Attentional Limitations in Doing Two Tasks at Once

The Search for Exceptions

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ABSTRACT—***People generally have difficulty doing two tasks at once. To explain this fact, theorists have proposed that central processing—the thought-like stages following perceptual encoding and preceding response processing—takes place for only one task at a time. Because this bottleneck imposes severe limits on human cognitive processes, research has attempted to find exceptions. There is now solid evidence that, at least in the laboratory, the entire bottleneck can be completely bypassed under favorable combinations of circumstances. While these findings provide a ray of hope for enabling parallel multitasking in real-world scenarios, it will not be easy to take advantage of the combination of conditions that appear to be necessary.***

KEYWORDS—*dual-task interference; central bottleneck*

The question of whether humans can perform multiple tasks in parallel has long been practically important for special populations—such as aircraft pilots and air traffic controllers—and has been the subject of considerable psychological research. In recent years, advancing technology has presented a wider segment of the population with multitasking challenges, most notably talking on cell phones while driving. In years to come, further challenges are sure to appear, such as using computerized navigational aids while driving. In addition, complex computerized systems—in everything from nuclear power plants to spaceships—will become increasingly capable of far more multitasking than human operators can easily keep up with.

Although many people believe they can parallel multitask, laboratory studies have, with remarkably few exceptions, found otherwise. Dual-task interference has been found with a wide range of tasks, including very easy ones. These findings led to the theory that central mental processing takes place for only one task at a time (Welford, 1952). This "central bottleneck theory" has important implications both theoretically and practically. Theoretically, the central bottleneck poses a mystery: Why should the human brain, which contains hundreds of subregions capable of working in parallel, act like a serial processor (i.e., a single-processor von Neumann computer)? Practically, the theory predicts that people will have trouble with real-world situations requiring simultaneous performance of multiple tasks (e.g., driving and talking).

In spite of the apparent generality of the central bottleneck, a few studies have reported successful multitasking. It is important to verify such reported exceptions. If true, they might provide a basis for promoting multitasking in the real world—modifying either the technology (through design) or the user (through training). For instance, could one eliminate interference between talking on cell phones and driving by modifying either phones or cars? The present paper discusses recent advances in the search for such exceptions to the central bottleneck and their implications for real-world scenarios.

ASSESSING DUAL-TASK INTERFERENCE

When assessing dual-task behavior, which measure of performance should one emphasize: accuracy or response time? A single-channel bottleneck will frequently cause response delays, but it need not produce any consequences that would count as an error. If you ask someone a question while they are typing a message, they will not necessarily answer the question wrongly or make a typographical error. However, they likely will pause, causing a measurable delay in typing the message.

To measure response-time delays in dual-task situations, laboratory studies have relied heavily on the psychological refractory period (PRP) paradigm. This paradigm requires participants to respond as quickly as possible to two tasks, Task 1 and Task 2, with a variable time between the stimulus onsets—known as the *stimulus onset asynchrony* (or SOA). At long SOAs, in which simultaneous work on both tasks is not required, one

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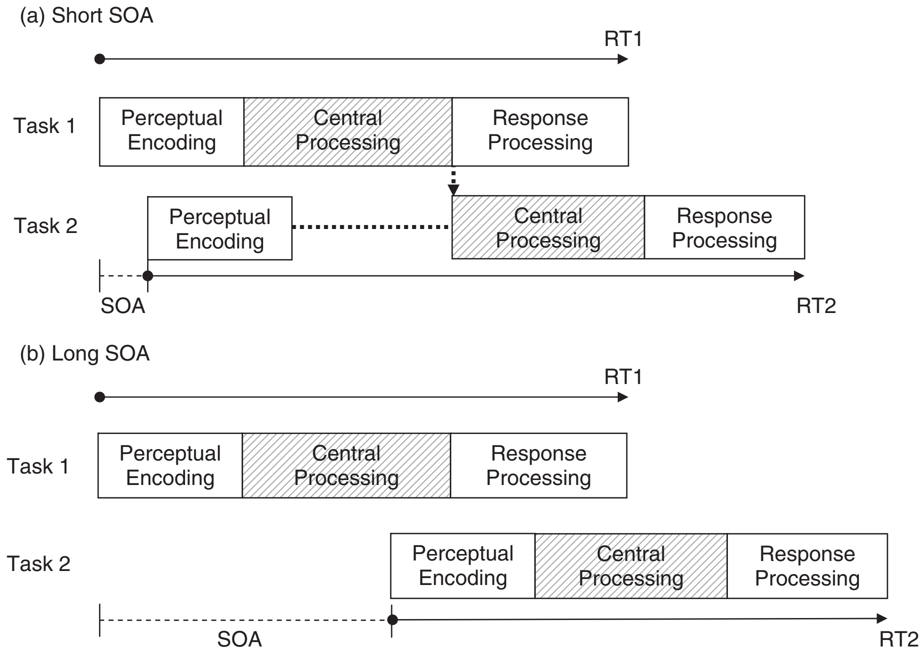

Fig. 1. The central bottleneck model. Task-2 central processing (e.g., response selection, memory retrieval, etc.) does not begin until Task-1 central processing is completed, resulting in a period of cognitive slack (dotted line in diagram a) when there is a short stimulus-onset asynchrony (SOA), but not when there is a long SOA (diagram b). The central stages are shaded. RT1 = response time for Task 1; RT2 = response time for Task 2.

can measure the baseline response time to Task 1 (RT1) and Task 2 (RT2). Using response times obtained at the long SOA as a baseline, one can then measure RT2 slowing at short SOAs, which require the stimuli for both tasks to be processed simultaneously. The ubiquitous result is a pronounced lengthening of RT2 at short SOAs (known as the PRP effect).

There is considerable evidence that PRP effects are due in large part to a central-processing bottleneck (e.g., Pashler, 1992). The key assumption, illustrated in Figure 1, is that Task-2 central processing is delayed until Task-1 central processing has finished. To facilitate intuitive reasoning about the hypothesized bottleneck, Pashler used the analogy of a bank teller who can handle only one customer at a time. If two customers arrive in close succession, the second will experience a "bottleneck delay."

THE SEARCH FOR EXCEPTIONS TO THE CENTRAL BOTTLENECK

To gain insight into why a bottleneck occurs, it is useful to determine when it does not occur. Accordingly, researchers have searched for special conditions, such as high similarity between stimulus and response, having practiced the tasks to a high degree, and the use of special response subsystems (e.g., eye movements), that might allow bottleneck bypassing.

Although this search seems straightforward, a problem is lurking. Tricks to promote bottleneck bypassing do so, in one way or another, by making the tasks easier, which inevitably shortens stage durations. But shortening the Task-1 central-processing stage can dramatically reduce, or even eliminate, the PRP effect without actually bypassing the bottleneck. In the extreme scenario shown in Figure 2, the bottleneck limitation is still present but is "latent"—that is, it has no observable effect on performance (Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003). Van Selst, Ruthruff, and Johnston (1999) estimated that a latent bottleneck can occur with mean RT1s of 200 to 400 milliseconds—just the range of RT1s found in recent efforts to demonstrate bottleneck bypassing.

Failure to appreciate the possibility that a bottleneck may be present but latent has led some researchers to equate the absence of observable bottleneck delays with the absence of the underlying bottleneck limitation. Careless reasoning may be invited by the common intermingling of two different senses of the word "bottleneck": the bottleneck time delay and the underlying bottleneck limitation. As a physical analogy of a bottleneck, consider traffic crossing a one-lane bridge. Spacing out traffic could entirely eliminate bottleneck delays, but would not eliminate the underlying bottleneck limitation: Still only one car can pass at a time.

OVERCOMING ROADBLOCKS TO DIAGNOSING BOTTLENECK BYPASS

So far, it might appear that we have reached an impasse: Trying to bypass the bottleneck by making tasks easier also makes it

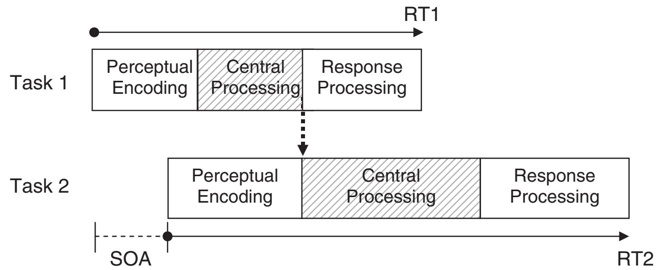

Fig. 2. A latent central bottleneck. When response time for Task 1 (RT1) is very short, Task-1 central processing might finish before Task-2 central processing is ready to begin. If so, a central bottleneck would not delay Task 2, even at a short stimulus onset asynchrony (SOA). (RT2 = response time for Task 2.)

harder to tell whether the bottleneck was in fact bypassed. Fortunately, recent research has shown several ways around this impasse. First, there are a number of supplementary empirical tests (beyond PRP size) for the presence of a bottleneck. For instance, trials that produce longer RT1s should also produce longer RT2 delays, leading to a positive correlation of RT1 and RT2. Also, whereas serial central processing (Task 1 then Task 2) should produce serial responding in the same order, parallel central processing should often produce response reversals (Task 2 then Task 1). These different tools often produce agreement about whether a bottleneck is present or absent.

Recent studies have hit on a different trick. Logically, bypassing the central bottleneck should not require making both tasks easy. If either Task 1 or Task 2 does not require the central-processing mechanism, that should be enough. Making Task 1 easy shortens RT1, which can eliminate interference regardless of whether or not the bottleneck is bypassed. Making Task 2 easy, however, shortens RT2 without inviting a latent bottleneck; as long as RT1 is relatively long, a bottleneck would still produce PRP effects. Thus, a promising strategy is to look for bottleneck bypassing with an easy Task 2 but not an easy Task 1.

APPLYING BOTTLENECK DIAGNOSTICS

Ideomotor Compatibility

Greenwald and Shulman (1973) investigated what they called *ideomotor-compatible* tasks, for which the “stimulus resembles sensory feedback from the response” (p. 70). An example would be responding to an auditory word by speaking the same word (e.g., say “high” when you hear “high”) or moving a joystick in the direction of an arrow. The hope is that such responses can reuse the mental codes used to represent the stimuli, eliminating the need for central processes. Greenwald and Shulman reported eliminating the PRP effect and therefore concluded that ideomotor-compatible tasks bypass the central bottleneck.

This plausible conclusion was widely accepted for decades, but it has recently been challenged (Lien, McCann, Ruthruff, & Proctor, 2005; Lien, Proctor, & Allen, 2002). We (Lien et al., 2005) studied different combinations of ideomotor-compatible tasks and other tasks. PRP delays were substantial when only Task 2 was ideomotor compatible but declined when Task 1 was also ideomotor compatible. This decline, however, was similar to the decline in RT1, just as a bottleneck model would predict. Note that Greenwald and Shulman (1973) did not explicitly consider the latent-bottleneck hypothesis. The data showed several other indications of a bottleneck, including a strong RT1–RT2 correlation. Furthermore, we (Lien et al., 2005) showed that computer simulations of a processing bottleneck could reproduce all the critical data trends.

Although ideomotor-compatible tasks apparently do not generally bypass the bottleneck, certain special cases might. Johnston and Delgado (1993) carried out PRP experiments for which Task 1 was judging whether a tone was high or low pitched and Task 2 was a special analog tracking task—requiring participants to keep a circle (whose position was controlled with a joystick) over a moving stimulus cross. In such a case, virtually no PRP interference was found, supporting the absence of a central bottleneck. The finding of frequent response reversals (Task 2 response before Task 1 response) confirmed this conclusion. Johnston and Delgado proposed that the tracking task had “pre-authorized” joystick responses to occur as needed without the usual central approval. Interestingly, the bottleneck returned when the joystick task was Task 1: Responses to a tone (Task 2) following the cross movement (Task 1) showed large PRP delays.

Practice

Does extensive practice on a task allow it to become “automatized” and thus bypass the central bottleneck? Several studies from the 1970s seemed to support this hypothesis. Spelke, Hirst, and Neisser (1976) found that, after 6 weeks of practice, participants had no difficulty reading stories while accurately transcribing spoken words. In addition, practice was found to dramatically improve search for a target on a screen (Schneider & Shiffrin, 1977). These studies do not, however, prove that practice eliminates dual-task interference. Spelke et al. (1976) focused on accuracy measures, which, as noted earlier, can be insensitive to dual-task interference. The visual-search findings suggest that certain perceptual processes can operate in parallel after practice, but they do not establish that central processes capable of commanding actions can occur in parallel.

A more rigorous assessment of practice effects is possible with the PRP paradigm. Early PRP studies found that practice not only failed to eliminate the bottleneck but barely even reduced its duration. Van Selst et al. (1999) showed that this curious result was an artifact of requiring manual responses in both tasks. With separate response modalities (manual and vocal), practice does reduce bottleneck delays. Other aspects of the data suggested that a residual bottleneck was still present, albeit reduced in size because mean RT1 was so short.

In some cases, practice appears to eliminate the central bottleneck entirely (e.g., Hazeltine, Teague, & Ivry, 2002). Ruthruff, Van Selst, Johnston, and Remington (in press) had participants practice one task alone for 8 sessions and then perform it, along with another task, in a PRP design. They reported several converging indications of bottleneck bypass, at least for a minority of participants. Interestingly, though, bypassing occurred primarily when participants had practiced the easier of the two tasks (a tone judgment) and this task served as Task 2.

Special Response Systems

Almost all of what we know about the central bottleneck comes from tasks with manual or vocal responses. Since the hands and voice are "general-purpose instruments," perhaps those responses are normally controlled by central processes (subject to the bottleneck), whereas narrow-purpose response systems (e.g., the eyes) are not.

Pashler, Carrier, and Hoffman (1993) found that focusing the eyes on an object as Task 2 in a PRP study bypassed the bottleneck. The converging lines of evidence included small PRP effects despite long RT1s, weak RT1–RT2 correlations, and response reversals. Importantly, these results were found without any attempt to make Task 1 easy (i.e., using a Task 1 that produced a bottleneck in previous research).

Eye movements might bypass the bottleneck because they are a quasi-reflexive action, possibly supported by special neural circuitry (bypassing general-purpose central resources). Another possibility, however, is that looking at a stimulus of interest is a highly-practiced action and it is the high practice levels that allowed bottleneck bypassing.

IMPLICATIONS FOR DUAL-TASK THEORY

The studies discussed above suggest three main conclusions with implications for dual-task theory. First, complete bottleneck bypassing, albeit rare, is in fact possible under favorable conditions. It has now been observed with an eye-movement task, a tracking task, and with a highly practiced tone judgment. Why did these particular tasks bypass the bottleneck when others did not? The key might be "preapproval" of the required response. Eye movements, for instance, are at low risk to conflict with other actions and might have "blanket" preapproval; typically, the eyes can track objects of interest without any conscious command to do so. It is plausible that analog tracking would encourage the same mental set. If this hypothesis is correct, training regimens that encourage preapproval of important tasks may improve dual-task performance.

Second, complete bottleneck bypassing is possible even when only one task is easy. Bypassing appears to be more likely with an easy Task 2 than with an easy Task 1. Why? Although automatized tasks do not need central resources, they might "greedily" use those resources anyway, if available (see Lien et al., 2005; Ruthruff et al., in press). Consider two bank customers: A, who must use the human teller; and B, who can use either the teller or the ATM machine. If customer A appears first and occupies the teller, customer B can use the ATM and avoid a bottleneck delay. But if customer B appears first, he or she may "greedily" use the available live teller, delaying customer A who must wait for the teller.

Third, complete bottleneck bypassing is rare. Hundreds of studies have reported the presence of a processing bottleneck, whereas only a handful of studies have reported the absence of a bottleneck. Even with highly-compatible or highly-practiced tasks, processing bottlenecks are often reported. So, for any new situation, the default assumption is that a processing bottleneck will be encountered.

IMPLICATIONS FOR REAL-WORLD SCENARIOS

Given that bottleneck delays are the rule in the laboratory, with simplified tasks and simplified paradigms, they may be the rule in the real world as well. In a driving simulation, Levy, Pashler, and Boer (2006) found that even a task as simple and highly practiced as braking was slowed markedly in dual-task conditions. Tasks like driving and talking on a cell phone might be impossible to fully automatize with practice because they contain many different subtasks and because too much of the processing is nonrecurring—one can hardly expect drivers to have previously encountered every possible scenario. Therefore, reports of substantial interference between these activities (Strayer & Johnston, 2001) will likely generalize widely. Although reported exceptions to the central bottleneck provide a ray of hope, it remains to be seen whether any combination of device design and human training can make multitasking a reliable real-world phenomenon.

DIRECTIONS FOR FURTHER RESEARCH

The present review discussed several well-documented exceptions to the central bottleneck. Further research is needed to determine precisely which conditions are critical for producing these exceptions and whether they can be successfully implemented in real-world scenarios. In particular, more research is needed to determine which forms of practice provide the most reliable path to bypassing the bottleneck. There is also a clear need for research into whether practice enables real-world tasks, which are more complicated than typical laboratory tasks, to bypass the bottleneck.

As the search for exceptions continues, it is important to learn from past mistakes and concentrate research efforts on conditions capable of diagnosing bottleneck bypassing. The studies reviewed above suggest trying to bypass the central bottleneck by making Task 2 easy, but not Task 1. This approach has been shown to facilitate bottleneck bypass while sidestepping the latent-bottleneck problem. It is quite fortunate that bypassing is (apparently) most likely under the very conditions (easy Task 2) in which it is easiest to detect. This may be a case where the keys are, in fact, right under the lamppost.

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