Journal of Experimental Psychology:
Human Perception and Performance
2001, Vol. 27, No. 4, 862-869

0096-1523/01/S5.00 DOI: 10.1037//0096-1523.27.4.862

Is Dual-Task Slowing Instruction Dependent?

Jonathan Levy and Harold Pashler
University of California, San Diego

When 2 tasks must be performed concurrently, each requiring a choice of response, dual-task slowing is typically found. However, E. H. Schumacher et al. (1997) reported that dual-task slowing can be eliminated when equal priority is assigned to each task. Experiment 1 largely confirmed this with the same tasks as Schumacher et al. (tasks using stimulus-response combinations of visual-manual and auditory-vocal pairings). Experiment 2 retained the equal-priority instructions but switched the task pairings (to visual-vocal and auditory-manual); substantial dual-task slowing occurred. Experiment 3 used the same two response sets but only a single stimulus; slowing was again obtained despite equal priority instructions. Equalizing task priority was not sufficient to eliminate interference; relatively unusual cases in which dual-task interference is eliminated seem to depend on task-specific features.

When people concurrently perform two tasks that both require a choice of response, the time taken to complete one or both tasks is typically longer than it is when the same task is performed alone (Welford, 1952, 1980). This dual-task slowing has been observed even with seemingly trivial tasks and even when the stimuli are presented in different sensory modalities (e.g., one visual and one auditory) and the responses are made with different effectors (e.g., hands and voice; see Pashler, 1994, for a review).

A common experimental paradigm used in studies of dual-task performance involves presenting two stimuli in rapid succession that both require an independent speeded response. The time between the onset of the two stimuli *(stimulus onset asynchrony;* SOA) is varied, and subjects are told to respond to each stimulus as quickly and as accurately as possible, often with emphasis on maintaining rapid responses to Task 1. At short SOAs, reaction times (RTs) for Task 2 are usually slower than they are at longer SOAs, with the slope relating RT to SOA sometimes nearing -1. This slowing is usually referred to as the *psychological refractory period* (PRP) *effect* (see Pashler & Johnston, 1998, for a review).

The central bottleneck (CB) theory accounts for dual-task slowing and the PRP effect by proposing that certain mental operations cannot be performed in parallel but instead must be performed one at a time (Welford, 1952). The operations subject to queueing are usually thought to include selection of responses *(stimulus-response translation* in Welford's terms), and more recent work suggests that the limitation also encompasses memory retrieval (Carrier & Pashler, 1995), short-term memory consolidation (Jolicoeur, 1999), manipulation of images (Ruthruff, Miller, & Lachmann, 1995), and perhaps other operations. According to the CB account, when central processing occurs in Task 1, central processing for Task 2 is delayed (see Figure 1). As a result, the shorter the interval between the two stimuli, the longer the Task 2 latencies. Studies in the 1960s and 1970s provided some support for the CB account (for reviews of early work, see Bertelson, 1966; Smith, 1967), and more recent chronometric studies provide what appears to be more definitive evidence involving patterns of interaction between variables targeted to affect different stages in each task (de Jong, 1993; Jolicoeur, 1999; McCann & Johnston, 1992; Pashler & Johnston, 1989).

Some researchers have recently disputed the generality of the CB hypothesis, however (Meyer et al., 1995). These writers suggest that the evidence for central queuing may have arisen because of task instructions that led subjects to give very high priority to one task at the expense of the other. In their view, the Task 2 slowing observed in the previous experiments reflected optional control strategies rather than any structural processing limitation. Meyer and colleagues (Meyer et al., 1995) have offered an alternative model of processing limitations that they call Executive-Process/Interactive Control (EPIC); according to EPIC, it is entirely possible to perform multiple central operations such as response selection and memory retrieval at the same time. However, this capability will not be realized if there are incentives to carry out processing sequentially or if there are peripheral conflicts in perception or response execution. Thus, EPIC makes the prediction that with appropriate instructions, motivation, and choice of tasks, it should be possible to eliminate dual-task slowing. We term this account the instruction dependent hypothesis (IDH).

What might appear to be compelling evidence for the IDH comes from a recent dual-task experiment in which subjects made a keypress response to the location of a disk appearing in one of three locations on a computer monitor and produced a vocal response to the pitch of a computer-generated tone (Schumacher et al., 1997). Subjects were instructed to give equal emphasis to each task, and this instruction was reinforced with financial incentives for fast and accurate performance. By the fifth session, there was no difference in speed and accuracy for trials on which both

Jonathan Levy and Harold Pashler, Department of Psychology, University of California, San Diego.

This research was supported by National Institute of Mental Health Grant R01-MH45584 to Harold Pashler and by a post-doctoral fellowship from the Lady Davis Trust to Jonathan Levy. We thank Valerie Cestone, Kay Chang, Shirli Hamudot, and Holly Nguyen for assistance in data collection.

Correspondence concerning this article should be addressed to Jonathan Levy, who is now at the Faculty of Industrial Engineering and Management, Technion-Israel Institute of Technology, Technion City 32000, Israel, or to Harold Pashler, Department of Psychology, 0109, University of California, San Diego, La Jolla, California 92093. Electronic mail may be sent to jlevy@tx.technion.ac.il or to hpashler@ucsd.edu.

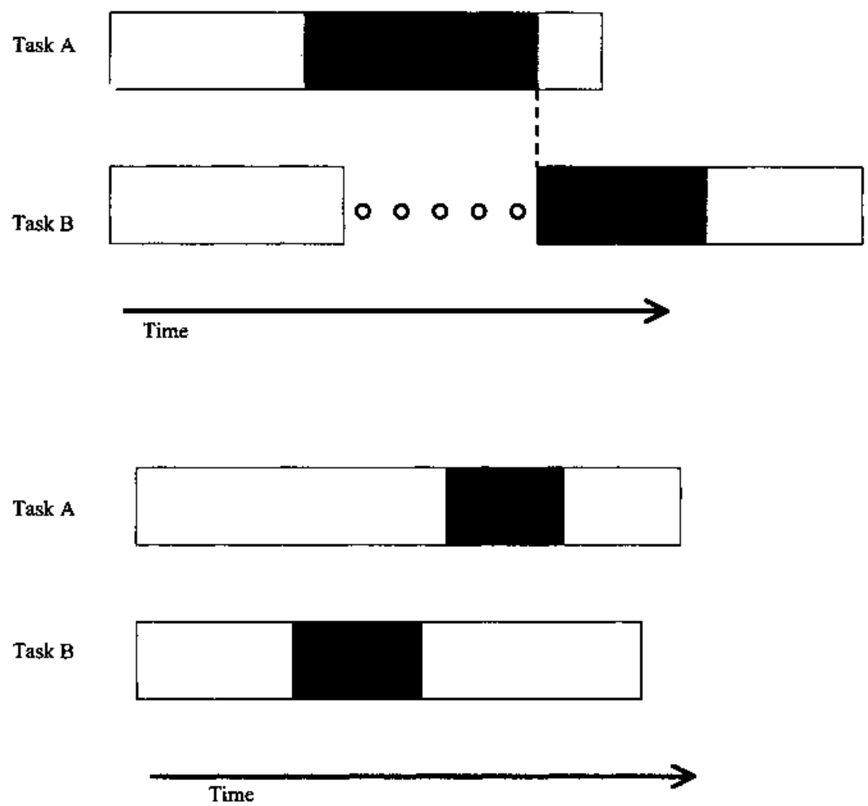

Figure L Hypothesized time course of mental processes (represented by boxes) for two tasks performed with a stimulus onset asynchrony equal to zero. Shaded boxes represent the operations that cannot overlap in time. The top panel shows a case in which this generates slowing; the bottom panel represents a case in which it does not.

stimuli were presented simultaneously compared with trials on which only one stimulus was presented. Schumacher et al. (1997) argued that these data provide clear-cut support for the IDH while refuting the CB hypothesis.

According to the IDH, providing instructions and financial incentives that favor parallel processing and avoiding peripheral conflicts are jointly sufficient conditions for obtaining parallel processing. The present experiments test this contention by examining several variants of the experimental design used by Schumacher et al. (1997). All of the present experiments provided instructions and financial incentives closely modeled after those of Schumacher et al. and retained the features of Schumacher et al.'s design that were intended to prevent peripheral conflicts. Experiment 1 was a close replication of that study except for the number of sessions.[1] Subjects made keypress responses to the location of a visual stimulus and vocal responses to the frequency of an auditory stimulus. Experiment 2 used the same design except that the mapping of input to output modalities for the two tasks was switched: Subjects made keypress responses to the frequency of the tone and vocal responses to the location of the disk. Finally, Experiment 3 required the subject to make two responses to separate attributes of a single stimulus. If instructions are indeed key in permitting dual-task interference to disappear in the situation studied by Schumacher et al., we should find comparable results in all three experiments.

Experiment 1

This study closely mimicked the experiment reported by Schumacher et al. (1997). Each of the two stimuli required its own speeded response. Subjects made a spoken response to the pitch of a tone and a keypress response to the position of a disk. There were four different types of experimental blocks. In each of the two single-stimulus blocks, only one type of stimulus was presented. In the OR block, either stimulus, but not both, was presented. Finally, in the AND block, both stimulus types were presented simultaneously. Subjects were informed at the start of each block as to which type they were about to be presented.

Method

Subjects

Sixteen subjects, recruited without restriction from the University of California, San Diego, subject pool, participated in exchange for partial

[1] As it turned out, it was not necessary to use as many sessions as Schumacher et al. (1997) did to obtain their result. In any case, the question at issue in this article concerns performance prior to any possible automatization of responding, should that occur (proponents of the CB hypothesis have not generally claimed that the bottleneck is immutable over extensive practice, and the role of practice remains an open question; see Van Selst, Ruthruff, & Johnston, 1999).

course credit and earned money on the basis of their performance (see the *Procedure* section).

Equipment

The experiments were run on IBM personal computers. A 60-Hz color monitor (NEC Multisync II or MAE Inndivision) displayed the visual information. A microphone, located in a stand in front of the seated subject, was connected to a voice-activated relay (Model G1341T, Gerbrands Corporation), which in turn was connected to the computer through the parallel port. The experiment was conducted in a sound-attenuated chamber or quiet room.

Stimuli and Responses

Warning stimulus. All trials began with a warning stimulus consisting of three adjacent horizontal white lines, each 2.2 cm in length, displayed in the center of the screen against a blue background. The separation between lines was 1.2 cm. From a typical viewing distance of 60 cm, each line subtended 2.1° visual angle. Stimulus presentation began 501 ms after the onset of the warning stimulus.

Tone stimulus. A computer-generated tone was emitted for 40 ms. The tone frequency was selected at random from one of three values (220, 880, and 3520 Hz) and the subject responded to the tone frequency by saying one of three words *(one, two,* or *three,* respectively).[2]

Disk stimulus. A solid white circular disk (radius of 2.2 cm, subtending 2.1° visual angle) replaced one randomly selected line. The disk and lines remained displayed until the subject pressed one of three adjacent keys using the index, middle, or ring finger of the right hand in response to the location of the circle. The three possible locations and the three response keys were spatially compatible (e.g., the left-most location corresponded to the left-most key).

Design

The sole within-subjects factor was block type. In each of the two single-stimulus blocks, only one type of stimulus (disk or tone) was presented throughout the entire block. In the OR block, a tone or a disk, but not both, was presented. The stimulus type was selected at random on each trial with the restriction that each was presented on half of the trials in the block. In the AND block, both stimuli were presented simultaneously and subjects responded to both. Thus, there were four block types (tone only, disk only, OR, and AND), and each was presented once every four blocks in a fixed order. Four different orders were constructed using a latin square design and were counterbalanced across subjects.

Subjects performed two sessions, each lasting about 1 hr. Session 1 began with practice of one block of each block type and eight trials per block. This was followed by the test session of eight blocks with 48 trials per block. Session 2 contained 12 blocks with 48 trials per block and did not include practice.

Procedure

The instructions followed Schumacher et al. (1997). We instructed the subject to respond as quickly and accurately as possible, and on trials in the AND block, "to respond to both stimuli as quickly and accurately as possible." The financial payoff scheme was also explained (see the following paragraph). The RT(s) was displayed on the monitor for 1,500 ms at the end of each trial, and on error trials a warning *(voice error* and/or *keypress error* in red letters) was also displayed. The next trial began 1,500 ms later.

A payoff schedule was modeled after Schumacher et al. (1997). Subjects earned money on the basis of fast and accurate performance. For each correct response faster than a particular deadline, subjects gained 100 points. For each incorrect response, subjects lost 100 points. Correct responses slower than the deadline resulted in no gain or loss in points. For every 50,000 points,[3] subjects were paid an additional $1. The deadline for each block was set to be the 75th percentile RT of the previous block of the same block type, and this was displayed at the start of each block. The deadline for the first block of each block type in Session 1 was set to 2,000 ms, and the deadline for the first block of each block type in Session 2 was based on the last block of each block type in Session 1. At the end of each block, the monitor displayed the average RT for correct trials, the percent correct, and the current point total. A subject-paced rest period was provided between blocks.

Results

Trials on which any response was incorrect, faster than 150 ms, or slower than 3,000 ms were not included in the RT analyses. The first session was considered practice, and one-way analyses of variance (ANOVAs), with block type as the within-subjects variable, were conducted on the RT and accuracy data for Session 2 only. For pairwise comparisons between the OR and AND block types, we used Fisher's least significant difference (LSD), as recommended by Howell (1997) for good power in comparing three groups without producing alpha inflation. Results are shown in Figure 2.

The mean RTs for the vocal responses to the tone were 595 ms (SE = 23) for the single block, 671 ms (SE = 22) for the OR block, and 676 ms (SE = 30) for the AND block. This difference was significant, $F(2, 30) = 17.85$, $p < .001$, $MSE = 1{,}835$, but there was no significant difference in the pairwise comparison between the OR and AND blocks, $q(2, 30) = 0.47$, $p < .05$, critical $q = 2.89$. The mean accuracy was 93.6% (SE = 1.0) for the single block, 90.7% (SE = 1.7) for the OR block, and 88.6% (SE = 2.0) for the AND block. This difference was significant, $F(2, 30) = 5.48$, $p < .009$, $MSE = 0.0018$, but there was no significant difference in the pairwise comparison between the OR and AND blocks, $q(2, 30) = 1.98$, $p < .05$, critical $q = 2.89$.

The mean RTs for the keypress responses were 323 ms (SE = 8) for the single block, 362 ms (SE = 8) for the OR block, and 465 ms (SE = 24) for the AND block. This difference was significant, $F(2, 30) = 27.40$, $p < .001$, $MSE = 3{,}130$. RTs were significantly slower in the AND block than the OR block, $q(2, 30) = 7.36$, $p < .05$, critical $q = 2.89$. The mean accuracy was 98.5% (SE = 0.3) for the single block, 98.5% (SE = 0.7) for the OR block, and 99.3% (SE = 0.2) for the AND block. This difference was not significant, $F(2, 30) = 1.09$, $p < .349$, $MSE = 0.0003$.

Discussion

This experiment provided a fairly close replication of Schumacher et al. (1997). Subjects made a keypress response to the location of a disk appearing in one of three locations on the computer monitor and a vocal response to a computer-emitted tone presented in one of three frequencies. The stimulus presentation

[2] A research assistant, seated in the experimental room, made a keypress entry for the vocal response using a separate keyboard, thereby allowing on-line scoring.

[3] E. H. Schumacher (personal communication, February 1998) recommended that we use this amount.

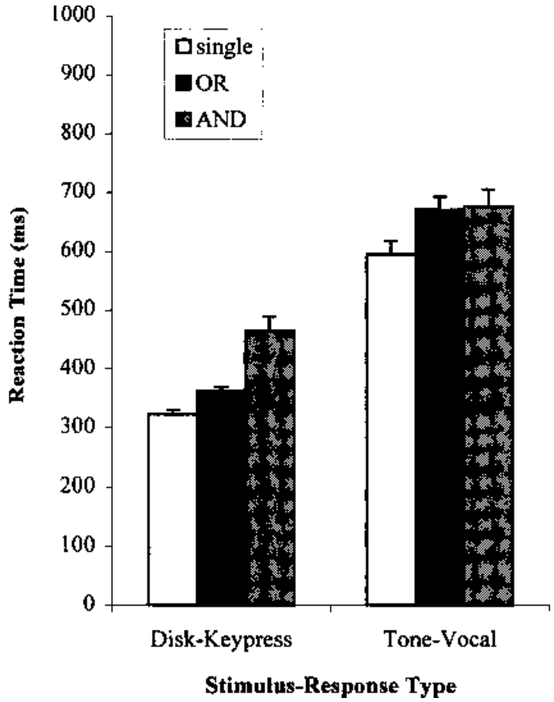

Figure 2. Experiment 1: Mean reaction times for each task as a function of block type.

varied between blocks: disk only, tone only, either (but not both) stimulus, or both stimuli.

The IDH and CB hypothesis make different predictions regarding performance in the OR and AND blocks, so we focused the analysis on these two blocks. In brief, with the IDH, there should be no difference in RTs between these blocks. By contrast, with the CB hypothesis, one would expect responses to be slower in the AND block assuming that the two tasks compete for central processing at the same time (see Figure 1, top panel).

In the tone task, there was no reliable difference between the OR and AND blocks. This is consistent with the IDH and seems incompatible with the CB hypothesis. However, the CB hypothesis entails dual-task slowing for the second performed of two responses if and only if central processing is still engaged in Task 1 when it is needed by Task 2. If central processing for Task 1 was completed by the time it was required for Task 2, then dual-task slowing would not arise (see Figure 1, bottom panel). Thus, the lack of observed slowing here is not an insurmountable problem for the CB model.

Is it plausible that central processing in the two tasks might not overlap in time? Perhaps, for two reasons. First, keypress responses were very fast (indeed, they were the fastest responses in all of the experiments reported here). On average, they were made over 300 ms faster than the vocal ones in the OR blocks and 200 ms faster in the AND blocks. Second, the assignment of responses to stimuli was optimally compatible in several respects (e.g., Wickens, 1984). Not only was the visual stimulus assigned to the manual response, but in addition, the specific stimulus-response mapping was highly compatible (e.g., the left-most position mapped to the left-most keypress). Thus, it seems at least conceivable that central processing for this task might have been completed before it was required for the vocal response.

For the disk task, on the other hand, RTs were significantly slower in the AND compared with the OR block. If this lag reflects dual-task interference, then IDH cannot readily explain it. Whereas dual-task slowing looks, at first glance, consistent with the CB model, the disk task was generally performed faster and one would have to make somewhat peculiar assumptions about stage durations to explain this slowing through the mechanism illustrated in the top panel of Figure 1. The results are consistent with the idea that subjects sometimes adopt a strategy of response grouping whereby two responses are produced close together in time (Borger, 1963; see Pashler & Johnston, 1989, Experiment 2, for a clearcut example of how grouping produced by instruction affects patterns of latencies and factor effects).

In sum, the results provide a reasonably satisfactory replication of Schumacher et al. (1997). The results by themselves neither strongly support nor clearly refute either the IDH or CB theory. Either theory needs some supplementation to explain the entire pattern of results, but it seems only fair to say that CB theory needs more. One might analyze this task combination further in various ways, for example, by introducing variation in SOA or by examining the joint response-time distributions in more detail. Although this would help elucidate what is happening with this task combination, for present purposes, we focused on the most clear-cut and testable prediction of the IDH hypothesis, namely that the instructions encouraging equal priority to the two tasks are sufficient for eliminating dual-task interference (or at least reducing it to the comparatively negligible proportions seen on the slower task used in this study).

Experiment 2

To further examine whether equal-priority instructions are sufficient, we made a slight modification in the experimental design. Experiment 2 was almost identical to Experiment 1, with the same instructions, financial incentives, stimuli, and responses. However, the mapping from input to output modalities in the two tasks was switched, so that a keypress response was made to the tone and a vocal response was made to the disk. On the IDH, there should still be no difference in RTs between the OR and AND blocks (and most specifically, no slowing of the slower task). On the CB model, on the other hand, the switched mapping should increase the likelihood of observing dual-task slowing to the extent that more central processing is required for each task.

Method

All aspects were the same as Experiment 1 except those noted below.

Subjects

Sixteen new subjects were recruited without restriction from the university subject pool.

Stimuli and Responses

The only change was in the mapping of stimuli to responses. Subjects made a keypress response with the right index, middle, or ring fingers in response to a low, medium, or high tone, respectively. They said *one, two,*

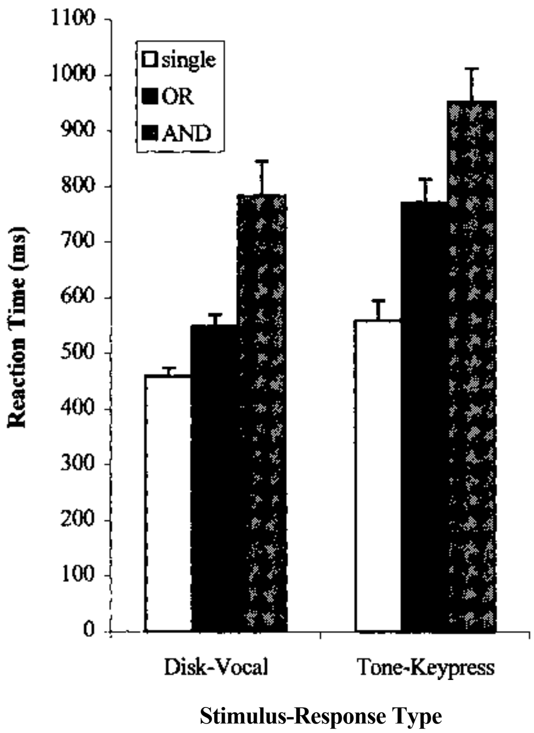

Figure 3. Experiment 2: Mean reaction times for each task as a function of block type.

or *three* in response to a disk in the left, middle, or right position, respectively.

Results

Data were analyzed as in Experiment 1. Results are shown in Figure 3.

The mean RTs of the vocal responses were 459 ms *(SE* =15) for the single block, 548 ms *(SE* = 21) for the OR block, and 783 ms *(SE* — 63) for the AND block. This difference was significant, $F(2, 30) = 29.71$, $p < .001$, *MSE* = 15,032. RTs were significantly slower in the AND block than in the OR block, $q(2, 30) = 7.67$, $p < .05$, critical $q = 2.89$. The average accuracy was 99.1% *(SE* = 0.3) for the single block, 99.2% *(SE* = 0.3) for the OR block, and 96.9% *(SE* = 0.5) for the AND block. This difference was significant, $F(2, 30) = 11.14$, $p < .001$, *MSE* = 0.0002. Accuracy was significantly lower in the AND block than in the OR block, $q(2, 30) = 6.51$, $p < .05$, critical $q = 2.89$.

The mean RTs for the keypress responses were 559 ms *(SE* = 36) for the single block, 772 ms *(SE* = 42) for the OR block, and 953 ms *(SE* = 59) for the AND block. This difference was significant, $F(2, 30) = 78.45$, $p < .001$, *MSE* = 7,958. RTs were significantly slower in the AND block than in the OR block, $q(2, 30) = 8.12$, $p < .05$, critical $q = 2.89$. The average accuracy was 92.8% *(SE* =1.1) for the single block, 89.4% *(SE* = 1.5) for the OR block, and 87.3% *(SE* = 1.8) for the AND block. This difference was significant, $F(2, 30) = 8.79$, $p < .001$, *MSE* = 0.0014. However, there was no significant accuracy difference in the pairwise comparison between the OR and AND blocks, $q(2, 30) = 2.25$, $p < .05$, critical $q = 2.89$.

Discussion

In this experiment, with the same stimuli and responses as Experiment 1 but with the mapping between stimuli and responses switched, RTs for each task were significantly longer in the AND block compared with the OR block. Our impression is that response grouping (holding onto Task 1 response until Task 2 and emitting both as a couplet) was frequent in this experiment, which explains why both responses were slowed (see Pashler & Johnston, 1989, for a chronometric analysis of response grouping). The interference and its magnitude are plainly inconsistent with the IDH.

Experiment 3

Experiment 3 explored another variation of the tasks used in the previous studies. We retained the same instructions, financial incentives, and responses as in the previous experiments, but presented no tone stimulus; instead, the disk was displayed in one of three different colors. Subjects made a keypress response to the color of the disk and a vocal response to its location. We expected the use of a single object to rather neatly eliminate peripheral conflicts in input and/or the need to execute eye movements, possibilities which have sometimes been suggested by proponents of the IDH to explain specific examples of dual-task interference reported in the literature.

Method

All aspects were the same as Experiment 1 except those noted below.

Subjects

Sixteen new subjects were recruited without restriction from the university subject pool.

Stimuli and Responses

On each trial, only one stimulus was presented: a disk. Two attributes of the disk were relevant: color and location.

Color task. Disks appeared in one of three colors (red, yellow, or green) and subjects responded by pressing one of three keys (9, 5, and 1, respectively, on the keyboard's numeric keypad) with the ring, middle, or index finger, respectively, of the right hand.

Location task. The disk could appear in one of three locations; subjects responded by saying *one, two,* or *three* corresponding to the left, middle, or right location, respectively.

Design

We used the same block types as in Experiment 1. However, here we denote block types according to the task the subject was performing rather than the type of stimulus presented (because it was always a disk). There were two single-task blocks. For the location task, a single white disk appeared in a randomly selected location from the set of three used in the previous experiments. For the color task, three disks, all the same color, were simultaneously presented, one in each of the three locations. In the OR block, one or the other of these stimuli was presented, that is, either a single white disk (location task) or three colored disks (color task). In the AND block, a single colored disk appeared in a randomly selected location.

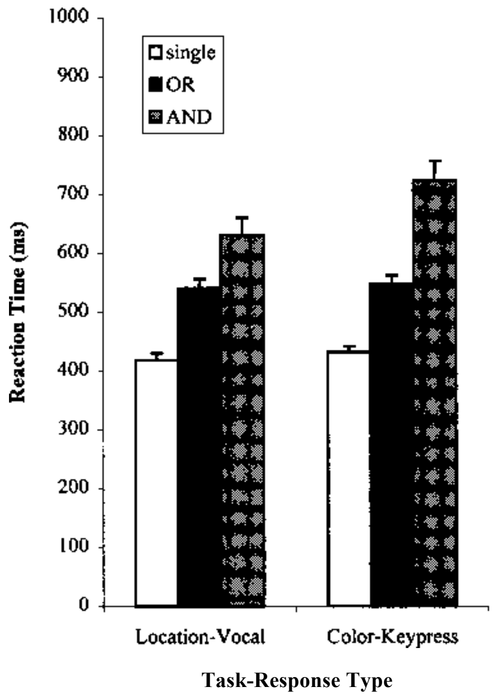

Figure 4. Experiment 3: Mean reaction times for each task as a function of block type.

Results

Data were analyzed as in Experiment 1. Results are shown in Figure 4.

The mean RTs of the vocal responses (for the location task) were 418 ms *(SE* = 12) for the single block, 540 ms *(SE* = 16) for the OR block, and 631 ms *(SE* = 30) for the AND block. This difference was significant, $F(2, 30) = 52.86$, $p < .001$, MSB = 3480. RTs in the AND block were significantly slower than RTs in the OR block, $q(2, 30) = 6.17$, $p < .05$, critical $q = 2.89$. Block type also had a significant effect on accuracy, $F(2, 30) = 9.80$,$p < .001$, $MSE = 0.0005$. The average accuracy was 99.0% correct *(SE* = 0.3) for the single block, 98.4% *(SE* = 0.5) for the OR block, and 95.6% *(SE* = 1.0) for the AND block. Accuracy in the AND block was significantly lower than in the OR block, $q(2, 30) = 5.01$, $p < .05$, critical $q = 2.89$.

The mean RTs for the keypress responses (for the color task) were 432 ms *(SE* = 10) for the single block, 547 ms *(SE* = 16) for the OR block, and 724 ms *(SE* = 34) for the AND block. This difference was significant, $F(2, 30) = 104.45$, $p < .001$, MSE = 3298. RTs in the AND block were significantly slower than RTs in the OR block, $q(2, 30) = 12.33$, $p < .05$, critical $q = 2.89$. The average accuracy was 94.9% *(SE* = 0.8) for the single block, 93.6% *(SE* = 1.1) for the OR block, and 94.0% *(SE* = 0.9) for the AND block. The effect of block type on accuracy was not significant, $F(2, 30) = 1.40$, $p < .26$, $MSE = 0.0006$.

Discussion

In this experiment, subjects made two responses, a vocal one to the disk's location and a keypress to its color. As in Experiment 2, responses were slower in the AND block compared with the OR block for both tasks (location and color). Whereas for the color task there was no significant difference in the accuracy between the two block types, accuracy was lower in the AND block for the location task. These data are inconsistent with the IDH but consistent with the CB hypothesis.

A straightforward comparison between the OR and AND block types for the color task is problematic because of a confound (which is, as far as we can tell, unavoidable). Three disks appeared in the OR block, whereas only one disk appeared in an uncertain location in the AND block. The positional uncertainty of the single disk and/or the smaller amount of displayed color information could conceivably have produced the slower RTs. We therefore ran a control experiment to assess this possibility. Sixteen new subjects performed one session of the color task only. For eight alternating blocks (with the starting block counterbalanced across subjects) with 48 trials per block, either one or three colored disks were presented. Responses to three colored disks were faster (450 ms, *SE=15)* than those to one disk (489 ms, *SE* = 15), $F(1, 15) = 19.70$, $p < .001$, $MSE = 598$, and they were also more accurate *(M* = 95.6%, *SE* = 1.0, and *M* = 93.0%, *SE* = 1.0, respectively), $F(1, 15) = 14.30$, $p < .002$, $MSE = 0.0004$. Thus, the size of the advantage was 39 ms *(SE* = 9). This difference is far smaller than the difference between AND and OR blocks in Experiment 3 (roughly 175 ms), so this confound is not the source of the dual-task interference found in that experiment.[4]

The finding that responses were slower in the AND block compared with the OR block, even when two responses are made to a single object, confirms the observations of Fagot and Pashler (1992), who noted that the PRP effect occurs even when the two tasks involve responding to different attributes of the same object.

General Discussion

Three experiments were designed to test the IDH of dual-task slowing. They all used the same design, instructions, and financial incentives. In Experiment 1, which was a close replication of Schumacher et al. (1997), subjects made keypress responses to the location of disks on a monitor and vocal responses to the frequency of a tone emitted by the computer. Experiment 2 was the same as Experiment 1, except the mapping of stimulus to response modality was switched: Subjects made keypress responses to the tones and vocal responses to the location of the disks. Experiment 3 did not use a tone stimulus but rather disks that appeared in various colors. Subjects made keypress responses to the disk color and vocal responses to the disk location.

The data from Experiment 1 confirmed some of the observations of Schumacher et al. (1997) and seem fairly consistent with the

[4] K. Arnell pointed out that this conclusion requires the assumption that the RT difference between the 1- and 3-disk conditions in the control experiment would not be magnified in Experiment 3. Whereas there are indeed differences between these two experiments (notably in the additional response-preparation requirements found in Experiment 3 but not in the control), it is not readily apparent to us how the RT difference might be magnified (other than when caused by a central bottleneck, of course). We note that the RTs in the 3-disk conditions were very similar in the control experiment (450 ms) and in the single-block condition in Experiment 3 (432 ms). In both cases, response preparation was limited to only one task, not two.

IDH. There was no significant difference between the OR and AND blocks of the vocal response RTs to the tone. However, RTs for the keypress responses to the disk were somewhat slower in the AND block as compared with the OR block. This effect seems troublesome for the IDH, but the results were not wholly supportive of CB, either, in that slowing was more pronounced in the task that elicited faster response times rather than the task that elicited slower response times.[5] The data from Experiments 2 and 3 directly challenge the IDH, however. RTs were substantially slower in the AND block than in the OR block for both vocal and keypress responses.

The contention that dual-task slowing arises only for strategic reasons or as a result of peripheral conflicts seems to be unsustainable in light of these data. The instructions and incentives used in these experiments were very closely modeled after those of Schumacher et al. (1997), and nothing in our procedure can reasonably be said to have encouraged queuing. Likewise, it seems implausible to maintain that there were peripheral conflicts in these designs involving one manual response and one vocal response. In Experiment 2, one input was auditory and one was visual, precluding sensory-level conflicts. In Experiment 3, the stimuli were aspects of the same object; this clearly excludes perceptual conflicts, requirements for eye movements, or other factors sometimes invoked by proponents of the IDH in explaining dual-task interference. The use of a single object also minimizes any possible role of competition for visual attention (Duncan, 1984).

How do these data relate to the central bottleneck theory? The results of Experiments 2 and 3 are plainly in line with what one would expect if the central portion of both tasks cannot be performed simultaneously. What about Experiment 1 (and the data of Schumacher et al., 1997, that were confirmed in their essentials)? As noted above, the CB hypothesis does not entail the notion that whenever any two tasks are combined, there must be a substantial delay in one or both responses. Rather, the CB model claims that central portions of each task cannot occur simultaneously. Even when two stimuli are presented simultaneously, the central demands for each task may or may not be required at overlapping periods of time (see Figure 1, bottom panel). The possibility that they might simply "miss each other" in time becomes particularly real when either or both tasks are very quick. Thus, it seems at least conceivable that central processing for the two tasks may not have overlapped, in which case we would not expect dual-task interference. This account could be tested by varying the SOA systematically using fine gradations.

Another possibility is that whereas relatively arbitrary stimulus-response translation processes are subject to queuing, the comparatively simple response lookup required in the visual-manual task used in Experiment 1, and perhaps any highly practiced stimulus-response translation, might not impose such a requirement. The literature already shows that certain highly compatible stimulus-response mappings are not subject to the bottleneck (e.g., some saccadic eye movements, see Pashler, Carrier, & Hoffman, 1993; shadowing, see McLeod & Posner, 1984) and the same may be true of highly compatible and/or highly practiced visual-manual mappings (see also Greenwald & Shulman, 1973).

Regardless of the explanation for the findings of the first experiment (and those of Schumacher et al., 1997), these results make it clear that relative emphasis on one task over another, or suggestions favoring response ordering, are not necessary for eliciting central dual-task interference, even in simple tasks. This conclusion does not imply that such instructions are irrelevant, of course. The reason most PRP studies have placed an emphasis on the response speed of Task 1 is because when this is not done, many subjects choose to group the two responses (Borger, 1963; Pashler & Johnston, 1989). Although it is conceivable that some subjects interpret these instructions as requiring them to respond in a particular order (even though that is rarely what they are asked to do), the present results show that instructional priority is not a necessary condition for dual-task interference, even in situations free of peripheral conflicts.

[5] This finding is not necessarily inconsistent with the CB model, however. If, on some percentage of trials, the central processing was first engaged for the tone task (even though, on average, RTs were slower for this task), then on these trials, central processing for the disk task would be delayed, resulting in longer RTs. The overall average RT for the disk task would therefore be longer in the AND block than in the OR block.

References

Bertelson, P. (1966). Central intermittency twenty years later. *Quarterly Journal of Experimental Psychology, 18,* 153-163.

Borger, R. (1963). The refractory period and serial choice-reactions. *Quarterly Journal of Experimental Psychology, 15,* 1-12.

Carrier, L. M., & Pashler, H. (1995). Attentional limits in memory retrieval. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 1339-1348.

de Jong, R. (1993). Multiple bottlenecks in overlapping task performance. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 965-980.

Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General, 113,* 501-517.

Fagot, C., & Pashler, H. (1992). Making two responses to a single object: Implications for the central attentional bottleneck. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 1058-1079.

Greenwald, A. G., & Shulman, H. G. (1973). On doing two things at once: II. Elimination of the psychological refractory period effect. *Journal of Experimental Psychology, 101,* 70-76.

Howell, D. C. (1997). *Statistical methods for psychology* (4th ed.). Belmont, CA: Duxbury Press.

Jolicoeur, P. (1999). Concurrent response-selection demands modulate the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1097-1113.

McCann, R. S., & Johnston, J. C. (1992). Locus of the single-channel bottleneck in dual-task interference. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 471-484.

McLeod, P., & Posner, M. I. (1984). Privileged loops from percept to act. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and performance X: Control of language processes* (pp. 55-66). London: Erlbaum.

Meyer, D. E., Kieras, D. E., Lauber, E., Schumacher, E. H., Glass, J., Zurbriggen, E., Gmeindl, L., & Apfelblat, D. (1995). Adaptive executive control: Flexible multiple-task performance without pervasive immutable response-selection bottlenecks. *Acta Psychologica, 90,* 163-190.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 16,* 220-244.

Pashler, H., Carrier, M., & Hoffman, J. (1993). Saccadic eye movements and dual-task interference. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 46A,* 51-82.

Pashler, H., & Johnston, J. C. (1989). Interference between temporally overlapping tasks: Chronometric evidence for central postponement with or without response grouping. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 41 A,* 19-45.

Pashler, H., & Johnston, J. C. (1998). Attentional limitations in dual-task performance. In H. Pashler (Ed.), *Attention* (pp. 155-189). East Essex, UK: Psychology Press.

Ruthruff, E., Miller, J., & Lachmann, T. (1995). Does mental rotation require central mechanisms? *Journal of Experimental Psychology: Human Perception and Performance, 21,* 552-570.

Schumacher, E. H., Seymour, T., Glass, J. M., Lauber, E. J., Kieras, D. E., & Meyer, D. E. (1997, November). *Virtually perfect time sharing in dual-task performance.* Paper presented at the 38th annual meeting of the Psychonomic Society, Philadelphia, PA.

Smith, M. C. (1967). Theories of the psychological refractory period. *Psychological Bulletin, 67,* 202-213.

Van Selst, M., Ruthruff, E., & Johnston, J. C. (1999). Can practice eliminate the psychological refractory period effect? *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1268-1283.

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

Welford, A. T. (1980). The single-channel hypothesis. In A. T. Welford (Ed.), *Reaction times* (pp. 215-252). New York: Academic Press.

Wickens, C. D. (1984). Processing resources in attention, dual task performance, and workload assessment. In R. Parasuraman & R. Davies (Eds.), *Varieties of attention* (pp. 63-102). New York: Academic Press.

Received September 13, 1999
Revision received October 17, 2000
Accepted October 25, 2000 •