, De Jong and Sweet (1994) reported larger decrements in second-task accuracy in quite similar experiments when they compared near-simultaneous presentation with a somewhat longer SOA (1000 ms), especially when they placed unusually great emphasis on the speed of the first task. These results are consistent with the assumptions that all of these tasks require preparation and that, with sufficiently long SOAs, preparatory states may change. They do not overturn the conclusion that visual search can frequently overlap central processing.

Studies combining speeded and unspeeded tasks make it seem unlikely that the machinery involved in visual processing as complex as identifying characters or detecting color-form conjunctions can be subject to the same bottleneck that delays responses in concurrent tasks. This confirms the conclusions derived from the factor manipulations in speeded tasks described earlier.

Within-Modality Perceptual Judgment Tasks

The pairs of tasks used in the investigations described thus far did not require difficult concurrent perceptual processing of stimuli in the same sensory modality. Concurrent perceptual processing has been extensively investigated in tasks such as visual search in which there is only one task (i.e., one response) per trial but many stimuli. This research has produced a large literature that cannot be reviewed here, but the main findings need to be related to the conclusions reached earlier. When perceptual tasks require difficult concurrent processing, accuracy often suffers. This has been most clearly demonstrated in visual search and dichotic monitoring tasks in which the subject sees or hears more than one stimulus but makes only a single response. In one particularly revealing experimental design, the subject makes a forced-choice judgment about which of two possible targets was present in a display (each item is followed by a mask). Performance is compared in two conditions: one in which the items are displayed simultaneously and one in which the items are displayed successively (the number of items is the same in the two conditions, holding decision noise constant; Duncan, 1980a). When display size is small and discriminations are relatively easy, accuracy is usually equally good in the two conditions, demonstrating parallel processing with no capacity limitations (C. W. Eriksen & Spencer, 1969; Shiffrin & Gardner, 1972). On the other hand, when discriminations become more difficult, performance is generally worse in the simultaneous condition (Duncan, 1987; Kleiss & Lane, 1986); the same is true when two targets are presented (Duncan, 1980b). These results amount to a decrement in performance as the SOA between two sets of stimuli is reduced, so they are analogous in some ways to a PRP effect.

What causes the interference in these detection tasks? One natural suggestion would be that the same central executive responsible for the PRP bottleneck carries out perceptual processing when that processing becomes sufficiently difficult (Broadbent, 1982). Several lines of evidence argue against this suggestion, however. First, the error rate in the second of two concurrent visual search tasks increases by the same amount whether or not the subject has to make a rapid response to the first display (Pashler, 1989). Second, when a speeded first-task response is required, the speed of this response shows little correlation with accuracy in the second task. Third, the problem in detecting two targets does not occur when both are attributes of the same object (Duncan, 1984), whereas the PRP effect is indifferent to this (Fagot & Pashler, 1992). In view of these findings, it is hard to see how perceptual capacity limits could possibly stem from the central bottleneck implicated by PRP studies. Figure 9 (from Pashler, 1989) represents the two different sources of interference at work when a pair of tasks engenders both perceptual and central interference. Different theorists have interpreted perceptual processing limits in different ways (e.g., Treisman & Sato, 1990; Wolfe, Cave, & Franzel, 1989); the point to be made here is simply that—whatever their nature—these processing limits appear to be functionally separate from the central bottleneck. There is also evidence that perceptual capacity limitations are at least partly confined within a given sensory modality (Treisman & Davies, 1973), further reinforcing this conclusion.

Continuous Dual-Task Performance

This review has focused primarily on studies involving pairs of simple punctate tasks. As noted in the introduction, a great deal of dual-task research—particularly research addressing

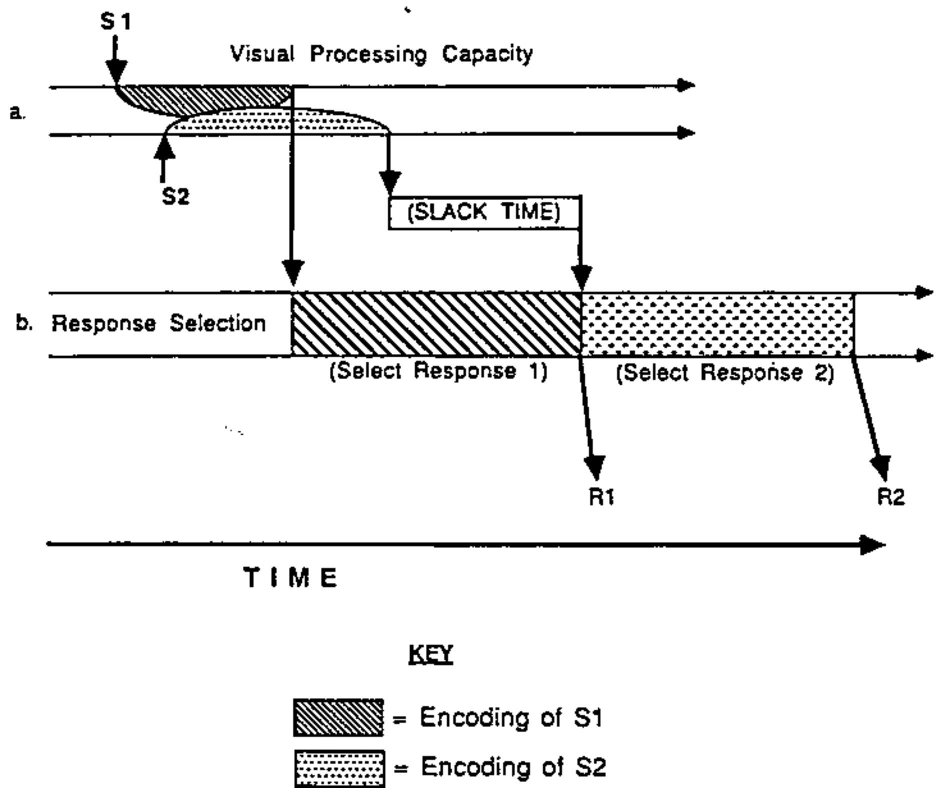

Figure 9. Two different sources of interference when two tasks compete for perceptual processing resources and also require sequential response selection. S = stimulus; R = response. From "Dissociations and Dependencies Between Speed and Accuracy: Evidence for a Two-Component Theory of Divided Attention in Simple Tasks" by H. Pashler, 1989, *Cognitive Psychology, 21,* p. 481. Copyright 1989 by the Academic Press. Reprinted by permission.

practical issues—has focused on performance in more continuous and complex tasks. Examples include visual-manual tracking, comprehending prose, answering questions, and shadowing speech. Generally, this kind of research has used aggregated performance measures obtained over periods of seconds or minutes, and the results have been interpreted in terms of graded sharing of single or multiple pools of attentional capacity. This large literature cannot be reviewed here, but the relationship between the conclusions derived from punctate tasks and the approach used in studying continuous tasks certainly needs to be addressed.

It is logically possible that performance in continuous tasks differs fundamentally from performance in the PRP situation. There is no particular reason to believe this is so, however. Decades ago, Craik (1947) pointed out that apparently continuous tasks may actually be composed of many intermittent decisions. One might still suppose, however, that when any task is carried out repeatedly, it might be "shifted onto autopilot" so that it would no longer interfere with extraneous activities. Pashler and Johnston (1994) looked for such an effect in several hybrid PRP-continuous experiments but found none: A task that had been performed over and over still delayed an unexpected (or expected) secondary task to at least as great an extent as when the first task was performed only singly.

One common finding in studies of continuous performance is that when subjects are instructed to vary the priority they give to different tasks, relatively smooth trade-off functions are found. Sometimes termed *attention operating characteristics* (e.g., Gopher, Brickner, & Navon, 1982; Sperling & Melchner, 1987), these trade-offs are widely assumed to demonstrate plainly that capacity can be allocated in a graded fashion. However, this is not the case. Because the dependent measures involve aggregate performance over many individual responses, smooth trade-off functions are perfectly compatible with performance being limited by a central bottleneck (or multiple bottlenecks). If central stages in each task are subject to a bottleneck, trade-offs may arise simply because the person controls the amount of time during which each task has access to the bottleneck mechanism. This, after all, is how time sharing works on a mainframe digital computer. If "resource sharing" is really time sharing, then capacity-sharing models offer a misleading picture (in the sense that it would be misleading to say that Jane and John share a plumbing resource for a whole day if the plumber spent the morning at Jane's house and the afternoon at John's).

A second area in which continuous tasks may need to be reinterpreted in light of the findings described here is in cases in which dual-task interference has been absent in continuous tasks. This absence has often been seen as rejecting single-channel bottlenecks or other structural limitations (e.g., Allport, Antonis, & Reynolds, 1972; Hirst, Spelke, Reaves, Caharack, & Neisser, 1980). If a central bottleneck is confined to particular mental operations—as argued earlier—continuous tasks may or may not interfere with each other. The reason (as pointed out by Broadbent, 1982) is simply that when two tasks each require a critical central mechanism only intermittently, essentially perfect performance may be achieved in both tasks by appropriate scheduling of the tasks to avoid placing simultaneous demands on this mechanism.

Summary

It has been argued here that the conclusions of PRP studies are fully consistent with the basic findings of a wide range of different kinds of dual-task studies. The assumptions often used in examining continuous tasks are questioned by the results of the more analytic studies described in earlier sections of this review.

Relating Single-Task and Dual-Task Phenomena

The preceding sections have mostly focused on experimental situations in which people carry out two distinct S-R tasks on each trial. I turn now to some interesting experimental situations that nominally involve only a single task but nonetheless provide important clues about the limits on concurrent mental operations. Most theoretical discussions of dual-task interference have excluded these phenomena from consideration (see Keele, 1973, for a notable exception), but any satisfactory account of processing limitations must account for performance in a broad range of different situations.

Flanker Effects

Selective attention studies usually require subjects to focus on one stimulus while attempting to ignore others. In certain cases, the identity of these other stimuli can affect the latency or accuracy of responses to the attended stimulus. One example is the so-called Eriksen task, in which the subject makes a speeded classification response to a centrally presented letter (the target) while trying to ignore some letters that flank the target (flankers). If the flankers are associated with a different response than the one that is appropriate for the central letter, responses to the central letter are typically slowed (B. W. Eriksen & Eriksen, 1974). (The well-known Stroop, 1935, effect, in which irrelevant color-word information slows down naming of the ink color of a stimulus, is another example of such an effect.)

In each of these cases, the interference depends on the response with which the irrelevant stimulus is associated. The usual interpretation is that irrelevant as well as relevant stimuli activate units representing their corresponding responses, and "competition" between these units delays the appropriate response. As Keele (1973) pointed out, this idea is hard to square with the existence of a response selection bottleneck in dual-task performance. If two stimuli can activate their own corresponding responses in parallel in the Eriksen task, why can they not do the same in the dual-task situation?

From the perspective of conventional information retrieval systems, there is indeed a paradox here. This line of thought led Keele (1973) to argue that the PRP effect must be caused by delays in later processes, contradicting the conclusions reached earlier. However, recent investigations of neural networks suggest some possible ways of reconciling the two lines of evidence. Consider, for example, so-called "pattern completion networks" composed of simple units connected with variable strengths. Selection of one response may involve a particular pattern of activity emerging in some subset of the units, whereas selection of a different response involves producing a different pattern in the same units. Putting different inputs into such a network might involve activating different subsets of units. The network could not select two different responses at the same time simply because the output units could not settle into two different states at the same time. On the other hand, different input units could be activated at the same time (in the Eriksen task, the irrelevant input might be attenuated). If the irrelevant input was associated with a different response than the relevant one, it could retard the process of settling into a final output state.

Thus, the idea of a distributed representation provides one possible way to reconcile two conclusions that would otherwise seem to conflict: that inputs cannot activate their own outputs simultaneously and that irrelevant inputs may slow down the selection of a response to a relevant input in a way that depends on the response with which they are associated. Of course, this account is only a post hoc conjecture; it remains to be seen whether it can make any distinctive predictions. One unattractive feature of this explanation is that there is no independent motivation for supposing that different outputs would be represented in the same units and different inputs would be represented in different units. Whatever its merits, this account does illustrate a more general point, however. Processing limitations may reflect the underlying neural circuitry in ways that cannot be understood in terms of conventional information retrieval systems.

Stop Signals and Go Signals

Another situation that may be relevant to the limits of concurrent mental operations is that in which an imperative stimulus is sometimes followed, after a delay, by another signal that informs the subject not to respond to the imperative stimulus (Lappin & Eriksen, 1966). Is deciding not to respond itself a form of response selection (or initiation) process, and is it, too, delayed by the central bottleneck? Logan and Burkell (1986) performed some interesting experiments to address this question. In the stop signal task, a letter was presented, requiring a button push classification response; on some trials, a tone sounded shortly after the letter, alerting the subject to inhibit the response to the letter. Not surprisingly, the likelihood that the subject succeeded in stopping fell as the delay of the tone was increased. In a further variant of this experiment that Logan and Burkell called the change task, the tone alerted the subject not only to inhibit the response to the letter but also to make a button push response using a finger of the other hand (the change response). Logan and Burkell found that the change response was slowed at short letter-tone intervals only on those trials in which the subject failed to inhibit the letter response; otherwise, the latency for the change response was essentially unaffected by the delay between the letter and the tone.

Logan and Burkell (1986) concluded—contrary to the conclusions drawn here—that dual-task delays must therefore be attributable to the production of the letter response rather than to a central bottleneck. Their observations can be accounted for in another way, however: On trials in which the letter response is successfully inhibited, the tone aborts the central processing, and therefore it is not delayed by the completion of that processing. Logan and Burkell's argument hinges on the assumption that central processing in the letter task runs to completion even on those trials in which the tone successfully stops the actual response and substitutes its own response. Other data from Logan's laboratory seem to question this assumption. Logan (1985) had subjects make a speeded classification of some words and analyzed their ability to recognize these words later (to determine whether the word classification judgment had been completed even when no overt response was made). He concluded that a simple stop signal did not abort classification but that a change signal did (when the stimulus disappeared). Zbrodoff and Logan (1986) concluded that a stop signal alone was enough to abort a mental arithmetic task.

In summary, Logan and Burkell's (1986) observations are intriguing, but they do not refute the existence of a central bottleneck; rather, they suggest that central stages may constitute an *interruptible* bottleneck. The notion of an interruptible central bottleneck requires that Stimulus 2 can undergo perceptual analysis while central processing triggered by Stimulus 1 is under way (as argued earlier). This raises various suggestions about performance outside of the laboratory. Take the case of driving and thinking about something else, which most people report that they do frequently. Driving may often consist simply of monitoring external stimuli for certain classes of events (e.g., pedestrians and looming cars). From what has been argued earlier, there is no reason that such a process could not occur along with unrelated central mental operations. It may be quite critical, however, that when a detection occurs, the central operations can be rapidly and completely aborted. Thus, although driving and thinking seem to represent a case of "simultaneous performance" and therefore a challenge to the bottleneck-oriented perspective advocated here, the lack of obvious interference may simply reflect two conclusions already reached: (a) that perceptual monitoring can occur at the same time as central processes and (b) that central processes can be interrupted quickly on the basis of detections made in the course of monitoring the environment.

Another interesting case is a go signal: an accessory stimulus occurring at an unpredictable time after a primary-task stimulus, indicating that a subject should respond to the primary stimulus without delay. Reed (1973) used go signals in a recognition memory primary task and found a growth in accuracy over several seconds. The typical time to respond to the go signal ranged between 200 and 400 ms (Logan & Cowan, 1984). Apparently the go signal does not "flush" the information accruing in the main task, given the accuracy function; however, processing the go signal may still interrupt the memory retrieval process.

General Implications and Theoretical Concepts

The preceding sections have tried to account for the main empirical observations about dual-task interference in simple tasks by means of five basic postulates: (a) a bottleneck encompassing response selection, memory retrieval, and certain other cognitive operations; (b) a limited ability to attain and maintain preparation of different S-R mappings; (c) separate perceptual processing limitations (which are probably modality specific); (d) the existence of only a single mental timer subserving both perception and motor production; and (e) inability to produce certain types of response streams simultaneously. Evidence for graded capacity sharing in central processes has been argued to be weak, although that possibility cannot be foreclosed. Given the complexity of dual-task performance, the most that can be realistically hoped is that these ideas provide a rough first approximation to reality. Rough though they may be, they nonetheless have some broad implications.

The next section describes some of these implications. In the course of that section, three theoretical concepts commonly used in connection with human performance are discussed critically: *attention, automaticity,* and *task similarity* (or cross talk between tasks). These concepts are sometimes assumed to be essential for analyzing human information-processing limits, yet—as the reader may have noticed—they have played almost no role in the discussion thus far. What role is there, if any, for these concepts in analyzing dual-task performance?

Implications Beyond Stimulus-Response Tasks

The discussion thus far has focused heavily on the concept of processing stages in elementary stimulus-response tasks. The concept of processing stages was developed by Donders (see Donders, 1969) in the context of the subtractive method and was subjected to extensive criticism around the turn of the century (Kulpe, 1909). In more recent times, Sternberg (1969) developed important new methods of analyzing processing stages, but since then various authors have expressed skepticism about the validity of these analyses as well (e.g., McClelland, 1979).

It is worth distinguishing different sorts of objections to stages. One objection rests on skepticism that processing stages are truly successive in S-R tasks. The results of PRP tasks described earlier assume that factors have a fairly high degree of selective influence on different processing stages, and the pattern of results discussed in fact adds support to the distinction among perception, response selection, and response execution stages and to the view that certain factors selectively influence these stages. However, the interpretation does not rely on the strict successiveness of stages that was postulated by Sternberg (1969). As Miller (1988) pointed out, one can envision a continuum of information transmission between stages; thus, strictly successive stages pass only a single piece of information at a given instant. The predictions described in Principles 1-4 do not require strict successiveness and might well be compatible with selective influence on processes that normally operate in cascade (McClelland, 1979). (Key predictions depend on the idea that once a stage is completed, factors selectively influencing that stage cannot have any later effects; in a cascade model, this would still be the case if a stage reached its asymptotic output level and then maintained that state for some period of time until following stages began to use that output.) However, recent empirical evidence tends to favor successive stage models over cascade models for classification tasks (Meyer, Yantis, Osman,

& Smith, 1985; Miller, 1988; Roberts & Sternberg, 1993: Sanders, 1990), even though information seems to be continuously accrued within stages such as memory retrieval (Yantis & Meyer, 1988).

A much more global criticism of stage models is that they falsely assume that human mental life is composed of discrete S-R events. This criticism misses the point of analyzing the time course of processing in elementary tasks. Diagrams of the sort shown in Figures 2 and 3, for example, are not models of the mental apparatus but depictions of how particular processes unfold in time when certain demands are imposed on the human information-processing system. Undoubtedly much— maybe most—human behavior outside the laboratory involves much longer sequences of covert events than a typical choice RT task. However, this does not reduce the importance or generality of the mechanisms that may be revealed most clearly in just such impoverished situations.

The way in which the limitations uncovered by studying S-R tasks apply to mental operations under internal control is an area ripe for empirical investigation; unfortunately, it is not easy to study. Cognitive psychologists generally assume that "silent thought" involves sequences of internal operations such as retrieving information from long-term memory, transforming the contents of short-term memory stores, and so forth. Do covert activities of this kind compete for the same mechanisms that produce a bottleneck in discrete S-R tasks? Quincy-Robyn Whipple and Pashler conducted some informal studies using a task requiring repeated silent subtraction of seven from a particular starting number and found that this task interfered dramatically with tasks involving response selection. The subtraction task interfered with perceptual monitoring tasks less markedly; to the degree it did, this may reflect interference with preparation of the two tasks. In summary, the central bottleneck reveals itself most clearly in S-R tasks, but many of the internally triggered operations that constitute covert thought may rely on the same limited-capacity machinery.

Attention

The use of the term *attention* to refer to the supposed source of dual-task performance limits is deeply rooted in both ordinary language and the writing of experimental psychologists (e.g., Baddeley, 1986; James, 1890). The term is most often used to refer to the process of selecting particular stimuli for awareness. The use of a common term for such instances suggests an implicit belief that they reflect different aspects of the same resource or mechanism. The evidence described earlier suggests that the most fundamental dual-task limitation has little to do with capacity limits in perception of stimuli in tasks such as visual search. One might think that this bottleneck mechanism nonetheless controls perceptual selection (even if not perceptual capacity), but recent experiments suggest that this is not the case (Pashler, 1991). In these studies, the subject hears a tone and makes a rapid button push response depending on its pitch. After a variable delay from the onset of the tone (which may be as short as 50 ms), a visual display appears, containing eight letters along with an arrow indicating the item in the display to which attention should be directed (and, later on, reported). If selecting and initiating responses in the tone task involves the same mechanisms as shifting attention as directed by the arrow, accuracy in the visual task should fall dramatically at short SOAs. This did not occur.

If sensory selection and the sort of central processing that produces a bottleneck operate independently, why is the word *attention* used as if it referred to a single resource or mechanism? One possibility is that there is, in fact, a unitary mechanism that is overlooked in experiments such as the one just described. Another possibility is that, because different limited-capacity and selective mechanisms for processing information are typically used in concert, people rather loosely speak as if there were a single substance that underlies both. This issue is a thorny one and leads into metaphysical questions about the unity of consciousness and of the self that are probably best left to philosophers. Empirically, however, "attentional" processes seem to involve various dissociable mechanisms. This is by no means a novel suggestion (e.g., Treisman, 1969), but the results described here provide a more concrete picture of some of these dissociations.

Automaticity

Closely related to the concept of attention is the concept of automaticity: People generally call an activity automatic when they would say it does not require attention. There has been debate about the proper definition of automaticity, but most psychologists define it as entailing that a mental operation must have two properties: proceeding without voluntary control (being obligatory) and not requiring capacity or processing re-.sources. Because there is no point in debating definitions, this one is simply accepted here. Do automatic processes—so defined—actually exist? A number of different lines of evidence have been adduced to show that they do.

One claim commonly made is that perceptual recognition of familiar objects is always automatic. This claim is a tenet of the well-known late-selection theory of attention (Deutsch & Deutsch, 1963), which proposes that even when people try to ignore a familiar stimulus, they identify the stimulus unconsciously and involuntarily. The literature on processing of unattended stimuli cannot be reviewed here except to note that evidence against this claim has been piling up in recent years (e.g., Kahneman & Treisman, 1984; Yantis & Johnston, 1990).

One well-known argument for the automaticity of recognition is based on findings of probe RT studies (e.g., Posner, 1978). Because subjects in such studies (e.g., the experiments of Posner and Boies described earlier) were trying to carry out both letter recognition and the probe task, the results cannot possibly show that recognition proceeds without voluntary control. To do so, one would need a situation in which the subjects have incentives not to recognize the two tasks. The Stroop effect is such a situation, because here people derive no benefit from reading the word. The effect demonstrates, therefore, that people cannot deliberately process only one attribute of an object (such as its color). However, they can often do a relatively good job of shutting out an entire word when they do not have to respond to its color (Kahneman & Treisman, 1984). For the same reason, the conclusion reached earlier—that perceptual processing is not ordinarily subject to the central bottleneck—was based on studies in which people try to perform two tasks concurrently, so it too provides no evidence for automaticity.

Studies of priming often cited to show automatic perceptual processing have essentially the same problem (e.g., Neely, 1977; Posner & Snyder, 1975). In these studies, primes facilitate recognition of later-presented stimuli to which the prime is semantically related, even though the primes are usually unrelated to the stimuli that follow them. However, because these priming effects are not harmful to performance, there is no reason to believe that subjects have any incentive to prevent the priming from taking place. Hence, there is no reason to believe that such effects are automatic. In fact, semantic priming can be markedly affected by what task people perform on the prime (Smith, 1979).

In summary, the claim that recognition of familiar objects is automatic is highly questionable. As Kahneman and Treisman (1984) have pointed out, recognition may nevertheless be partially automatic in the sense that once attention is allocated to an object for any reason, recognition of the object cannot be prevented.

A more general thesis about automaticity—often attributed to Schneider and Shiffrin (1977)—is that any mental operation that has been practiced consistently becomes automatic. The best-known support for this thesis comes from studies in which subjects performed visual and memory search tasks while holding on to a concurrent memory load. When the search task has been consistently practiced, a concurrent memory load sometimes ceases to make much difference. This does not have much bearing on whether central interference goes away with practice, however. As noted earlier, holding on to a memory load probably interferes with concurrent tasks not because it uses the central bottleneck but because it makes it harder to fully prepare for the tasks. The interactions between practice and memory load observed by Logan (1979) are quite compatible with the idea that practice simply reduces these preparatory demands. There is no evidence that practice causes the central interference indexed by the PRP effect to disappear (Gottsdanker & Stelmach, 1971), although this question needs to be investigated more thoroughly. If there is no good reason to believe that practice eliminates central interference, does it at least cause mental operations to show a lack of voluntary control (the other property associated with automaticity)? Here too, the evidence is unconvincing. Many highly practiced behaviors can be readily inhibited even when the appropriate stimulus is presented. For example, Logan (1982) found that highly practiced copy typists could prevent themselves from typing a word when a stop signal was sounded.

In summary, there is no reason to believe that either familiar object recognition in particular or consistently practiced activities in general qualify as automatic. However, no one would deny that having a conversation disrupts a novice driver more than it does an experienced driver, and everyday introspections about automaticity must surely reflect some important changes that occur with practice. Several possibilities should be considered. First, practiced tasks obviously take less time, and this fact by itself is bound to make it less disruptive to switch between performing the task and engaging in other activities (e.g., having a conversation). Momentary interruptions in a train of thought or line of conversation may go undetected so long as one can resume the thought or conversation a fraction of a second later. Second, practice may allow a person to prepare a task much more quickly and with less effort than initially possible (see Logan, 1979). For example, a new driver may need to prepare particular S-R contingencies (e.g., "Brake if there is a red light") individually; after practice, however, the entire ensemble of conditional behaviors that constitute the activity of driving may be "loaded" at the same time, as a consequence of generating the conscious intention to drive. This practice with response sequences may allow a whole sequence to be selected as a unit and then executed without invoking the central bottleneck. Together, these factors may cause one to believe that all sorts of behaviors are automatic when, in fact, they are not. These suggestions are speculative. Regardless of their particular merits, the main point is that in its beguiling simplicity, the idea of automaticity may obscure rather than clarify the effects of practice on performance (and the conscious experience that accompanies it).

Similarity and Cross Talk

The first section of this article described the suggestion that cross talk or similarity may be the crucial determinant of dual-task interference. This view has been offered in connection with more elaborate experimental tasks than the usual PRP task. Two predictions follow naturally from this perspective. First, if cross talk is the sole difficulty in carrying out two tasks at once, one should find that interference is absent when two tasks are sufficiently different. When tasks are similar, interference should appear. Second, manipulations designed to prevent sequential processing (e.g., extreme speed pressure) should produce errors reflecting the occurrence of cross talk.

Most of the PRP studies conducted in the 1960s and 1970s that investigated choice tasks combined tasks that were fairly similar to one another (e.g., moving a bar up or down with each hand depending on which disk was illuminated; Gottsdanker & Way, 1966). However, more recent studies have examined pairs of tasks that seem very dissimilar in terms of stimuli, responses, and the mapping between them. For example, pressing a button depending on the pitch of a tone has no obvious similarity to naming the highest digit in a display (Pashler, 1989, Experiment 3), verbalizing the response element of a set of paired-associate words (Carrier & Pashler, in press), or moving the eye rightward if a central color patch is red and another direction if the patch is green (Pashler, Carrier, & Hoffman, 1993). Similarly, making a foot response to a tone and making a hand response to a letter seem to be dissimilar (Osman & Moore, 1993). In each of these cases, however, hundreds of milliseconds of slowing were observed as the SOA was reduced. Perhaps one could conjure up some purported similarities, but, from a commonsense perspective, these would seem to be about as different as two simple speeded tasks can be. Therefore, it is hard to see how dual-task interference can be attributed to cross talk (or an optional strategy used to prevent it).

But even if cross talk is not a necessary condition for dual-task interference, it still might modulate interference in certain cases. Some studies have shown that similarity can exacerbate interference. Navon and Miller (1987) "intertwined" the semantic content of two tasks and found substantial disruption.

For example, one experiment involved the tasks of searching among a pair of words (presented diagonally) for a boy's name and searching the other diagonal pair for a city name. In the dual-task condition, responses in Task A were slower when the distractor in Task B was a target in Task A (or was semantically associated with it). Hirst and Kalmar (1987) had subjects monitor dichotically presented speech consisting of sequences of words, letters, or numbers on each channel. An example of one of their tasks was verifying that a sequence of letters correctly spelled out a prespecified target word or verifying that each number in a sequence was equal to the previous number plus two. When the same type of task was completed on both channels (e.g., verifying one number sequence on the left and another on the right), subjects performed much worse than when a different task was performed on each channel.

It certainly makes intuitive sense that this sort of task confusability would create problems. These manipulations of similarity may be so extreme, however, that they do not explain much about the role of similarity in more typical cases. Hirst and Kalmar's (1987) task required holding on to the accumulated partial results of each task in short-term memory, and similarity is known to impair short-term memory (Baddeley, 1966). The similar distracters in Navon and Miller's (1987) task may have transformed the task from searching for words of particular categories to the more difficult task of searching for particular category-spatial location conjunctions.

It remains to be demonstrated that variation in similarity of content in two tasks—short of such extremes as those just described—has any effect on how much the two tasks interfere. The data of Pashler and O'Brien (1993), although not collected for that purpose, may provide some clues. In several experiments, S1 was a disk presented either above or below the fixation point to which the subject responded, using fingers of the left hand, by pressing one of two response keys arrayed in a corresponding fashion. In one case, the second task involved making a right-hand response to a disk (identical task); in another, it entailed responding to the identity of a letter, also using the right hand (different task). There was little difference in the extent of interference (PRP effect). At the moment, then, there is no sign that similarity exacerbates dual-task interference except when the subject becomes confused about the task instructions or must rely on limited short-term memory (in which case the similarity manipulation produces retrieval interference). Future work may revise these conclusions, of course.

Conclusions

This review suggests that a focus on relatively simple tasks reveals much about the underlying limitations on people's ability to perform different tasks at the same time. The results show that people have surprisingly severe limitations on their ability to carry out simultaneously certain cognitive processes that seem fairly trivial from a computational standpoint. On the other hand, it is clear that mental operations frequently overlap with each other, for example, people can readily monitor sensory input at the same time that they carry out unrelated central processes such as memory retrieval. Central processes can sometimes be aborted on the basis of the outcome of perceptual analyses. Future research could profitably extend these analyses "upward" and "downward." In the upward direction, much more remains to be learned about how the mechanisms apparent in simple tasks manifest themselves in more complex activities of comprehension, reasoning, and thought. In the downward direction, the challenge is to uncover the physiological bases for the processing limitations seen in simple tasks. Do mental processes produce a bottleneck because they require the activity of a single brain structure or ensemble of structures or because of mutual inhibition, or do they do so for some as-yet-unsuspected reason? The detailed analysis of the time course of processing in dual tasks that has been useful in exploring the sources of interference at a functional level may also prove useful in exploring the relationship between mental events and neural mechanisms.

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