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What causes residual dual-task interference after practice?

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Abstract Practice can dramatically reduce dual-task interference, but typically does not eliminate interference entirely. Residual interference after practice is especially large with certain non-preferred modality pairings (e.g., auditory–manual and visual–vocal). Does this residual interference imply the existence of a persistent central-processing bottleneck? To address this question, we transferred participants with previous dual-task practice to a psychological refractory period design. Although we observed residual dual-task costs in all four experiments, there was no evidence for a bottleneck, even with non-preferred modality pairings. We conclude that practice can eliminate the bottleneck limitation, but performance is still subject to other sources of interference, such as competition between central codes of the two tasks.

What causes residual dual-task interference after practice?

Although dual-task interference between novel tasks is generally severe, recent studies have shown that interference can be greatly reduced with practice. It is still unclear, however, whether this reduction reflects a purely quantitative change in performance (shortening stage durations), or a qualitative change (eliminating the central processing bottleneck). The present study tackled this issue by testing for the presence of a bottleneck after

practice. Looking ahead, we find evidence that practice can entirely eliminate the bottleneck, even for non-preferred input/output modality pairings that produce substantial residual dual-task interference.

Background

In the widely used psychological refractory period (PRP) paradigm, the stimulus onset asynchrony (SOA) between two tasks is varied. The typical finding is a dramatic slowing of responses to the second task at short SOAs (high task overlap) compared to long SOAs (low task overlap). To explain this slowing, Welford (1952) proposed the central bottleneck model, shown in Fig. 1. Each task is assumed to comprise three discrete stages: input, central, and output. By hypothesis, the input and output stages of one task can proceed in parallel with any stage on the other task, but central stages proceed on only one task at a time. At short SOAs, the onset of the central stage for the second task will be delayed, resulting in a PRP effect. The central bottleneck model makes several strong predictions that have been confirmed in numerous dual-task studies (for reviews see Lien & Proctor, 2002; Pashler & Johnston, 1998; but see also Navon & Miller, 2002; Tombu & Joliceour, 2002, 2003, for arguments in favor of capacity sharing).

Although a central bottleneck appears to occur with novel, relatively unpracticed tasks, there are several reasons why it might be eliminated with practice. If the bottleneck reflects competition for scarce general-purpose central resources, then practice might produce “jumper cable” pathways directly linking stimuli and responses. If the central bottleneck instead reflects a purely strategic choice (e.g., Meyer & Kieras, 1997a, b), then practice might allow participants to learn to schedule central operations in parallel.

Consistent with this conjecture, Schumacher, Seymour, Glass, Kieras, and Meyer (2001) found negligible dual-task costs after five practice sessions (see also Hazeltine, Teague, & Ivry, 2002). They used a

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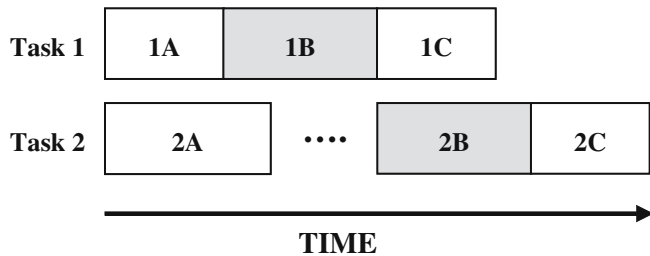


Fig. 1 A generalized bottleneck model. Processing is decomposed into three stages: pre-bottleneck (a), bottleneck (b), and post-bottleneck (c). Stages A and C can proceed in parallel with any stage of the other task. Stage B, however, proceeds on only one task at a time

non-PRP paradigm in which participants performed pure single-task blocks and mixed blocks of single-task trials and dual-task trials. Because only the 0 ms SOA was used on dual-task trials (with equal emphasis on the two tasks), we refer to this as the *simultaneous-presentation paradigm*. They required participants to respond manually to the location of a visual stimulus and respond vocally (“one,” “two,” or “three”) to the pitch of a tone (low, medium, or high).

Levy and Pashler (2001) questioned the conclusion that practice can generally eliminate the bottleneck because Schumacher et al.’s (2001) visual–manual task was unusually easy (see also Tomblu & Jolicoeur, 2004). They also noted that a central bottleneck can exist yet be “latent” (producing little dual-task cost); when the central stage durations of the two tasks are short (as one would expect for easy, well-practiced tasks), they might rarely be demanded at the same time (see also Byrne & Anderson, 2001; Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003). To address these issues, Levy and Pashler compared performance after two practice sessions on the original Schumacher et al. modality pairings (visual–manual and auditory–vocal) and the opposite modality pairings (visual–vocal and auditory–manual). Even though the stimuli and responses were identical in the two cases, dual-task costs were much larger for the original pairings than for the opposite pairings.

Levy and Pashler’s (2001) findings raise the possibility that practice can eliminate the bottleneck for certain preferred modality pairings but not for others. One intriguing possibility is that the auditory–vocal and visual–manual pairings produce more efficient dual-task performance (see Shaffer, 1975; Wickens, Sandry, & Vidulich, 1983) because they share a common representational domain (e.g., sound, space) and are more practiced (e.g., people often reach for visual objects). Henceforth, we refer to these as preferred pairings and to the opposite ones as non-preferred pairings.

It should be noted, however, that Levy and Pashler’s (2001) participants received only two practice sessions. It remains possible that the bottleneck could be eliminated with more extensive practice. Furthermore, the interpretation of the modality pairing effect is unclear. The

original Schumacher et al. (2005) tasks not only involved preferred modality pairings but also had higher stimulus–response compatibility. For example, it would seem much easier to respond to the position of a visual stimulus using a finger in the corresponding position than to say the number of the position.

Hazeltine, Ruthruff, and Remington (2005) addressed these issues by providing extensive practice (16 sessions) and by equating the inherent S–R compatibility for the preferred and non-preferred modality pairings. For the preferred pairings, participants said “one,” “two,” or “three” to low-, medium-, and high-pitched tones and pressed the left, middle, or right response key to indicate whether a visually presented word was a type of bug (e.g., ANT), food (e.g., EGG), or tree (e.g., OAK). For the opposite (non-preferred) pairings, participants pressed the left, middle, or right response key in response to low-, medium-, and high-pitched tones, and said “BUG,” “FOOD,” or “TREE” in response to visually presented words. If modality-pairings are unimportant, there is no obvious reason why it should be more difficult to indicate the relative pitch of a tone with a compatible vocal response than with a compatible manual response or to indicate the category of a word by saying the category name rather than by pressing an arbitrary key. Nevertheless, dual-task costs were much smaller for the preferred modality pairings than for the non-preferred pairings throughout practice (35 vs. 90 ms in the final session; see also Hazeltine & Ruthruff, 2005). Accordingly, Hazeltine et al. concluded that auditory–vocal and visual–manual modality pairings are inherently compatible, allowing more efficient dual-task performance than is possible with visual–vocal and auditory–manual modality pairings.

The present study

The findings of Hazeltine et al. (2005) raise several questions. First, do the substantial residual dual-task costs observed with the less preferred modality pairings imply that practice did not eliminate the bottleneck? For that matter, do the small but non-zero residual dual-task costs observed with the preferred pairings suggest that practice did not eliminate the bottleneck with these pairings either? If the bottleneck was in fact eliminated, what is the source of the residual dual-task costs? The goal of the present research was to answer these questions.

The simultaneous-presentation paradigm of Hazeltine et al. (2005) and Schumacher et al. (2001) was designed to provide optimal conditions for eliminating the central bottleneck. Unfortunately, this paradigm is not well-suited for determining whether the bottleneck actually was eliminated. The use of a single SOA (0-ms SOA) raises the possibility that the bottleneck remained, but had little effect at that particular SOA (was latent). Equal-task emphasis complicates data analysis because

the central processing order cannot be predicted in advance. Equal-task emphasis might also promote response grouping, which means that response time (RT) could be artificially inflated by the time of waiting for the slower response to be selected.

The PRP paradigm, in contrast, provides less optimal conditions for eliminating the bottleneck but is extremely well designed for determining whether the bottleneck was eliminated. Sampling a wide range of SOAs greatly increases the chances of finding an SOA at which a bottleneck would produce dual-task costs. Furthermore, PRP instructions emphasize Task 1 (defined as the task usually presented first), which deters response grouping. These instructions also strongly encourage a particular central processing order (Task 1 then Task 2), making bottleneck presence/absence easier to diagnose.

In the present study, therefore, we transferred the highly-practiced participants from Hazeltine et al. (2005) to a PRP-like paradigm. One obvious concern is that this paradigm would cause a bottleneck to occur where it had previously been eliminated (cf. Schumacher et al. 2001). To assess whether this happened, we also mixed in single-task trials. Thus, we were able to measure dual-task costs in essentially the same way as Hazeltine et al. (dual-task vs. single-task). As will be seen, transfer to the PRP paradigm did not, in fact, increase dual-task costs.

Predictions

The central bottleneck model makes several clear predictions for the present PRP experiments. Because the instructions emphasized rapid performance of Task 1 (the task usually presented first), participants presumably would choose to perform central operations on Task 1 before Task 2. This means that the Task 2 response should usually be emitted after the Task 1 response. Also, dual-task interference should primarily appear on Task 2 and primarily at the shortest SOAs (where central operations are demanded by both tasks at the same time). Because delays in pre-bottleneck or bottleneck stages of Task 1 should in turn delay the bottleneck stage of Task 2 at short SOAs, there should also be a strong positive correlation across trials between the RT to Task 1 (RT1) and the RT to Task 2 (RT2).

Experiment 1

The participants of Experiment 1 had previously performed 17 sessions with the preferred modality pairings in Hazeltine et al. (2005). At this point in training, dual-task costs were small, totaling 30 ms across the two tasks. We transferred them to a PRP paradigm using the exact same tasks. They were told to prioritize Task 1 (auditory–vocal, or AV) because this task would usually be presented before Task 2 (visual–manual, or VM). In addition to the standard PRP trials, we also mixed in

single-task trials. We computed both the PRP effect (the effect of SOA on dual-task trials) and the dual-single effect (as in Hazeltine et al.).

Method

Participants Seven students (three male) from community colleges in the Mountain View, California area were paid to participate in a single session. All were right-handed, between the ages of 18 and 25.

Stimuli Each tone was presented for 300 ms at 220, 880, or 3520 Hz. The word, presented in white against a black background, remained until a response was made. It subtended 1.4° horizontally by 1.9° vertically. There were four bug words (ANT, FLEA, APHID, BEETLE), four food words (EGG, SOUP, CANDY, COOKIE), and four tree words (OAK, PINE, CEDAR, SPRUCE).

Procedure Participants responded to the 220, 880, and 3,520 Hz tones by saying “one,” “two,” and “three”, respectively, and they responded to bug, food, and tree words by pressing the J, K, and L keys. In each session, they completed 15 blocks of 60 trials each (plus three warm-up trials). The first three blocks were not analyzed. Each block contained 36 dual-task trials, 12 single-task trials for the AV tasks, and 12 single-task trials for the VM task (randomly intermixed).

Participants were asked to respond quickly and accurately to both tasks, giving special emphasis to the AV task (Task 1); they were warned against delaying their vocal response to the tone until their manual response to the word was also ready. Following Hazeltine et al. (2005), participants were also told that they would receive a monetary bonus if they responded quickly and accurately to both tasks. Bonuses were based on single-task performance only. One cent was added for each correct response, 5 cents were deducted for each error. The bonus incremented when the mean RT for a block was less than that participant’s previous best (50 cents), within 50 ms (25 cents) or within 100 ms (10 cents). The bonus averaged about \$5 per session.

Dual-task trials began with the presentation of a fixation cross for 500 ms, followed by a blank field for 300 ms, followed by the tone and the word. The SOA between the tone and word was randomly selected from the set {−50, 50, 250, 800 ms}, with the restriction that each SOA occur equally often within each condition. The event timing was the same for single-task trials, except that one stimulus or the other was omitted. If an error was made, an error message (2 s) indicated on which task the error was made. The next trial began 500 ms later. Participants received performance feedback (RT, percent correct, and monetary bonus) after each block.

Analyses Trials were excluded if either response was incorrect or if either RT fell outside the cutoff values

(150 and 2,000 ms) or was more than 2.5 standard deviations from the mean for that condition (~3% of trials in each experiment). One ANOVA compared single-task and dual-task performance at the shortest SOA only. Another ANOVA compared performance across SOAs in the dual-task condition (to measure PRP effects). A related ANOVA compared just the shortest (-50 ms) and longest (800 ms) SOAs, to provide a more sensitive test for SOA effects.

Results

Figure 2 shows mean RT1 and RT2 as a function of SOA. The data points on the far right side of the graph show single-task RT. Table 1 shows error proportions.

Task 1 RT There was a significant dual-single effect (measured using the 0-ms SOA only) on mean RT1 of 7 ms (dual 291 ms; single 284 ms), $F(1, 6) = 11.4$, $MSE = 26.8$, $P < 0.05$. There was also a significant PRP effect on mean RT1 of 10 ms (short SOA 291 ms; long SOA 281 ms), $F(1, 6) = 7.3$, $MSE = 47.2$, $P < 0.05$.

Task 2 RT There was a marginally significant dual-single effect on mean RT2 of 24 ms (dual 470 ms; single 445 ms), $F(1, 6) = 5.82$, $MSE = 602.0$, $P = 0.052$. The PRP effect on mean RT2 was 19 ms (short SOA 469 ms; long SOA 450 ms); it was not significant overall, $F(3, 18) = 1.65$, $MSE = 329.8$, $P > 0.2$, or when comparing just the two extreme SOAs, $F(1, 6) = 1.83$, $MSE = 746.0$, $P > 0.2$.

RT1/RT2 relationship When performance is limited by a central bottleneck, any delay in the completion of the Task-1 central stage will in turn delay the Task-2 central stage by an equal amount. Thus, one distinctive sign of a bottleneck is a strong dependency between RT1 and

RT2 across trials. To assess this relationship in the current experiment, we first sorted dual-task trials for each participant and each condition into five bins according to RT1 (see Pashler, Carrier, & Hoffman, 1993). We then calculated, for each SOA, the slope relating RT2 to RT1 across the five bins. The results are shown in Fig. 3. Although RT1 and RT2 were positively correlated ($P < 0.05$), the slopes were only 0.23 and 0.12 at the shortest SOAs. Thus, for every 100 ms increase in RT1, less than 25% carried over onto RT2. As we discuss later, previous PRP studies have typically shown slopes of 0.5–1.0, even with mean RTs as short as ours.

Discussion

The small dual-task costs (a total of 31 ms across the two tasks at the -50 ms SOA) closely replicated the findings of Hazeltine et al. (2005). One difference, however, is that most of this cost was borne by Task 2 in the present experiment, whereas costs were divided evenly across tasks in Hazeltine et al. This difference presumably reflects the emphasis on Task 1 in the present experiment.

The critical question was whether we would find any evidence of a bottleneck. The PRP effect on RT2 (19 ms) was weak. Furthermore, the slope relating RT2 to RT1 across trials was only 0.23 and 0.11 at the -50 and 50 ms SOAs, respectively. Thus, we obtained no evidence of a central bottleneck.

Experiment 2

Although Experiment 1 provided no evidence of a central bottleneck, it did not provide strong evidence against a bottleneck either. When the Task-1 central stage is completed very quickly (as was the case in Experiment 1, with mean RT1 of only 285 ms), this stage would not necessarily cause a noticeable delay in the Task-2 central stage (see Ruthruff et al., 2003). The obvious solution to this problem is to present the tasks in the opposite order, so that the much slower VM task ($M = 451$ ms) would serve as Task 1. Because the Task-1 central stage take more time to complete with this task order, the PRP effect should be much larger (by 100+ ms; see Van Selst, Ruthruff, and Johnston 1999 for discussion of the PRP/RT1 relationship). Experiment 2 tested this prediction.

Method

The participants were the same as those of Experiment 1, except that one participant was unavailable. The instructions still emphasized Task 1, which was now the

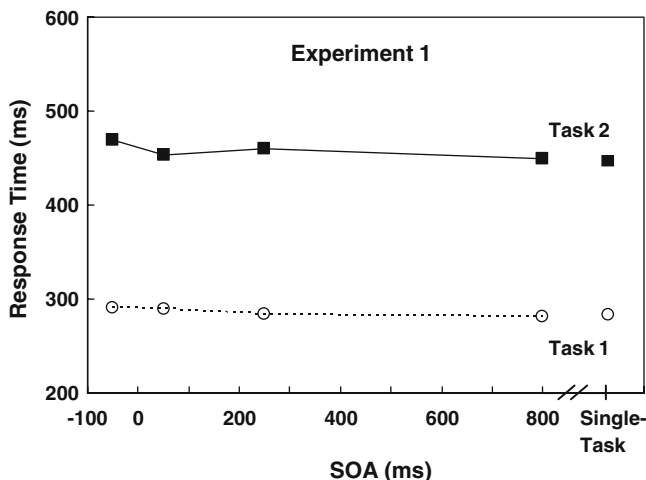


Fig. 2 Experiment 1: mean response time to Task 1 and Task 2 as a function of the stimulus onset asynchrony (SOA)

Table 1 Proportion of Errors as a Function of Task Type, SOA, and the Number of Tasks (Dual vs. Single) in Experiments 1 to 4

	Single Task	Dual Task				
		SOA -50	SOA 50	SOA 150	SOA 250	SOA 800
Experiment 1						
Task 1	0.039	0.032	0.019	–	0.030	0.028
Task 2	0.059	0.046	0.043	–	0.040	0.051
Experiment 2						
Task 1	0.039	–	0.071	0.049	0.065	0.061
Task 2	0.029	–	0.016	0.042	0.049	0.032
Experiment 3						
Task 1	0.018	0.017	0.027	–	0.027	0.027
Task 2	0.036	0.084	0.056	–	0.054	0.036
Experiment 4						
Task 1	0.034	–	0.044	0.065	0.057	0.112
Task 2	0.018	–	0.014	0.041	0.045	0.039

VM (words) task, rather than the AV (tones) task. The SOAs were 50, 150, 250, and 800 ms. We chose a shortest SOA of 50 ms, so that the event timing would be identical to that of the shortest SOA in Experiment 1.

Results

Figure 4 shows mean RTs and Table 1 shows error proportions.

Task 1 RT The dual–single effect was -4 ms (dual 436 ms; single 432 ms), $F(1, 5) < 1$. The PRP effect on RT1 was -2 ms (short SOA 432 ms; long SOA 434 ms), $F(1, 5) < 1$.

Task 2 RT The dual–single effect on RT2 was a non-significant 15 ms (dual 313 ms; single 298 ms), $F(1, 5) = 2.37$, $MSE = 507.3$, $P = 0.18$. The PRP effect on RT2 was actually negative 23 ms (short SOA 313 ms; long SOA 336 ms); it was not significant overall, F

(3, 15) = 1.67, $MSE = 663.0$, $P > 0.2$, or comparing just the two extreme SOAs, $F(1, 5) = 1.34$, $MSE = 1161.3$, $P > 0.2$.

RT1/RT2 relationship Once again, the relationship between RT1 and RT2 across trials was weak, producing a slope of 0.22 at the 50 ms SOA and 0.15 at the 150 ms SOA (see Fig. 3). Even more importantly, the relationship was no stronger at the short SOAs than at the long SOAs.

Discussion

Experiment 2 provided no evidence of a central bottleneck. Given the relatively long mean RT1 (436 ms), a central bottleneck should have produced a relatively large PRP effect (100–200 ms). Instead, the PRP effect was negligible. In addition, the slope relating RT2 to RT1 across trials was once again quite weak at short

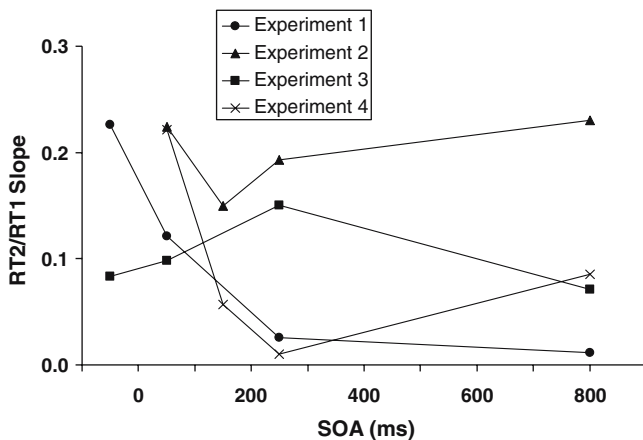


Fig. 3 Slope relating response time to Task 2 (RT2) and Task 1 (RT1) as a function of the stimulus onset asynchrony (SOA) for each experiment

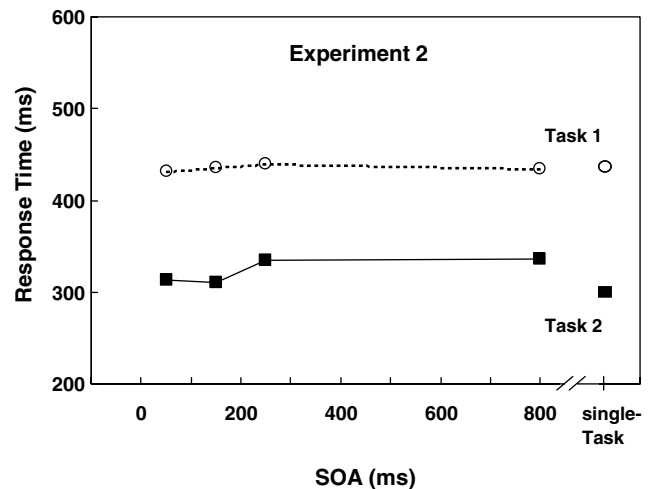


Fig. 4 Experiment 2: mean response time to Task 1 and Task 2 as a function of the stimulus onset asynchrony (SOA)

SOAs. Furthermore, participants often responded to Task 2 well before Task 1 at the shortest SOA (50 ms). Thus, it is clear that any Task-1 emphasis was accomplished without actually postponing central operations on Task 2.

To explain responses to Task 2 before Task 1 at the shortest SOA, one could propose that participants set themselves to perform central operations on Task 2 before Task 1. If so, delays in Task-1 central stages should produce a PRP effect on Task 1. Contrary to this hypothesis, there was no hint of Task-1 slowing at any SOA.

Experiment 3

Hazeltine et al. (2005) found much larger dual-task costs when participants performed non-preferred modality pairings (auditory-manual and visual-vocal) rather than preferred modality pairings (auditory-vocal and visual-manual). One simple explanation is that a central bottleneck limited performance with the non-preferred pairings (despite extensive practice), but not with the preferred pairings. To test this hypothesis, Experiments 3 and 4 transferred participants who had practiced the non-preferred modality pairings in Hazeltine et al. to a PRP-like design. Experiment 3 presented the auditory-manual (AM) task as Task 1 and the visual-vocal (VV) task as Task 2; Experiment 4 used the opposite task order.

Method

Except where noted, the methods were identical to those of Experiment 1.

Participants The four participants (two male) had practiced the non-preferred modality pairings in experiments reported by Hazeltine et al. (2005).

Procedure Participants responded to the 220, 880, and 3,520 Hz tones by pressing the 'J', 'K', and 'L' keys, respectively, (the AM task) and responded to bug, food, and tree words by saying "bug," "food," or "tree" (the VV task). Special emphasis was placed on responding quickly to the AM task (Task 1). As in Experiment 1, the SOAs were -50, 50, 250, and 800 ms.

Results

Figure 5 shows mean RTs and Table 1 shows error proportions.

Task 1 RT There was a significant dual-single effect on mean RT1 of 46 ms (dual 463 ms; single 417 ms), $F(1, 3) = 10.78$, $MSE = 632.3$, $P < 0.05$. There was a non-significant PRP effect on mean RT1 of 43 ms (short SOA

463; long SOA 420 ms), $F(1, 3) = 12.79$, $MSE = 298.0$, $P > 0.05$.

Task 2 RT There was a significant dual-single effect on RT2 of 51 ms (dual 476 ms; single 425 ms), $F(1, 3) = 20.9$, $MSE = 390.0$, $P < 0.05$. The PRP effect on Task 2 was only 8 ms (short SOA 476 ms; long SOA 468 ms); it was not significant overall, $F(3, 9) < 1$, or comparing just the two extreme SOAs, $F(1, 3) < 1$.

RT1/RT2 relationship Once again, the relationship between RT1 and RT2 across trials was very weak (see Fig. 3). The slope relating RT2 to RT1 was only 0.09 at the -50 ms SOA and 0.10 at the 50 ms SOA. These slopes are no steeper than those observed with the preferred modality pairings.

Discussion

The total dual-single effect observed with the non-preferred modality pairings was 92 ms, similar to that found by Hazeltine et al. (2005). This cost is three times as large as the cost observed with the preferred modality pairings (Experiments 1 and 2). Although the residual interference was substantial, the data indicate that it was not due to a central bottleneck. The PRP effect (8 ms) on Task 2 was much smaller than one would expect given that RT1 was relatively long (428 ms). Furthermore, we found a very weak relationship between RT1 and RT2 at the short SOAs.

Experiment 4

Experiment 4 was designed to replicate Experiment 3 with the opposite task order (VV as Task 1 and AM as Task 2).

Method

Participants were the same as those in Experiment 3. They were instructed to prioritize the VV task (Task 1). As in Experiment 2, the SOAs were 50, 150, 250, and 800 ms.

Discussion

Figures 6, 7 shows mean RTs and Table 1 shows error proportions.

Task 1 RT There was a marginally significant dual-single effect on mean RT1 of 24 ms (dual 460 ms; single 436 ms), $F(1, 3) = 6.07$, $MSE = 299.6$, $P = 0.09$. There was a non-significant PRP effect on mean RT1 of 17 ms (short SOA 460 ms; long SOA 443 ms), $F(1, 3) < 1$.

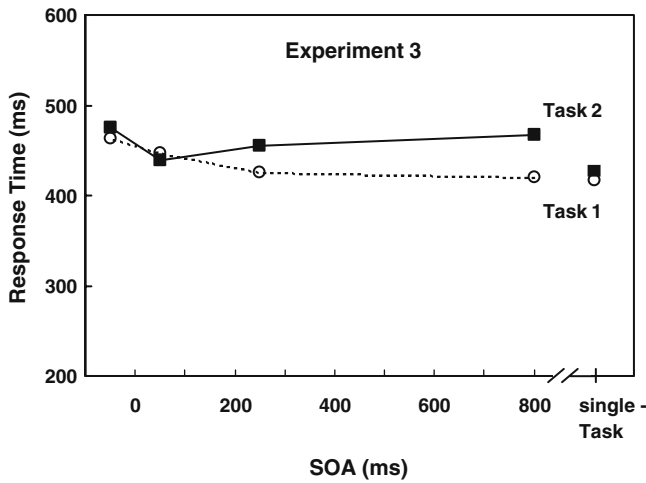


Fig. 5 Experiment 3: mean response time to Task 1 and Task 2 as a function of the stimulus onset asynchrony (SOA)

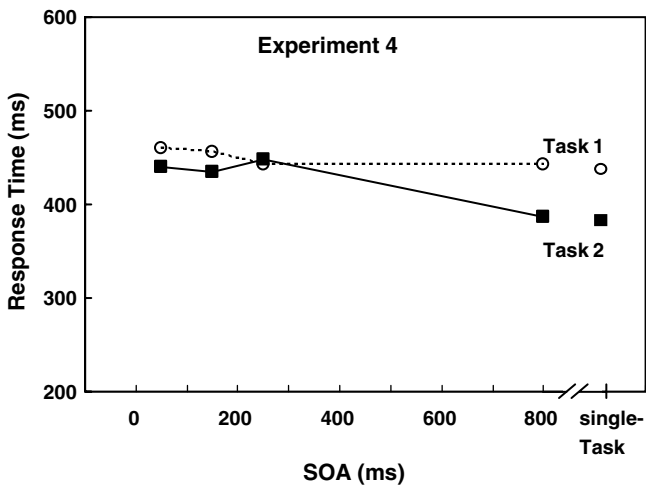


Fig. 6 Experiment 4: mean response time to Task 1 and Task 2 as a function of the stimulus onset asynchrony (SOA)

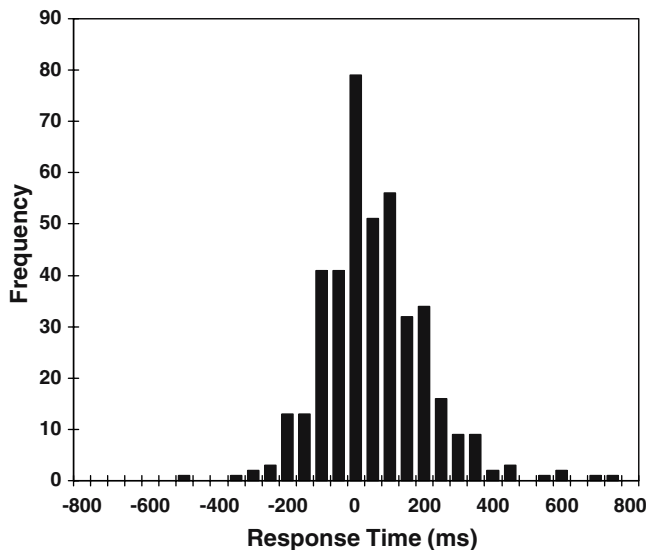


Fig. 7 Inter-response-intervals in Experiment 4 (SOA = 50 ms)

Task 2 RT There was a marginally significant dual-single effect on RT2 of 56 ms (440 vs. 384 ms), $F(1, 3) = 7.76$, $MSE = 1298.1$, $P = 0.069$. The PRP effect on Task 2 was 54 ms (440 vs. 386 ms); it was not significant overall, $F(3, 9) = 2.73$, $MSE = 1149.0$, $P > 0.2$, or comparing just the two extreme SOAs, $F(1, 3) = 2.04$, $MSE = 2875.6$, $P > 0.2$.

RT1/RT2 relationship As shown in Fig. 3, the relationship between RT1 and RT2 across trials was once again very weak, even at the shortest SOA (slope = 0.22).

Discussion

The total dual-task cost at the shortest SOA was 80 ms, similar to that found in Experiment 3. Despite these dual-task costs, the data once again provided no evidence of a residual central bottleneck. There was essentially no decrease in RT2 across the three shortest SOAs. Furthermore, the relationship between RT2 and RT1 at the shortest SOA was weak.

General discussion

Previous studies have demonstrated that practice reduces, but usually does not eliminate, dual-task interference. Hazeltine et al. (2005) found especially large residual dual-task costs with certain non-preferred pairings of input and output modalities (e.g., auditory-manual and visual-vocal). The present study investigated whether these costs are due to a residual central bottleneck by transferring the highly-practiced participants of Hazeltine et al. to a PRP design. Each group performed two PRP experiments, one for each possible task order.

Was the bottleneck eliminated?

We failed to confirm the main bottleneck-model predictions in any of the four experiments. First, we failed to observe large PRP effects. Even with mean RTs longer than 400 ms (Experiments 3 and 4), PRP effects across the first few SOAs were virtually non-existent. With such long RTs, it is unlikely that a central bottleneck could exist without producing large costs at some of the SOAs. Also, when we did observe non-zero PRP effects, they were often found even at relatively long SOAs (e.g., 250 ms), where central stages would rarely be demanded simultaneously. This finding suggests that the observed costs were not due to serial access to a scarce central resource.

We also failed to confirm the bottleneck model prediction of a strong relationship between RT1 and RT2 across trials at short SOAs. The slope relating RT2 to

RT1 at short SOAs averaged 0.16. In contrast, Lien, McCann, Ruthruff, and Proctor (2005) reported slopes of about 0.5 in several experiments with unpracticed but easy tasks that produced mean RTs and standard deviations similar to those of the present experiments (see also Pashler, Carrier, & Hoffman, 1993, Experiment 5); furthermore, quantitative simulations showed that, under these conditions, slopes of about 0.5 were consistent with a processing bottleneck. Furthermore the slopes relating RT1 and RT2 in the present experiments were no steeper at short SOAs than at long SOAs. Thus, the observed RT1/RT2 relationships could be due to trial-to-trial variations in general alertness rather than competition for central resources.

We also failed to confirm the bottleneck model prediction that participants would consistently respond to Task 1 before Task 2. At short SOAs, participants often responded in the other order (Task 2 before Task 1) by as much as 100–200 ms (see Experiment 2). To explain these response order reversals, one could add the assumption that participants performed central processes on a first-come, first-serve basis. If so, the two processing orders should produce two distinct patterns of inter-response intervals (Task 1 well before Task 2, or Task 2 well before Task 1). However, none of the experiments showed this pattern; Fig. 6, for example, shows a unimodal IRI distribution at the 50 ms SOA in Experiment 4. Furthermore, this hypothesis predicts substantial dual-task costs on one or both tasks, contrary to our observations.¹

In summary, the present findings provide no evidence for a central bottleneck. We conclude that practice can eliminate the bottleneck, even for less preferred modality pairings. Contrary to common belief, compelling evidence for the elimination of the bottleneck is quite rare (even in studies that provide extensive practice). Although several previous dual-task practice studies reported small dual-task costs after practice, they used relatively easy tasks (producing RTs less than 300 ms) and tested only a single SOA (0 ms). Therefore, it is difficult to determine whether the bottleneck limitation was eliminated, or whether it persisted but produced little dual-task interference (because the brief central stages were rarely demanded simultaneously).

¹If central stages shrink to negligible durations and are handled first-come, first-serve, with negligible switch costs, then a bottleneck limitation would produce no detectable interference between tasks. Such a model, however could never be ruled out and therefore has little scientific value. Moreover, the usual conception of a programmable central resource or a supervisory process does not naturally predict very short central stage durations. These short central stage durations are especially implausible when, as in Experiments 3 and 4, the mean RT is over 400 ms on an average (and over 500 ms on a substantial proportion of trials)

Relation to previous studies

The present findings contradict those of Schumacher et al. (2001), who observed large PRP effects (~175 ms) when participants were transferred from the simultaneous-presentation paradigm to a PRP paradigm. The key might be that Schumacher et al. told participants to never respond to Task 2 before Task 1 and deducted bonus money whenever it happened. Perhaps these strong priority instructions promoted a voluntary bottleneck (a conclusion endorsed by Schumacher et al.), whereas our more subtle priority instructions did not. Also note that participants in the present study received more practice than those in the Schumacher study.

The present experiments also seem to contradict Van Selst, Ruthruff, and Johnston's (1999) finding that 36 PRP practice sessions did not eliminate the bottleneck. Perhaps practice in the PRP paradigm (with Task-1 emphasis) does not promote automatization as readily as practice in the simultaneous-presentation paradigm (with equal emphasis on both tasks). Another possibility is that the visual task used by Van Selst et al. (which mapped a subset of alphanumeric characters incompatibly onto responses) was more difficult than the present visual task.

How did participants eliminate the bottleneck?

Dual-task studies with low practice levels have not revealed evidence for bottleneck elimination, even with preferred modality-pairings and other favorable conditions (e.g., Ruthruff, Pashler, & Hazeltine, 2003; Ruthruff, Pashler, & Klaassen, 2001). It appears, therefore, that practice is critical for eliminating the bottleneck.

Recent practice studies have provided a few clues as to how practice sometimes eliminates the bottleneck. Ruthruff, Van Selst, Johnston, and Remington (2005) found that some PRP participants eliminated the bottleneck following eight single-task practice sessions on an auditory–vocal task (similar to the present auditory–vocal task). They concluded, therefore, that this task was automatized with practice (i.e., could be carried out without central resources). This automatization hypothesis is also supported by follow-ups to the present PRP experiments (using the same participants) in which we paired one of the highly-practiced tasks with a new task. The bottleneck remained absent when we paired the old auditory–vocal task with an entirely new visual–manual task. However, the bottleneck returned (as evidenced by large PRP effects and a strong RT1/RT2 relationship) when we paired the old visual–manual task with a new auditory vocal task. These findings suggest that the auditory–vocal task (but not the visual–manual task) was automatized and therefore did not compete for central resources with any other task.

The mechanism by which practice automatizes tasks is not yet known. As a working hypothesis, however, we

propose that each performance of a task strengthens the association between the stimulus category and its assigned response (see Logan, 1988, for a somewhat different view). At least for certain tasks, this association might eventually enable very strong activation of the correct response without the involvement of central resources (see also Hommel, 1998; Logan & Schulkind, 2000). Note that humans, quite fortunately, do not execute all responses that become active. Therefore, in addition to strong response activation, it might also be necessary for executive mechanisms to pre-approve the execution of certain likely responses.

A warning regarding the interpretation of dual-task costs

Even though we observed non-negligible dual-task costs for both the preferred (~30 ms) and the non-preferred modality pairings (~90 ms), we found no evidence for a central bottleneck. Thus, just as the absence of dual-task costs does not necessarily indicate the absence of a bottleneck (Ruthruff et al., 2003), the presence of costs does not necessarily indicate the presence of a bottleneck. To diagnose the presence/absence of a bottleneck, other indicators must be called upon (such as the relationship between RT1 and RT2).

What caused the residual dual-task costs?

Having argued against the central bottleneck model, we now turn to the question of what did cause the observed dual-task costs. The available data do not point to a unique answer. One attractive explanation, however, is that central codes (e.g., the stimulus category and response category) for the two tasks compete for representation in a limited-capacity working memory. After performing a task, the central codes might not be immediately flushed from working memory. Persisting central codes, for example, could help explain why (in single-task studies) performance improves when stimulus and response categories repeat from one trial to the next. One implication of persisting central codes is that interference on a second task could occur even at relatively long SOAs, just as found in the present experiments.

This account could be extended to explain modality-pairing effects. Note that salient stimuli routinely activate associated responses even when those responses conflict with current goals. To ensure that activated response codes are executed only when in service of a particular task goal, people might need to bind the response code with the corresponding stimulus code and task goal (e.g., see Hommel, Müsseler, Aschersleben, & Prinz, 2001). It might be most natural to bind auditory stimuli with vocal responses because they operate on a related domain (e.g., sound) and because they are commonly connected in the real world (e.g., when conversing); for analogous reasons, it might also be

natural to bind visual stimuli with manual responses. The opposite bindings (auditory stimuli to manual responses or visual stimuli to vocal responses) would need to fight this natural tendency. The binding problem with the less preferred modality pairings would be especially severe in a dual-task condition, because the stimulus categories would tend to bind with the response categories for the wrong task. Therefore, this hypothesis provides a natural account of the magnified dual-task costs observed with the less preferred modality pairings (see also Hazeltine et al., 2005).

Summary

The present experiments provide evidence that practice can eliminate the central bottleneck, even for certain non-preferred modality pairings (auditory–manual and visual–vocal) that produce robust dual-task costs. Other necessary conditions for eliminating the bottleneck might include the absence of modality conflicts and the use of relatively easy tasks with few stimulus–response combinations. We proposed that certain tasks can be automatized with practice, eliminating competition for central resources. Further research is needed to better understand how and when practice causes this qualitative change in performance. Even when the bottleneck is eliminated, however, residual dual-task costs can be caused by other factors, such as competition between central codes for the two tasks.

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