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## Modality pairing effects and the response selection bottleneck

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**Abstract** The present experiment examined the effects of input/output modality pairings on dual-task performance using the psychological refractory period (PRP) procedure. Four groups of participants performed two tasks composed of the same sets of inputs (visual and auditory) and the same sets of outputs (manual and vocal), but with different input/output modality pairings. Whereas modality pairings had only small effects on single-task reaction times, they had large effects on dual-task reaction times. The modality pairing effect cannot stem from differences in the difficulty of stimulus classification or response execution, because these task demands were the same across groups. The effect also does not appear to result from changes in stimulus–response compatibility. The present findings suggest dual-task interference arises not only from postponement of central operations (due to a central bottleneck), but also from a slowing of central operations whose magnitude is sensitive to the input/output modality pairings.

**Keywords** Dual-task · Modalities · Response selection · Central bottleneck · Psychological refractory period

### Introduction

Flexibility is a hallmark of human behavior; we are able to respond to any stimulus reaching consciousness in an almost infinite number of ways. Sensory information from visual, auditory, and tactile modalities, for instance, can be used to elicit movements of the arms, feet, and articulatory system. Given the ability to form stimulus–response (S–R) associations regardless of the sti-

mus and response modalities, theorists have generally assumed that response selection processes are generic: the representations engaged by these processes are abstract, stripped of modality-specific features. However, a recent surge of interest in dual-task performance has underscored how little is certain about the architecture of the cognitive processes engaged during response selection.

### The central bottleneck model

A dominant model of human cognitive architecture holds that dual-task costs occur because tasks must compete for access to a central bottleneck mechanism that is required across a broad range of tasks. Some versions of this model assume that the central bottleneck can operate on only a single task at a time. Thus, central operations for one of the tasks must be deferred until the central bottleneck has completed operations required for the other task (e.g., Byrne & Anderson, 2001; Pashler, 1984, 1994b; Pashler & Johnston, 1989; Ruthruff, Pashler, & Hazeltine, 2003; Welford, 1967). Others have proposed that the bottleneck has a limited capacity that can be shared by multiple tasks simultaneously (e.g., Navon & Miller, 2002; Tombu & Jolicoeur, 2002, 2003). Under many conditions, these two versions make similar predictions, although the capacity-sharing model can account for a more diverse range of findings.

The central bottleneck mechanism is thought to be responsible for a wide range of computations, including response selection, memory retrieval, and mental rotation (e.g., Carrier & Pashler, 1992; Johnston, McCann, & Remington, 1995; Lien, Schweickert, & Proctor, 2003; Pashler, 1991; Ruthruff, Miller, & Lachmann, 1995). Accordingly, it is often conceived as a general-purpose resource, not tied to any particular input modality or any particular output modality. Therefore, we refer to this account as the generic central bottleneck (GCB) model. It is the generic aspect of the central resource that explains why a central bottleneck occurs (or so it seems)

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regardless of what tasks are paired together; if the central mechanism required for visual-manual tasks differed from that required by auditory-vocal tasks, then no dual-task costs should be observed.

Much of the evidence supporting the GCB model comes from the psychological refractory period (PRP) paradigm (Pashler, 1984, 1994a; Telford, 1931; Welford, 1952). In this paradigm, stimuli for two tasks are separated in time by a variable stimulus onset asynchrony (SOA). Participants are instructed to give priority to the task whose stimulus is presented first (Task 1) and, so long as they do not slow processing on that task, to respond to the other task (Task 2) as quickly as possible. These methods generally produce a characteristic pattern of RTs: Task 1 RT (RT1) is roughly the same at all SOAs, whereas Task 2 RT (RT2) is lengthened as the SOA becomes shorter. This slowing is known as the PRP effect.

The logic supporting the bottleneck interpretation of the PRP effect has been detailed elsewhere (see Hazeltine, Diedrichsen, Kennerley, & Ivry, 2003; Pashler & Johnston, 1989; Tombu & Jolicoeur, 2002), but because this logic plays a major role in the present evaluation of the GCB model, we briefly review it here. As depicted in Panel A of Fig. 1, RTs for each task reflect the summed durations of three discrete processing stages: a prebottleneck stage (Stage A), which can proceed in parallel with any other processing stage; a bottleneck stage (Stage B), which cannot proceed in parallel with the bottleneck stage for other tasks; and a postbottleneck stage (Stage C), which can proceed in parallel with any other processing stage. When the SOA is long, the bottleneck stages (see Panel A, Fig. 1) are not required at the same time, and the RTs for both tasks are determined only by the sum of the durations of the three component stages. Equations 1 and 2 express this straightforward starting point.

$$RT1_{\text{long}} = A1 + B1 + C1 \quad (1)$$

$$RT2_{\text{long}} = A2 + B2 + C2 \quad (2)$$

However, when the SOA is sufficiently short, the bottleneck stage for Task 2 is required before the bottleneck stage for Task 1 is complete (see Panel B, Fig. 1). Under these conditions, Stage B processing for Task 2 is delayed until the bottleneck stage for Task 1 is completed. The RTs for the two tasks should then reflect the set of processes described by Eqs 3 and 4.

$$RT1_{\text{short}} = A1 + B1 + C1 \quad (3)$$

$$RT2_{\text{short}} = A1 + B1 + B2 + C2 - SOA_{\text{short}} \quad (4)$$

Subtracting  $RT2_{\text{Long}}$  (Eq. 2) from  $RT2_{\text{short}}$  (Eq. 4) yields Eq. 5, which describes the predicted magnitude of the PRP effect in terms of the component stage durations (see Hazeltine et al., 2003; Pashler & Johnston, 1989; Tombu & Jolicoeur, 2002).

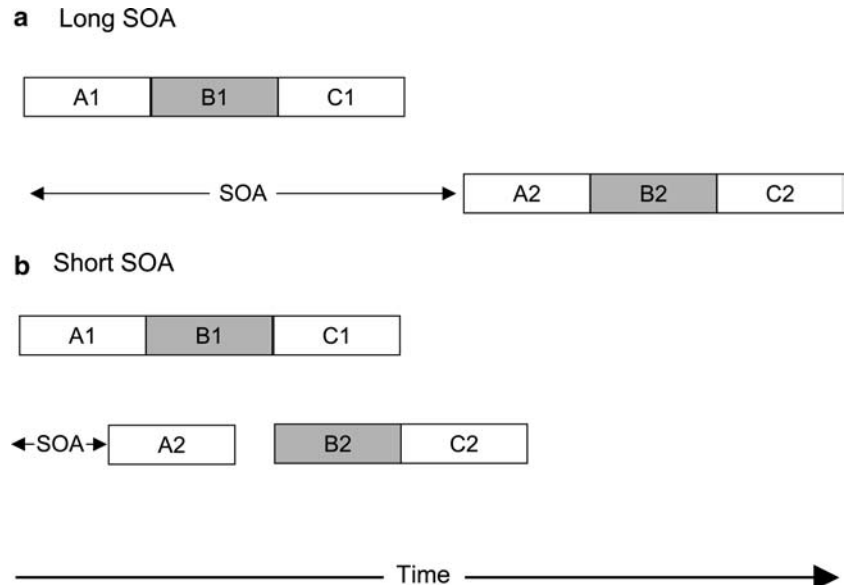
$$\begin{aligned} \text{PRP effect} &= RT2_{\text{short}} - RT2_{\text{long}} \\ &= A1 + B1 - A2 - SOA_{\text{short}} \end{aligned} \quad (5)$$

Thus, according to the GCB model, the magnitude of RT2 slowing depends on the duration of the bottleneck stage for Task 1 (B1) and the difference in the durations of the pre-bottleneck stages for Tasks 1 and 2 (A1-A2). This straightforward model can account for findings from many PRP experiments, in particular the finding that SOA effects are additive with manipulations of Task 2 response selection difficulty (a bottleneck process) but underadditive with manipulations of Task 2 perceptual discriminability (a prebottleneck process).

### A test of the GCB model

This elegant model derives considerable predictive power from the assumptions that the stage durations are

**Fig. 1** Panel **a** Three stages of processing for Tasks 1 and 2 at a long stimulus onset asynchrony (SOA, when the SOA is long, the bottleneck stages (Stage B) for the two tasks are required at nonoverlapping times, so each task proceeds without interruption. Panel **b** Three stages of processing for Tasks 1 and 2 at a short SOA. When the SOA is short, the bottleneck stage (Stage B) for Task 2 must wait for the bottleneck stage for Task 1 to be completed, so Task 2 is slowed



constant across SOA and unaffected by the operations taking place in other stages (at least when there is no dimensional overlap between the two tasks). The only source of slowing is postponement of central stages. Although, the model is simple and makes straightforward assumptions about central resources and the nature of dual-task interference, it has been remarkably successful in accounting for diverse dual-task findings. In the present study, we test whether this model is equally successful in accounting for dual-task interference with different pairings of input and output modalities.

According to the GCB model, the prebottleneck stage (Stage A) entails stimulus categorization and the post-bottleneck stage (Stage C) entails response execution. Neither should be affected much by the *pairings* of input and output modalities. If modality pairings do affect stage durations, they should primarily affect the central stage durations. There is some evidence that modality pairings can have a modest effect on overall RT in single-task conditions (Baldo, Shimamura, & Prinzmetal, 1998; Hazeltine, Ruthruff, & Remington, submitted; McLeod, 1977; McLeod & Posner, 1984; Shaffer, 1975; Teichner & Krebs, 1974; Virzi & Egeth, 1985; Wickens, 1980, 1984). In such cases, the choice of modalities might alter the stimulus–response (S–R) compatibility. Although, the modality pairings might alter the duration of the bottleneck stages, they should not qualitatively change the way how the bottleneck mechanism operates. Increases in the duration of Task 1 central stages should simply lead to equivalent increases in the PRP effect, as indicated by Eq. 5.

The present study evaluated these predictions of the GCB model by measuring dual-task performance in the PRP paradigm with different pairings of input modalities to output modalities. The input modalities were auditory (220 and 3520 Hz pure tones) and visual (the symbols ‘#’ and ‘%’). The output modalities were vocal (‘one’ and ‘two’) and manual (the ‘H’ and ‘J’ keys). One set of participants performed an auditory-vocal task with a visual-manual task, which we refer to as the ‘‘standard’’ modality pairings. The other set of participants performed an auditory-manual task with a visual-vocal task, which we refer to as nonstandard pairings. Within each set of participants, one group performed the tasks in one order and the other group performed the tasks in the opposite order. The four resulting conditions are summarized in Table 1.

## Method

### *Participants*

96 students from community colleges in the Mountain View, California area were paid to participate. All the participants were right-handed and between the ages of 18 and 25.

### *Stimuli*

Auditory stimuli were 220 or 3,520 Hz tones presented for 300 ms. Visual stimuli were the symbols ‘%’, and ‘#’. These symbols, subtending 1.4° horizontally by 1.9° vertically, were white against a black background. They remained visible until a response was made.

### *Procedure*

The 96 participants were divided into four groups of 24 each. The groups differed in terms of the S–R associations for the two tasks (see Table 1). Participants in the auditory-vocal/visual-manual (AVVM) group, responded to the 220 Hz and 3,520 Hz tones by saying the words ‘one’ and ‘two’, respectively (Task 1), and responded to the ‘#’ and ‘%’ symbols by pressing the ‘H’ and ‘J’ keys, respectively (Task 2). Keypresses were produced with the middle and index fingers of the right hand. Participants in the visual-manual/auditory-vocal (VMAV) group performed the same two tasks as the AVVM group, except that the visual-manual task was Task 1 and the auditory-vocal task was Task 2. Participants in the auditory-manual/visual-vocal (AMVV) group responded to the 220 Hz and 3,520 Hz tones by pressing the ‘H’ and ‘J’ keys, respectively (Task 1), and responded to the ‘#’ and ‘%’ symbols by saying the words ‘one’ and ‘two’, respectively (Task 2). Participants in the visual-vocal/auditory-manual (VVAM) group performed the same two tasks as the AMVV group, except that the visual-vocal task was Task 1 and the auditory-manual task was Task 2. Thus, the tasks for each of the four groups involved the same set of stimuli and the same set of responses. The only differences among the groups was the way the stimuli and responses were paired with each other to construct the two tasks and the order of presentation.

There were three trial types, differing according to the SOA. For the short SOA, the stimulus for Task 2 was presented 50 ms before the stimulus for Task 1 (i.e., the SOA was –50 ms). This SOA was chosen to ensure that there was overlap between central operations for the two tasks consistently at shortest SOA (see Ruthruff, Johnston, Van Selst, Whitsell, & Remington, 2003; Van Selst, Ruthruff, & Johnston, 1999). For the long SOA, the stimulus for Task 2 was presented 1,000 ms after the stimulus for Task 1 (i.e., the SOA was 1,000 ms). For trials with the intermediate SOA, the SOA varied between 1 and 699 ms at increments of 2 ms (e.g., 1, 3, 5, ..., 699 ms). The final data set for each participant consisted of 100 trials at the short SOA, 100 trials at the long SOA, and one trial at each of the 350 possible intermediate SOAs. The SOA range between 0 and 700 ms represents the most likely transition from dual-task performance with overlapping central processes to performance without overlapping central processes.

Each trial began with the presentation of a fixation cross for 500 ms, then a blank field for 300 ms, followed

**Table 1** Four task combinations used in the experiment

		Task 1 Stimulus	
		Auditory	Visual
Mapping:	Standard	AVVM	VMAV
	Nonstandard	AMVV	VVAM

The first two letters indicate the composition of Task 1, (*AM*: Auditory stimulus, Manual response; *AV*: Auditory stimulus, Vocal response; *VM*: Visual stimulus, Manual response; *VV*: Visual stimulus, Vocal response). The second two letters indicate the composition of Task 2, using the same abbreviations as for Task 1

by the stimulus for Task 1 or, if it was a short SOA trial, the stimulus for Task 2. On short SOA trials, the stimulus for Task 1 was presented 50 ms after the stimulus for Task 2. On long and intermediate SOA trials, the stimulus for Task 2 was presented following the stimulus for Task 1 after the appropriate SOA had elapsed.

Participants performed a practice block consisting of 10 short SOA trials, 10 long SOA trials, and 35 intermediate SOA trials spaced every 20 ms along the 1–699 ms SOA range. After practice, they performed 10 experimental blocks identical to the practice blocks, except that each intermediate SOAs was performed exactly once during the 10 blocks. After each block, the computer displayed feedback on mean RT and accuracy for each task. Participants were instructed to respond to both tasks as quickly and accurately as possible, but to be certain not slow their responses to Task 1.

## Results

Only correct responses with RTs greater than 250 ms and less than 3,000 ms were included in the RT analyses. Less than 3% of RTs fell outside these cutoff values.

*Long and short SOA trials. RT1* Task 1 RTs at the long and short SOAs, shown in Fig. 2, were submitted to a three-way ANOVA with SOA (long vs. short) as a within-subjects factor and stimulus (auditory vs. visual) and response (manual vs. auditory) as between-subjects factors<sup>1</sup>. There were no significant main effects (SOA:  $F(1,92) = 1.18$ ;  $p > 0.25$ ; stimulus:  $F(1,92) = 2.65$ ;  $p > 0.1$ ; response:  $F(1,92) < 1$ ), but there were statistically reliable interactions between stimulus×response ( $F(1,92) = 16.76$ ;

$p < 0.001$ ;  $MSe = 23027.68$ ), SOA×stimulus ( $F(1,92) = 4.98$ ;  $p < 0.05$ ;  $MSe = 1057.30$ ) and SOA×stimulus×response ( $F(1,92) = 10.81$ ;  $p < 0.001$ ;  $MSe = 1057.30$ ).

The stimulus×response interaction reflected an advantage for the groups using a Standard modality pairing (AVVM: 457 ms; VMAV: 472 ms) compared to the groups using a Nonstandard modality pairing (AMVV: 526 ms; VVAM: 582 ms). Although, the interactions involving SOA were statistically reliable, it is apparent from Fig. 2 that they stemmed from fairly subtle effects. Given the small magnitude of these interactions, they will not be discussed further.

*Long and short SOA trials. RT2* Task 2 RTs at the long and short SOAs, shown in Fig. 3, were submitted to the same three-way ANOVA applied to the RT1 data. There were main effects of SOA ( $F(1,92) = 1326.67$ ;  $p < 0.0001$ ;  $MSe = 4573.77$ ) and response ( $F(1,92) = 17.02$ ;  $p < 0.001$ ;  $MSe = 23351.65$ ) but not stimulus ( $F < 1$ ). The effect of SOA reflected the PRP effect (355 ms average advantage for long SOA trials), and the effect of response reflected an overall 54 ms advantage for vocal responses. All the two-way interactions and the three-way interaction were also statistically reliable (SOA×stimulus:  $F(1,92) = 17.02$ ;  $p > 0.001$ ;  $MSe = 4573.77$ ; SOA×response:  $F(1,92) = 4.40$ ;  $p < 0.05$ ;  $MSe = 4573.77$ ; stimulus×response:  $F(1,92) = 22.28$ ;  $p > 0.001$ ;  $MSe = 23351.65$ ; SOA×stimulus×response:  $F(1,92) = 98.87$ ;  $p > 0.0001$ ;  $MSe = 4573.77$ ). To better understand these interactions, separate ANOVAs were performed on the Task 2 RTs, one for the long SOA and one for the short SOA.

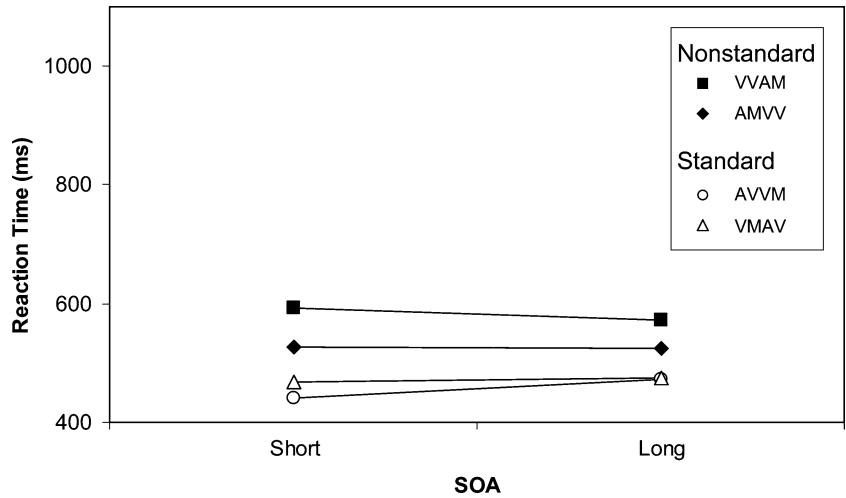
Unlike Task 1 at the long SOA, Task 2 at the long SOA represents almost a pure single-task case, because participants have completed Task 1 and can focus entirely on Task 2 without having to attend to the Task 1 stimulus or maintain the Task 1 S-R mapping. For these data, a two-way ANOVA yielded marginally significant main effects of stimulus ( $F(1,92) = 2.79$ ;  $p = 0.098$ ;  $MSe = 7444.18$ ) and response ( $F(1,92) = 3.76$ ;  $p = 0.056$ ;  $MSe = 7444.18$ ) but no stimulus×response interaction ( $F < 1$ )<sup>2</sup>. Thus, there was no evidence for an advantage for the Standard modality pairings at the long SOA. In sum, although there was an overall advantage for auditory stimuli and an overall advantage for manual responses, mean RT2s for the four groups were all within 65 ms of each other at the long SOA.

In contrast, RT2 at the short SOA showed much greater variation across groups (e.g., VMAV: 721 ms; VVAM: 997 ms). Some of this variation was due to a marginally significant effect of stimulus ( $F(1,92) = 3.06$ ;  $p = 0.084$ ;  $MSe = 20481.24$ ) and a reliable effect of re-

<sup>1</sup>Because both stimulus and response have only two levels, interactions between the two factors are essentially equivalent to a main effect of a single two-level factor (e.g., “Pairing”) indicating whether the participants used standard or nonstandard mappings. There are small differences between the two ANOVAs due to changes in the degrees of freedom, but these are subtle and barely affect the  $p$  values. Therefore, in every case, when an interaction involving stimulus and response is reported, the same result is obtained as a main effect of (or interaction involving) pairing in an ANOVA with the pairing factor replacing stimulus and response. As evident in the figures, these interactions consistently indicate performance costs for nonstandard pairs

<sup>2</sup>Nearly identical results are obtained when the analysis is restricted to trials in which RT1 was less than 1000 ms. This additional criterion ensures that tasks processes on that trial are not overlapping and eliminates an additional 2–5% of the data

**Fig. 2** Reaction times for Task 1 at the long and short SOAs for the four experimental groups.



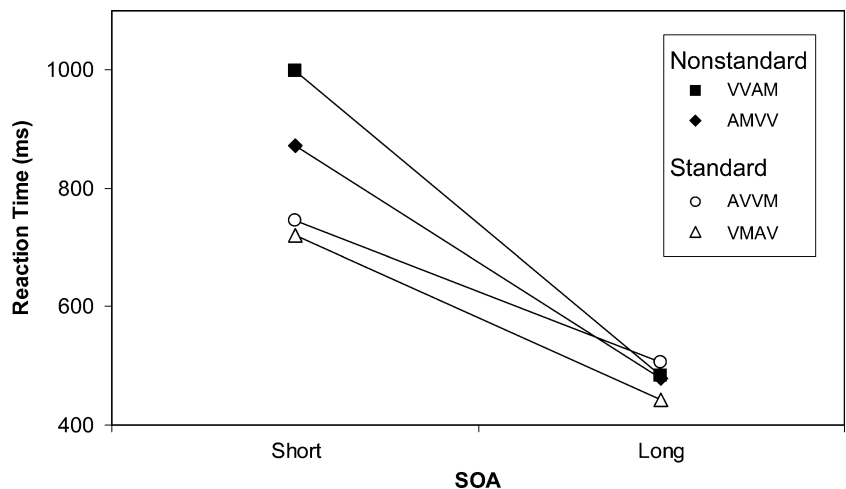
sponse ( $F(1,92) = 6.61$ ;  $p < 0.05$ ;  $MSe = 20481.24$ ). However, most of this variation was due to a statistically reliable stimulus $\times$ response interaction ( $F(1,92) = 47.53$ ;  $p < 0.0001$ ;  $MSe = 20481.24$ ); mean RT2 was 201 ms longer for the nonstandard pairings than that for the standard pairings.

Comparing RT2 at the short and long SOAs, the PRP effects were larger for the AMVV (391 ms) and VVAM (513 ms) groups than for the AVVM (238 ms) and VMAV (278 ms) groups. On average, the Nonstandard groups showed 194 ms more dual-task interference than the standard groups,  $t(94) = 9.04$ ;  $p < 0.0001$ . This reliable advantage for the Standard groups cannot be attributed to differences in overall Task 2 difficulty, because RT2s at the long SOA were similar across the four groups. Furthermore, the differences in the dual-task costs cannot be attributed to interactions between the stimuli or between the responses, because the combinations of stimuli and the combinations of responses were identical for all four groups.

The GCB model predicts that a lengthening of RT1 should lead to an equivalent increase in the magnitude of the PRP effect, assuming that the Task 1 lengthening is in the prebottleneck or bottleneck stages. The increase in the PRP effect (194 ms), however, was nearly twice as large as the increase in RT1 (105 ms). To see if this difference was significant, we performed an ANOVA on the magnitude of the PRP effect minus the short SOA RT1. In this way, any carry-over of RT1 modality-pairing effects onto RT2 at the short SOA should be subtracted out, leaving only direct effects of modality pairings on Task 2 slowing.

This ANOVA revealed no significant main effects of stimulus ( $F(1,92) = 2.51$ ;  $p > 0.1$ ) or response ( $F(1,92) < 1$ ), but did reveal a significant interaction between stimulus and response ( $F(1,92) = 16.79$ ;  $p < 0.001$ ;  $MSe = 11331.23$ ). This interaction indicates that the Nonstandard groups produced much larger PRP-RT1 differences (AMVV:  $-135$  ms; VVAM:  $-79$  ms) than the Standard groups (AVVM:  $-202$  ms; VMAV:  $-189$  ms). Thus, even after accounting for differences in

**Fig. 3** Reaction times for Task 2 at the long and short SOAs for the four experimental groups



mean RT1, the dual-task costs on Task 2 were still significantly larger (by 89 ms) for the Nonstandard groups.<sup>3</sup>

*Long and short SOA trials. Accuracy* The proportions of correct responses, summarized in Table 2, were submitted to the same three-way ANOVAs as the RTs. For Task 1, there were significant main effects of SOA ( $F(1,92)=56.72$ ;  $p<.0001$ ;  $MSe=.001$ ) but not stimulus ( $F(1,92)=1.93$ ;  $p=0.17$ ;  $MSe=0.001$ ) or response ( $F(1,92)=1.69$ ;  $p=0.20$ ;  $MSe=0.001$ ). There were also statistically reliable interactions between stimulus $\times$ SOA ( $F(1,92)=36.23$ ;  $p<0.0001$ ;  $MSe=0.001$ ) and among stimulus $\times$ response $\times$ SOA ( $F(1,92)=21.42$ ;  $p<0.001$ ;  $MSe=0.001$ ). These findings are generally consistent with those observed in the RT data and indicate that our conclusions are not the result of speed-accuracy trade-offs.

For Task 2, there was a significant main effect of SOA ( $F(1,92)=36.71$ ;  $p<0.0001$ ;  $MSe=0.001$ ) but not stimulus or response ( $F$ 's  $< 1$ ). Furthermore, the interactions between stimulus $\times$ response ( $F(1,92)=11.05$ ;  $p<0.001$ ;  $MSe=0.001$ ) and SOA $\times$ response ( $F(1,92)=4.57$ ;  $p<0.05$ ;  $MSe=0.001$ ) were statistically reliable. In contrast to the RT data for Task 2, there was no indication of a three-way interaction ( $F < 1$ ), and the stimulus $\times$ response interaction was robust at both SOAs. In other respects, the findings were generally consistent with the RT data (see Table 2).

*Intermediate SOA trials. RT1* The Task 1 RTs from the intermediate SOAs were divided into five 140 s bins for each participant. The correlation between the SOA and reaction time was computed for each bin and each participant. The resulting correlation coefficients and slopes were submitted to  $t$ -tests in which the values were compared to zero for each of the groups. The results can be described simply: none of the groups produced correlation coefficients or estimated slopes that differed from zero. In sum, the RTs for Task 1 did not vary with SOA, consistent with the GCB model.

<sup>3</sup>One explanation is that participants in the VVAM group withheld their vocal responses to Task 1 so as to avoid speaking at the same time the tone for Task 2 is presented. The Task 1 RTs for the VVAM group changed 19 ms from the long to the short SOA (Long: 572 ms; short: 592 ms;  $t(23)=1.91$ ;  $p=0.07$ ). Although, the difference is small, it is possible that these participants were unable to adjust their strategy after producing the Task 1 response. Presumably, an effect of delaying the Task 1 response on the magnitude of the PRP effect would be accounted for by subtracting out RT for Task 1. However, it is unclear exactly how participants' concerns about speaking over the tone might affect their performance, so a more cautious approach is to compare only the data from the AMVV group to the two groups using a Standard mapping. The AMVV group used a Nonstandard mapping but did not include conditions in which the vocal response might occur at the same time as the auditory stimulus. The PRP effect for the AMVV group is significantly larger than the PRP effect for either the AVVM ( $t(23)=5.63$ ;  $p<.0001$ ) or the VMAV ( $t(23)=3.94$ ;  $p<.001$ ) groups.

*Intermediate SOA trials. RT2* The same analysis applied to the RT1 data was also applied to the RT2 data. The correlation coefficients were reliably negative for all groups for the first two SOA bins (SOA = 1–139; 141–279; all  $t(23)$ 's  $> 3.2$ ;  $p$ 's  $< 0.005$ ), and reliably negative for the VMAV, AMVV, and VVAM groups for the third SOA bin (SOA = 281–419;  $t(23)$ 's  $> 3.2$ ;  $p$ 's  $< 0.005$ ). However, in all of these cases the mean coefficients across participants were not impressive, ranging between  $-0.13$  and  $-0.24$ .

The mean slopes from the regression analyses are shown along with mean RT2s in Fig. 4. Consistent with the GCB model, these slopes tended to decrease as the SOA increased. At short SOAs, the GCB model predicts that the slope should approach  $-1$ , because the SOA should determine the time that the bottleneck stage for Task 2 can begin. The slopes for the two Nonstandard groups are steeper at the short SOA than the slopes for the Standard groups ( $t(47)=3.13$ ;  $p<0.005$ ). This pattern suggests that there was indeed greater dual-task interference for the Nonstandard groups, although the difference could be attributable to the Task 1 RTs. The trend for the slopes (AMVV:  $-1.11$ ; VVAM:  $-1.18$ ) to be steeper than  $-1$  is intriguing, although they did not differ from  $-1$  reliably ( $t(47)=1.26$ ;  $p=0.21$ ). Slopes steeper than  $-1$  suggest that dual-task costs are caused by more than just the delays imposed by a bottleneck.

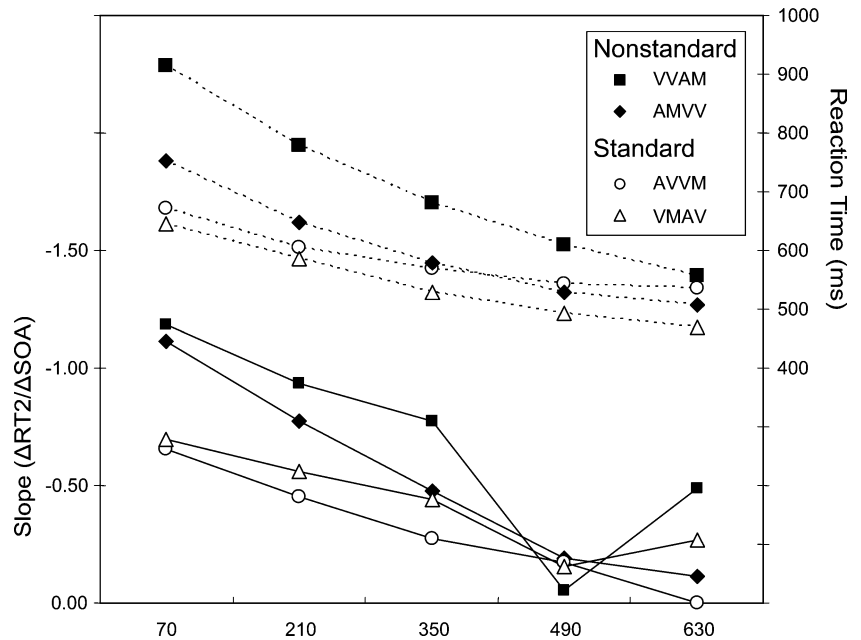
## Discussion

The present experiment demonstrated that dual-task costs depend strongly on the modality pairings even though the stimuli, their classifications, and the responses for the two tasks are held constant. The changes caused by modality pairings are not subtle but are on the order of hundreds of milliseconds. Most importantly, the increased dual-task costs cannot be attributed to a straightforward lengthening of the bottleneck stages of Task 1, because the differences in the PRP effects were much larger than the differences in mean RT1s. Thus, the present data argue against the GCB model, which attributes dual-task costs exclusively to a general-purpose (modality-independent) central resource.

**Table 2** Reaction times and accuracies for the long and short SOA conditions for the four experimental groups

	Reaction time Task 1 short	Task 1 long	Task 2 short	Task 2 long
AMVV	526	525	871	480
AVVM	441	473	745	507
VMAV	467	476	721	443
VVAM	592	573	997	484
Accuracy				
AMVV	0.93	0.98	0.95	0.96
AVVM	0.95	0.99	0.96	0.99
VMAV	0.98	0.96	0.96	0.98
VVAM	0.95	0.98	0.94	0.96

**Fig. 4** Mean slopes and RTs for task 2 for 5 SOA bins for the four experimental groups. RTs are shown connected by *dotted lines*; slopes are connected by *solid lines*. The slopes and RTs were computed separately for each participant and averaged in five 140 ms bins, labeled by their midpoint along the x-axis



### Explaining modality pairing effects

How can the GCB model be modified to account for the observed modality pairing effects? One approach would be to relax the assumption that modality pairings do not affect the input or output stages. Specifically, stages A2 and/or C1 might be longer for the Standard groups than for the Nonstandard groups. This account is unappealing because it is rather implausible that the tasks with the shorter overall RTs would actually have much longer input and output stages. An related possibility is that the processing stream for the Nonstandard tasks involves longer bottleneck processes (e.g., Virzi & Egeth, 1985) or a second bottleneck stage (e.g., De Jong, 1993). However, these additional processes should have also lengthened RT2 at the long SOA, yet no such effect was observed.

It may be that the longer bottleneck stage for the Nonstandard pairings is accompanied by shorter pre-bottleneck or postbottleneck stages. In other words, to account for the similarity in long SOA RT2 across conditions, it might be assumed that some operation that is part of the prebottleneck stage for the Standard pairings is part of the bottleneck stage for the Nonstandard pairings. For instance, the nature of the processes subject to the bottleneck might be partially under strategic control. Under the appropriate conditions, the bottleneck stages might include not only central operations but also perceptual processing or response execution. This reassignment would increase the bottleneck delay (explaining the increase in dual-task costs) without concomitantly increasing mean RT1 or long SOA RT2.

Another approach to explaining the present findings within the GCB model framework is to relax the assumption that postponement of the Task 2 bottleneck stage is the only source of dual-task interference. In

addition to the postponement, there might also be substantial lengthening of the Task-2 bottleneck stage at short SOAs (i.e., a reduction in the rate of processing). If this slowing is greater for the Nonstandard groups than for the standard groups, then the effect of modality pairings on dual-task costs would exceed the effect on RT1 and long SOA RT2. While possible, these explanations assert that nonstandard pairings alter bottleneck processes without explaining why.

As an alternative to the all-or-none central processing constraint of the GCB model, some theorists have argued that central capacity can be flexibly distributed to multiple tasks simultaneously (see Navon & Miller, 2002; Tombu & Jolicoeur, 2002, 2003). This account provides no obvious explanation for the apparent transfer of processing from peripheral to central (capacity-limited) stages. However, Tombu and Jolicoeur (2003) proposed that overhead costs associated with maintaining and coordinating two tasks may drain more central capacity at short SOAs than at long SOAs (see also, Luria & Meiran, 2003). If one assumes that the overhead costs were greater for the Nonstandard groups than the Standard groups, then such a mechanism could account for the observed pattern of data. However, it remains unclear why the modality pairings of the two tasks should affect overhead costs in this way. Furthermore, the key prediction of capacity-sharing models is a slowing of RT1 at short SOAs, which was not observed in the present experiments.

Models that assume no limitations in the simultaneous execution of central operations (e.g., EPIC, Meyer & Kieras, 1997) also offer mechanisms that can modulate dual-task costs, but they do not specify why these mechanisms are engaged in different ways by the different modality pairings. For example, EPIC could assume that participants adopted a more conservative strategy for overlapping operations for the Nonstandard

groups than the Standard groups, leading to different patterns of dual-task costs. However, it is unclear what differences between the two pairings would cause this to happen.

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### Rethinking central limitations

What is needed is a theoretical account that directly addresses why pairing auditory stimuli with vocal responses and visual stimuli with manual responses reduces dual-task costs compared to the converse arrangement. Wickens (1980; 1984; Wickens & Liu, 1988; Wickens, Sandry, & Vidulich, 1983) developed a “code-compatibility” theory to explain compatibility between input and output modalities and the intervening codes used to perform stimulus–response translation. Such a theory seems well-suited to explain the present findings. However, Wickens’ theory assumes that conflict is restricted to interactions between stimuli, between codes, and between responses. Each of these forms of conflict should have been the same across the standard and nonstandard modality pairings.

To explain why increases in RT2 are greater at short SOAs than at long SOAs (i.e., overadditive effects such as those observed with the manipulations of the modality pairings), the notion of crosstalk is often invoked (e.g., Ivry, Franz, Kingstone, & Johnston, 1998; Lien et al., 2003; Spijkers, Heuer, Steglich, & Kleinsorge, 2000). Crosstalk between motor commands, for example, refers to motor parameters appropriate for one set of effectors being transmitted to a different set of effectors. This peripheral form of interference has been proposed as major source of delay when two tasks must be performed with the two hands close together in time (e.g., Heuer, 1995; Spijkers et al., 2000). In the present case, however, the response combinations (along with the stimulus combinations) were identical for the Standard and Nonstandard groups. Therefore, crosstalk, if responsible for the changes in dual-task costs, must occur at the level of central representation that is not strictly contingent on stimuli or responses.

The possibility of crosstalk between central operations has received some attention in the dual-task literature (see Hirst & Kalmar, 1987; Koch & Prinz, 2002; Logan & Schulkind, 2000; Schuch & Koch, 2004). However, the present case differs from previous proposals in that there is no obvious relationship between the stimulus categories for the two tasks. Nonetheless, even in the absence of categorical overlap, it is possible that the central codes for the Nonstandard groups are more similar, and thus more prone to crosstalk than those for the standard groups. Given that these central codes link the stimuli with the responses, they likely include information about both the input and output associated with the S–R rules (i.e., these central codes are not generic, but rather are tied to specific modalities). For the Nonstandard groups, the rules for both tasks involve

sounds, and this overlap may lead to crosstalk between the two S–R codes activated on a given trial. For the Standard groups, the S–R codes may be overlap less, minimizing the crosstalk.

Crosstalk is transient, affecting only synchronous or nearly synchronous processes (Spijkers, Heuer, Steglich, & Kleinsorge, 1997; Swinnen & Wenderoth, 2004). Therefore, it would lengthen the duration of central stages at short SOAs more than at long SOAs. In this way, crosstalk is similar to the overhead costs proposed by Tombu and Jolicoeur (2003). The critical difference is that overhead costs should depend on the S–R sets of the two tasks, whereas crosstalk should depend on the particular S–R pairs present on a given trial. Further research is necessary to resolve which framework better describes the inter-task interaction.

One specific hypothesis akin to crosstalk that can explain why the Nonstandard pairings prolong central processes is that response selection involves the binding of stimulus and response features (see Hommel, Müseler, Aschersleben, & Prinz, 2001; Logan & Gordon, 2001). For the Nonstandard pairings, sounds (auditory stimuli and vocal responses) were associated with both tasks, whereas for the Standard groups, these two events were associated with the same task. The latter conditions may make binding stimuli to responses easier, because there is less potential for confusing which sound belongs with which task. An analogous argument can be made for the visual and manual tasks, both of which have a spatial component.

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### Summary

Modality pairing was a topic of considerable research in the 1970s and 80s (Allport, Antonis, & Reynolds, 1972; McLeod & Posner, 1984; Pashler, 1990; Teichner & Krebs, 1974; Wickens, 1980, 1984; Wickens & Liu, 1988; Wickens et al., 1983), but has since received relatively little attention. The majority of studies have used what we have termed Standard pairings or have not differentiated between interference at a central level, as in the present case, and interference at a peripheral level, such as crosstalk between outgoing motor codes. The present experiment makes clear that modality pairings can have a dramatic effect on the way tasks interact without changing the amount of conflict for peripheral processes.

Although some recent studies have pointed to limitations in the central bottleneck model and suggested that response selection can proceed at least partially in parallel for two tasks (e.g., Hazeltine, Teague, & Ivry, 2002; Hommel, 1998; Ruthruff, Van Selst, Johnston, & Remington, in press; Schuch & Koch, 2004; Schumacher, Seymour, Glass, Kieras, & Meyer, 2001; Tombu & Jolicoeur, 2002), the present study offers a different critique. Our results suggest that the GCB model does not explain the pattern of dual-task costs suffered by Task 2. That is, the GCB model appears to understate rather than

overstate the forms of interactions between concurrently performed tasks. It is apparent that modality pairings directly affect the manner in which concurrently performed tasks interact, even when overlap between stimuli and between responses is held constant. Specifying the mechanisms behind this modality pairing effects is critical for understanding the nature of central processing limitations.

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