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Separate and Shared Sources of Dual-Task Cost in Stimulus Identification and Response Selection

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There is often strong interference if a second target stimulus (T2) is presented before processing of a prior target stimulus (T1) is complete. In the ''Psychological Refractory Period'' (PRP) paradigm, responses are speeded and interference manifests as increased response time for T2. In the ''Attentional Blink'' (AB) paradigm, stimuli are masked and responses unspeeded; interference manifests as reduced T2 accuracy. While different causes have usually been considered for PRP and AB phenomena, recent evidence has supported a unified account based on a single, shared restriction on concurrent processing. Here we show that a full assessment of separate and shared resource limitations requires direct comparison of hybrid PRP/AB trials with corresponding pure PRP and AB cases. Randomizing trial types in such a comparison also brings substantial benefit in addressing possible changes in task preparation or readiness. The data from two such experiments—combining speeded auditory (SA) and unspeeded visual (UV) task events—provide clear evidence for both separate and shared resource limitations. Often interference is strongest for T1 and T2 events of the same type, reflecting predominantly different limitations in SA and UV processing. With modest increases in demand, however, interference between different event types can also be made arbitrarily large, reflecting arbitrarily important shared limitations. For even such simple tasks as these, T1–T2 interference reflects a combination of relatively local and relatively global sources. © 2002 Elsevier Science (USA)

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When people attend to two targets (T1 and T2) presented within half a second of each other, performance on the second target (T2) is typically impaired. When both targets are unmasked and require on-line speeded responses, the response times (RTs) to T2 are inflated at short target–target stimulus-onset asynchronies (SOAs) as compared to long target–target SOAs. This effect is known as the Psychological Refractory Period (or PRP) phenomenon (e.g., Pashler, 1994a; Smith, 1967; Welford, 1952). When both targets are masked and require off-line, unspeeded responses, the report accuracy of T2 is reduced at short target–target SOAs as compared to long target–target SOAs. This effect is known as the Attentional Blink (AB) (Raymond, Shapiro, & Arnell, 1992).

Conventional Accounts

The PRP and the AB both demonstrate reduced performance on T2 if it is presented shortly after T1. Despite the fact that both phenomena represent dual-task costs at short T1–T2 SOAs, they have generally been ascribed to quite different causes. Until recently (Jolicoeur, 1998, 1999a, 1999b, 1999c; Jolicoeur & Dell' Acqua, 1998, 1999), indeed, there has been little consideration of the possibility that these two phenomena could reflect the same underlying processing limitation.

Perhaps the most widely accepted view is that the PRP reflects a bottleneck on central response selection operations (e.g., McCann & Johnston, 1992; Pashler, 1994a; Welford, 1952). According to this model, response selection operations (mapping from stimulus identity to the required response) can only proceed for one stimulus at a time. If T1 is undergoing response selection, then T2 must wait, and this waiting accounts for the increased RTs observed at short SOAs. Evidence for this view comes from experiments employing the locus of slack logic. In these experiments manipulations of perceptual or encoding factors are shown to have underadditive effects with SOA (e.g., McCann & Johnston, 1992; Pashler, 1984; Van Selst & Jolicoeur, 1994a). According to locus of slack logic, such underadditivity indicates that these manipulations have their effect before the dual-task processing bottleneck. Using the same logic, findings that response selection and response execution manipulations remain additive with SOA provide evidence that the dual-task bottleneck occurs at or after response selection (e.g., McCann & Johnston, 1992; Pashler, 1984; Ruthruff, Miller, & Lachmann, 1995; for contrary evidence see Schumacher et al., 1999).

In contrast to the PRP phenomenon, theories of the AB phenomenon have typically focused on early stimulus encoding processes[1] (e.g., Duncan, Martens, & Ward, 1997; Potter, Chun, Banks, & Muckenhoupt, 1998; Raymond

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[1] In this article the phrase ‘‘stimulus encoding’’ is used simply to refer to consolidating a stimulus representation such that its identity can be reported after a backward mask. No more specific interpretation of this process is intended.

et al. 1992; Shapiro, Raymond, & Arnell, 1994). Indeed, the intention in paradigms that use delayed, unspeeded responses is specifically to remove on-line response selection and hence to examine specifically perceptual limitations. Some such investigations, furthermore, have shown no interference or reduced interference when T1 and T2 are presented in different sensory modalities (e.g., Duncan et al., 1997; Potter et al., 1998; Rollins & Hendricks, 1980; Treisman & Davies, 1973). Though such results are not universal (Arnell & Jolicoeur, 1999), they suggest at least a partial contrast with the strong PRP effect that is obtained even when T1 and T2 are in different sensory modalities (Pashler, 1994a). Correspondingly, extensive physiological work documents strong attentional modulation of responses in early visual processing areas (Desimone & Duncan, 1995), including primary visual cortex (Tootell et al., 1998) and the network of extrastriate areas to which visual information then projects (Moran & Desimone, 1985). The suggestion is that interference in the detection or identification of concurrent visual inputs arises largely through local competition for processing in these early visual areas (Desimone & Duncan, 1995).

Hybrid Paradigms

The most direct experimental evidence concerning the relationship between PRP and AB phenomena has come from hybrid PRP–AB paradigms. In these, one target requires a speeded response, while the other requires an unspeeded response. More specifically, experiments have typically combined speeded responses to auditory inputs (SA) with unspeeded responses to visual inputs (UV). Undoubtedly, both SA and UV processing events involve multiple components, affording multiple opportunities for mutual interaction or interference. An SA event, for example, imposes some requirement for stimulus encoding as well as stimulus–response translation. Though the intention in UV tasks is to avoid any need for speeded response selection, still the task requires such control processes as maintaining appropriate identification criteria, discarding unwanted mask information, and so on. Still, if PRP and AB do largely reflect different kinds of performance limitation, the SA–UV combination provides one plausible opportunity for observing little if any T1–T2 interference.

In line with this possibility, Blake and Fox (1969) reported no accuracy reduction when subjects reported the identity of a degraded, unmasked, visual letter (T2) which closely followed a tone requiring a speeded two-alternative forced-choice (AFC) response (T1). Similarly, Pashler (1989) used a two-AFC speeded response to the pitch of a tone as the T1 task. When the T2 task was the unspeeded identification of the highest digit in an eight-digit array, Pashler found only a very small (2%) accuracy reduction for the digit responses when the arrays were presented within 150 ms of the tone. The same result was obtained when the T2 task was changed to visual search for a conjunction target among an array of distractors, and subjects made unspeeded responses indicating whether the target was present or absent. Ruthruff and Pashler (unpublished) also reported no accuracy reduction when subjects made unspeeded two-AFC responses indicating the identity of a masked visual letter (T2) when the letters closely followed a T1 tone requiring a speeded two-AFC pitch discrimination. These null or minuscule T2 accuracy reductions are convincing because (1) T2 accuracy was never at ceiling in any of the above experiments and (2) the T1 task employed (speeded two-AFC pitch discrimination) has been shown to produce reliable T2 response slowing in pure PRP paradigms.

Results of this sort are evidently in line with conventional theories ascribing PRP and AB phenomena to largely separate causes. Specifically, Pashler (1989, 1994) proposed that UV tasks, because they are not speeded, are not influenced by queueing in the response selection bottleneck that is responsible for the PRP. SA tasks do not share significant perceptual encoding limitations with UV tasks, either because their encoding demands are trivial or because such limitations are largely modality-specific. In this article, we shall refer to this as the *separate-limitation* view of SA–UV processing.

More recent evidence from SA–UV paradigms, however, suggests a different picture. De Jong and Sweet (1994) performed experiments similar to Pashler (1989), except they emphasized the need to respond quickly to the T1 tone task and added a longer maximum SOA (1000 ms instead of 600 ms). De Jong and Sweet found substantial T2 accuracy reductions of about 10–20% at short SOAs. Similarly, Jolicoeur (1998, 1999a, 1999b, 1999c) and Jolicoeur and Dell' Acqua (1999) have demonstrated that speeded two-AFC tone discriminations (T1) produce accuracy reductions for subsequent (T2) unspeeded identifications of masked visual letters at short SOAs. Jolicoeur and Dell' Acqua (1998, 1999) have also shown the reverse pattern where unspeeded identification of a masked visual letter presented as T1 produces response slowing for speeded T2 tone pitch discriminations at short SOAs.

Such results present an important challenge to the separate-limitation view. Indeed, they have been interpreted in support of an entirely different model, according to which both PRP and AB phenomena arise from a single, central processing bottleneck (Arnell & Jolicoeur, 1999; Jolicoeur, 1998, 1999a, 1999b, 1999c; Jolicoeur and Dell' Acqua, 1998, 1999). More specifically, these authors propose that the same, strictly serial processing system is involved both in speeded response selection and in consolidating stimulus descriptions in working memory. Both PRP and AB phenomena arise from queueing in this serial system; while it is busy with response selection or stimulus consolidation for T1, it is not free to deal with either response selection or stimulus consolidation for T2. If T2 is speeded, this results in an RT increase (PRP); if T2 is unspeeded and masked, queueing results in information loss before consolidation can complete (AB). In this article, we refer to this as the *shared-limitation* view.

In the present work we reconsider the question of separate vs shared limitations in the PRP and AB. Though the hybrid SA–UV experiment is telling, we show that, for unambiguous interpretation, results should be directly compared with matched, ‘‘pure’’ SA–SA (conventional PRP) and UV–UV (conventional AB) cases. When this is done, apparent discrepancies in previous results are resolved, leading to a clear picture of relations between PRP and AB phenomena.

Separating Specific and General Forms of Dual-Task Interference

In fact, the issue of PRP–AB relations is reminiscent of a much older debate in the dual-task literature, the debate between single- and multiple-resource[2] theories (see, e.g., Allport, 1980; Kahneman, 1973; Navon & Gopher, 1979; Treisman & Davies, 1973). Some conceptual background from this earlier work, indeed, is useful in considering the present question.

According to early single-resource models, all instances of dual-task conflict were explained by the same processing limitation. In some versions, this limitation was conceived as a fixed pool of processing capacity, dual-task interference occurring when the available capacity was insufficient to support both concurrent activities. In others—as in the Jolicoeur (1998) model above—it was conceived as a serial processing bottleneck. The key concept in such models was that any given task is associated with a single quantity, the demand it makes on the single limited processing resource. In parallel models, this ‘‘demand’’ would be the amount of processing capacity consumed. In serial models, it would be the time for which the bottleneck was required. A strong prediction follows. The amount to which any one task X interferes with others A, B . . . is determined simply by its single demand value. If X has higher demand than Y, it must interfere more strongly with *all* concurrent tasks, whatever their content. Indeed, such consistency in the pattern of interference across multiple dual-task combinations can sometimes be observed, especially if tasks are chosen all to be dissimilar in terms of input modality, output modality, and other aspects of processing and content (Bourke, Duncan, & Nimmo-Smith, 1996).

In multiple-resource models there are multiple separate causes for dual-task interference. In the simplest case, there might be two separate resources, one for example supporting visual tasks, the other supporting auditory tasks. Now the above consistency will no longer hold: If X makes heavy demands

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[2] In the dual-task literature, terms such as ‘‘capacity’’ and ‘‘resource’’ have been used with varying degrees of theoretical precision. For present purposes, we use ‘‘resource’’ to refer entirely neutrally to *any* source of interference, competition, or conflict between concurrent mental operations. For example, a resource could be divisible (as in conventional parallel models) or allocated all-or-none (as in conventional serial models); among other possibilities, a ‘‘resource’’ could be construed as a particular processor called on by two operations, as a mental commodity required by both, or as some form of informational cross-talk between them.

on resource 1, while Y makes heavy demands on resource 2, then X rather than Y will produce the greater interference on other tasks that are also dependent on resource 1, while Y rather than X will produce the greater interference on other tasks that are also dependent on resource 2. Essentially, the test for a multiple-resource model is a test for this kind of inconsistency in the pattern of results across an appropriate set of dual-task pairs (Navon & Gopher, 1979).

An experiment by Treisman and Davies (1973) makes this reasoning more concrete. In this experiment, subjects monitored two concurrent word streams for the occurrence of a prespecified target. Concurrent streams could be both auditory, both visual, or one of each. Even when streams were in different modalities, it was harder to monitor both rather than just one or the other. Taken on its own, this result implies that there is some resource limitation sufficiently broad to affect word recognition in different modalities. Performance was very much worse, however, when both streams were in the same modality, either both auditory or both visual. Taken together, the results suggest both within- and between-modality sources of dual-task interference. In general, any dual-task interference observed when tasks are very dissimilar suggests a rather broad form of resource limitation (Bourke, Duncan, & Nimmo-Smith, 1996). Stronger interference when tasks are made more similar suggests additional, more specific limitations.

Consider now a typical ‘‘hybrid’’ PRP–AB experiment, along with the corresponding ‘‘pure’’ PRP and AB experiments from which it is derived. One component single task is to make a speeded response to an unmasked auditory stimulus (SA). The other is to make an unspeeded identification of a masked visual event (UV). There are now four possible dual tasks. In the first (SA–SA), both T1 and T2 are auditory and require speeded responses. This is a typical pure PRP experiment. In the second (UV–UV), both T1 and T2 are visual and require unspeeded identification. This is a typical pure AB experiment. These first two we call ‘‘within task/modality’’ cases. The remaining two are hybrids, SA–UV and UV–SA. These we call ‘‘crossed task/modality’’ cases. Comparison of all four cases has the same structure as the Treisman and Davies (1973) experiment and allows the same sorts of conclusion.

First consider the possibility of no shared resources between the processing events associated with SA and UV targets. Reliable dual-task costs are expected only when participants perform the same task for T1 and T2 (within task/modality), and no dual-task costs are expected when participants perform different tasks for T1 and T2 (crossed task/modality). Thus, we would find reduced identification accuracy for unspeeded responses to visual T2s when they are presented shortly after a visual T1, but not when they are presented shortly after an auditory T1 requiring a speeded response. Similarly, we would find inflated response times to auditory T2s only when they are presented shortly after an auditory T1 requiring a speeded response, but not when they are presented shortly after a visual T1 requiring an unspeeded response.

Such results are illustrated in Figs. 1A (UV task) and 1B (SA task). In these figures, T1 data are shown at negative SOAs (timing back from T2), while T2 data are shown at positive SOAs (timing forward from T1). The UV–UV task, accordingly, would contribute both T1 and T2 data to Fig. 1A (within task/modality curve). At short SOAs there is a substantial drop in T2 accuracy (AB). The SA–SA task would contribute both T1 and T2 data to Fig. 1B (within task/modality curve). At short SOAs there is a substantial increase in T2 RT (PRP). The UV–SA task would contribute T1 data to Fig. 1A and T2 data to Fig. 1B, while the SA–UV task would contribute T1 data to Fig. 1B and T2 data to Fig. 1A (crossed task/modality curves). In these hybrid tasks there is no effect of SOA.

Second, consider the possibility that the critical processing resources required for response selection and stimulus encoding are shared, and there are no additional within-task or within-modality processing resources. Jolicoeur's (1998) bottleneck model is an example: both PRP and AB derive from demands on the same, serial bottleneck.[3] For simplicity, let us first assume that the speeded auditory task and the unspeeded visual task called on the shared resource to the same extent, despite the fact that such matching would be highly unlikely and fortuitous. In the Jolicoeur (1998) model, this would mean that serial bottleneck processing for T1 was completed at the same time whether T1 was SA or UV. Under these conditions, substantial dual-task costs are expected in all task combinations. Furthermore, equal accuracy reductions for UV T2s would be expected when they closely follow both UV T1s and SA T1s (Fig. 1C), and equal RT slowing for SA T2s would be expected when they closely follow both UV T1s and SA T1s (Fig. 1D).

More generally, the shared-resource model admits the possibility that SA and UV tasks might differ in resource demand. In the Jolicoeur (1998) model, the bottleneck might be occupied for different durations. Still, however, the model must predict consistency in the pattern of interference across task combinations. As an example, assume that demands are lower for the SA task than for the UV task. Expected UV results under such conditions are depicted in Fig. 1E. The T2 accuracy cost would be expected to be greater following a UV T1 than an SA T1, given that greater resource consumption by the UV T1 would result in greater dual-task costs. In this case, however, the accompanying SA results must be those shown in Fig. 1F: An SA T2 must also suffer less interference from an SA than from a UV T1. The same

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[3] It is worth pointing out that models like Jolicoeur's (1998) imply no commitment to the full single resource theory of dual-task interference. For present purposes, all that is important is whether PRP and AB phenomena reflect the same resource limitation, not the extension of this limitation to any other dual-task case.

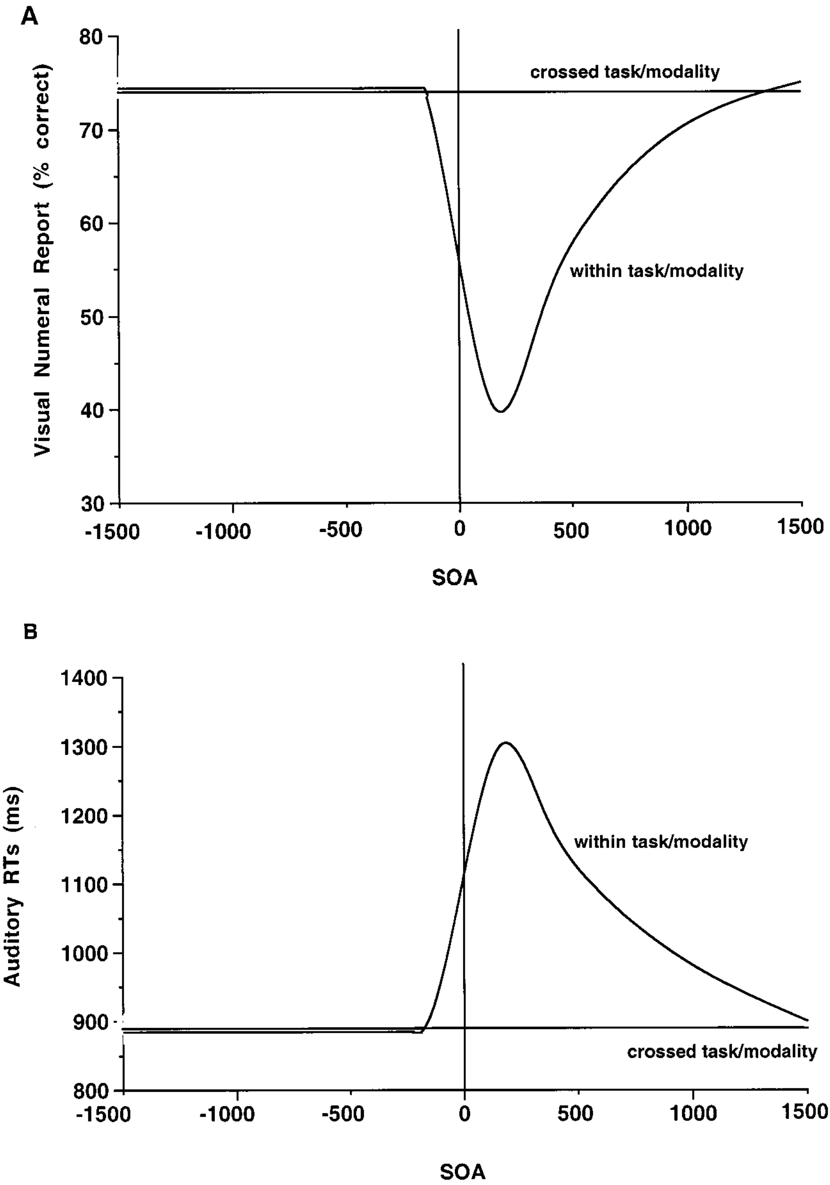


FIG. 1. (A) A theoretically possible pattern of accuracy results and (B) a theoretically possible pattern of RT results under conditions where there are only task-specific resource limitations.

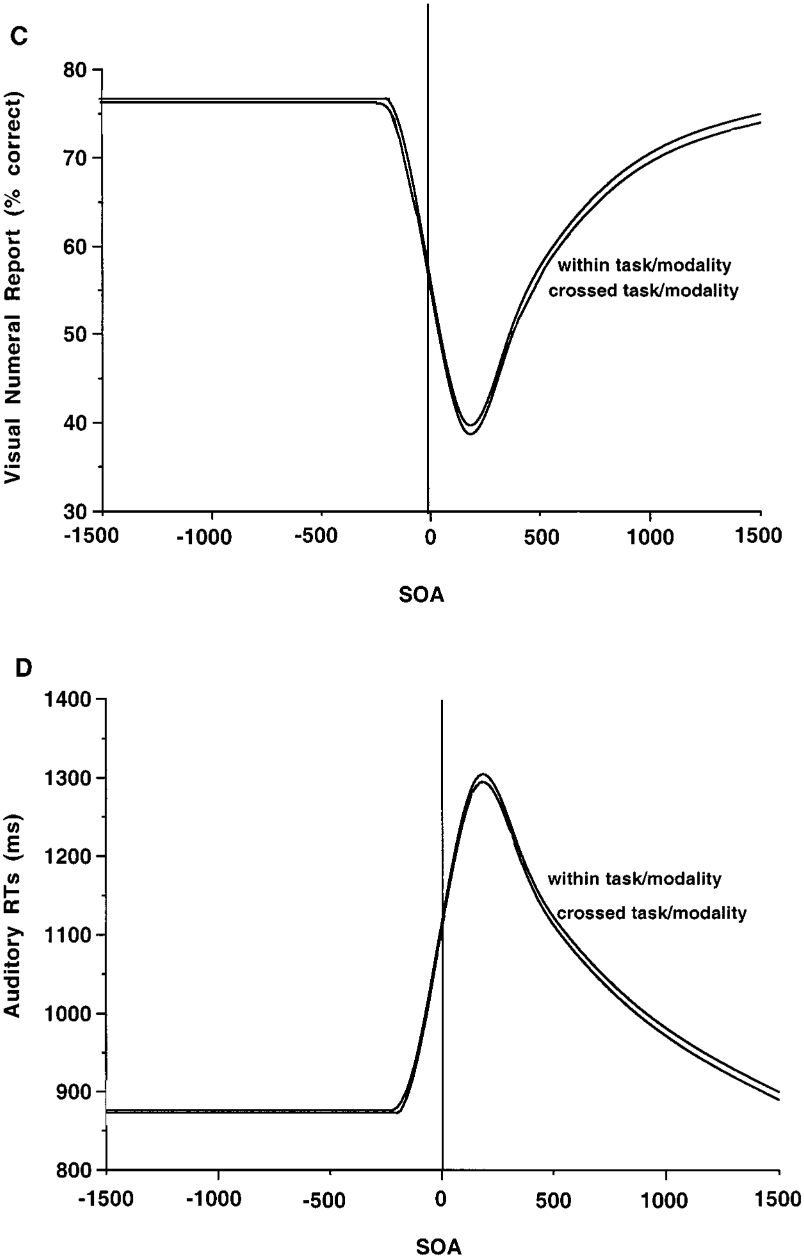
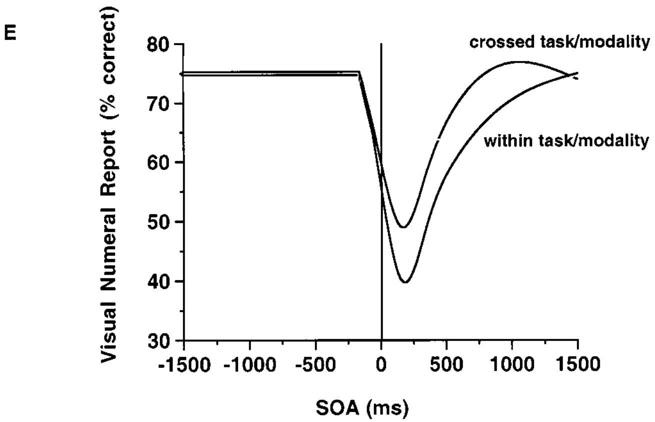
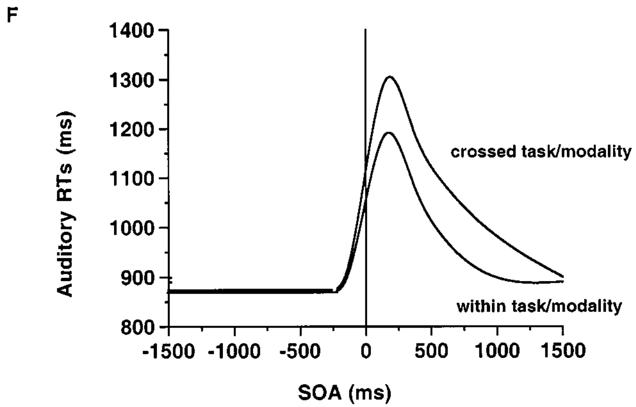


FIG. 1—*Continued* (C) A theoretically possible pattern of accuracy results and (D) a theoretically possible pattern of RT results under conditions where there is only a single resource limitation shared across tasks.


E
Visual Numeral Report (% correct)
80
70
60
50
40
30
-1500
-1000
-500
0
500
1000
1500
SOA (ms)
crossed task/modality
within task/modality


F
Auditory RTs (ms)
1400
1300
1200
1100
1000
900
800
-1500
-1000
-500
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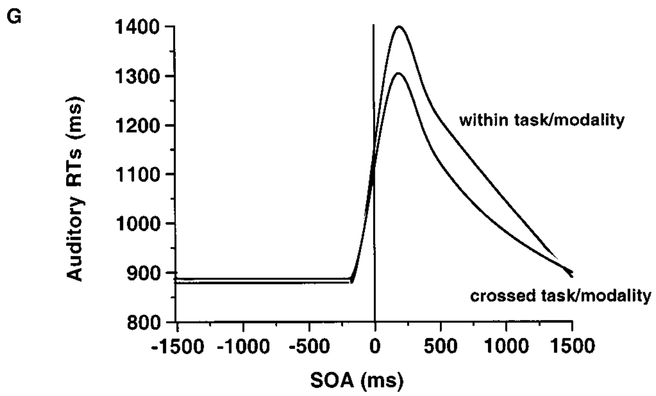
500
1000
1500
SOA (ms)
crossed task/modality
within task/modality


G
Auditory RTs (ms)
1400
1300
1200
1100
1000
900
800
-1500
-1000
-500
0
500
1000
1500
SOA (ms)
within task/modality
crossed task/modality

consistency is required if instead it is the SA event whose demand is greater; now the pattern of results must be reversed for both UV and SA data.

Consider in contrast the combination of results shown in Figs. 1E and 1G. On the one hand, this data pattern is inconsistent with a pure separate-limitation view, with only task-unique resource limitations. This view is ruled out by significant cross-task interference. On the other hand, the pattern is also inconsistent with a single shared-limitation view; a UV T2 suffers most interference from a UV T1, while an SA T2 suffers most interference from an SA T1. When this data pattern is observed, both extreme models can be eliminated; instead some mixture of both shared and separate resource limitations is required.

It is worth emphasizing that many such mixtures could be envisaged. One simple possibility is that each task depends on both some discrete task-specific resource (e.g., auditory and visual encoding resources) and some specific shared resource (e.g., some domain-independent working memory). A second possibility is that there are only two discrete resources rather than three; if the SA task, for example, depended on both a shared (e.g., perceptual encoding) and a specific (e.g., response selection) resource, the data could still be fit as long as the UV task made the greater demands on the shared resource. A UV T2 would suffer most interference from a UV T1 (Fig. 1E), but an SA T2 could suffer more interference from an SA T1 because of additional, task-specific resource conflict. A third possibility is that UV and SA tasks are dependent on the same two or more resources, but to different degrees. For example, the data would follow if the UV task made especially heavy demands (and was especially dependent on) some encoding resource, while the SA task made especially heavy demands (and was especially dependent on) some working-memory resource. In this case cross-task interference would arise because each task made at least some demand on each resource, but within-task interference would evidently be stronger. Finally, the data would also be consistent with more continuous rather than discrete resource models. Plausibly, each task requires a large sample of processing steps or elements, and interference between successive events could depend on how many of these elements they share (cf. for example, the cerebral distance model of Kinsbourne & Hicks, 1978). Again, interference would be strongest when successive events had similar demands. What all these

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FIG. 1—*Continued* (E) Displays a theoretically possible pattern of accuracy results under either of two conditions: (i) shared limitation, with heavier resource demand for the visual task; and (ii) both shared and task-specific limitations. These alternatives may be distinguished by the accompanying RT results, as shown in F and G. (F) The expected results with only a shared limitation and heavier demand for the visual task. (G) The expected results with both shared and task-specific limitations. Positive SOAs reflect T2 performance at each SOA after T1, and negative SOAs reflect T1 performance at each SOA backward from T2.

models share is a mixture of shared and separate resource limitations, however those limitations are conceived.

With the possible data patterns of Fig. 1 in mind, we may reconsider the conflicting results obtained in previous hybrid PRP–AB experiments. Recall that, in several experiments, Pashler (1989) demonstrated that a speeded two-AFC frequency (high/low) decision for easily discriminable T1 tones produced very small (2%) accuracy deficits for unspeeded responses to masked visual T2 arrays presented at short SOAs. Most importantly, interference in this hybrid PRP–AB case was much weaker than interference in largely comparable pure PRP and AB-like cases. Strong interference when two tasks are similar (pure PRP and AB cases), coupled with weak interference when they are dissimilar (hybrid PRP–AB), provides evidence for some task-specific resource limitation. It is much weaker evidence, however, that cross-task resource limitations must always be weak or negligible. Though Pashler's (1989) results resemble those shown in Figs. 1A and 1B for the case of only task-specific resource limitations,[4] distinguishing this from the case of *both* specific and shared limitations (Figs. 1E and 1G) is a matter of accepting the null hypothesis for zero cross-task interference. In particular, one might hesitate to accept this null hypothesis based on a single data set with tasks of unknown resource demand; if demands on cross-task resources are modest, the cross-task interference predicted in Figs. 1E and 1G can be expected to be correspondingly modest, leading to a result indistinguishable from that in Figs. 1A and 1B. As they stand, Pashler's (1989) experiments provide strong evidence in favor of task-specific limitations; they do not provide strong evidence against additional, cross-task or shared limitations.

Jolicoeur (1999a) and Jolicoeur and Dell'Acqua's (1999) finding of dual-task costs in the SA–UV condition could be explained purely by the existence of a single resource limitation shared across tasks. This time, however, these findings do not rule out the existence of task-specific processing limitations in addition to any shared limitation: Since only crossed task/modality conditions were run, it is impossible to distinguish the single-resource model (Fig. 1C, crossed task/modality) from the model with both shared and task-specific resources (Fig. 1E, crossed task/modality). As they stand, the experiments provide strong evidence that a shared, cross-task resource limitation can be substantial and significant; they do not provide evidence against additional, task-specific limitations.These considerations lead to the first constraint on the method developed in the present work. This constraint is that all four relevant task combinations should be examined: SA–SA, SA–UV, UV–SA, and UV–UV. With this design, task-specific and shared resource

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[4] Among other differences from the complete set of tasks and data illustrated in Figs. 1A and 1B, note that Pashler (1989) did not run the hybrid UV–SA case (Fig. 1B, crossed task/modality).

limitations can be separately evaluated and compared, if necessary, across a range of task difficulties or demands.

Task Switching

In many experimental designs, including many pure PRP and AB as well as hybrid cases, there is a further issue complicating data interpretation. Consider any experiment in which tasks are different for T1 and T2. In the typical PRP experiment, for example, T1 may be drawn from one set of stimuli (e.g., tones), with its corresponding set of response alternatives (e.g., left hand keypresses), while T2 is drawn from a different set of stimuli (e.g., visual shapes), with a different set of response alternatives (e.g., right hand keypresses). In the typical AB experiment, T1 may be a white letter to be selected and identified from among a stream of black distractors, while T2 is a black X to be detected after T1 has occurred. In a hybrid experiment, T1 may be a tone requiring a speeded response, while T2 is a masked visual letter to be identified. In all such cases, data may be complicated by strategic task switching; or in other words, by shifts in the state of readiness for one task or the other during the course of the trial (Gottsdanker, 1980).

The reasoning here is as follows. Undoubtedly, states of readiness for any two tasks (i.e., any two sets of stimuli, responses, and stimulus-response mappings) might be somewhat incompatible. In other words, it might be impossible to maintain perfect readiness for both tasks simultaneously. When task order is fixed in a PRP, AB, or hybrid experiment, there is the strong possibility that subjects might begin the trial optimally prepared for the task (Task1) required by T1, then, when T1 has arrived, switch to optimal preparation for the task (Task2) required by T2. This possibility is illustrated in Fig. 2A. At the start of the trial readiness is maximal for Task1. After T1 has occurred, there is a switch to readiness for Task2, leading to progressive improvement in T2 performance as SOA is increased.

This kind of alteration in relative readiness for two tasks has been extensively documented, indeed, in the recent ‘‘task switching’’ literature (Allport, Styles, & Hsieh, 1994; Meiran, 1996; Rogers & Monsell, 1995). As in PRP and AB experiments, task switching studies generally involve two separate tasks performed in a block of trials. In this case, however, tasks are not temporally overlapping as they are in PRP and AB cases; instead the block is a series of single-task trials, with trials of the two tasks intermingled and a variety of means including trial-to-trial sequential effects (e.g., Allport et al., 1994; Rogers & Monsell, 1995) and explicit instruction cues (e.g., Meiran, 1996) are used to alter relative readiness for one task or the other. The results of such experiments show quite clearly that, at least for many task pairs, optimal preparation for both members of the pair is impossible, making changes in relative preparation a potentially potent influence on performance.

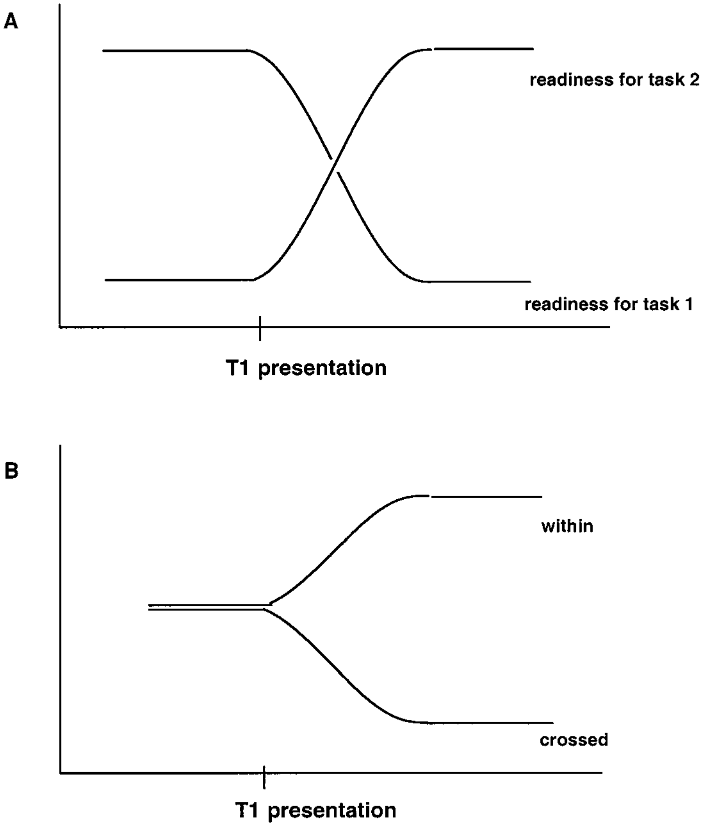

FIG. 2. Each panel represents a theoretically possible pattern of task readiness during a dual task trial. Time moving forward within the trial is represented on the *x* axis. Readiness for each task is represented on the *y* axis. (A) A possible pattern of readiness when T1 and T2 involve different tasks and/or modalities and target order is known. Notice full readiness for T1 until it occurs and then a switch to readiness for T2 (‘‘endogenous’’ task switching). (B) A possible extension to the case in which T1 and T2 are independent, producing both within and crossed task/modality trials. Since task/modality for T1 is unknown at the start of the trial, there is no selective readiness before T1 onset. When T1 occurs, however, it alters the state of readiness in favor if its own task/modality (‘‘exogenous’’ task switching).

It is important to be clear on the conceptual difference between resource limitation models like those illustrated in Fig. 1, and task switching models like those illustrated in Fig. 2. Rather than simple *costs* associated with processing T2 during ongoing processing of T1, task switching models (e.g., Allport et al., 1994; Meiran, 1996; Rogers & Monsell, 1995) imply *reciprocal* changes in relative efficiency of processing two types of events. When readiness is maximal for Task1 (Fig. 2A, before T1 onset) it is minimal for

T2 and vice versa. With fixed order of Task1 and Task2, this is indistinguishable from simple resource limitation (Fig. 1) simply because Task2 performance is never measured before onset of T1, and Task1 performance is never measured after T1 has been dealt with. The only aspect of reciprocal readiness changes that is manifest in the data is the improving performance on Task2 with increasing preparation interval; a result indistinguishable from the effects of resource limitation on concurrent T1/T2 processing. For many PRP, AB and hybrid experiments it is uncertain how much task switching of this sort might have contributed to the data. Some authors, indeed, have proposed that both PRP (De Jong & Sweet, 1994) and some AB (Potter et al., 1998) phenomena should be ascribed largely to this cause.

As argued by Pashler (1994b), the obvious way to avoid strategic task switching is to use exactly the same set of stimulus and response alternatives for T1 and T2. Since possible events following T1 are exactly the same as those before T1 has occurred, the optimal state of readiness should be constant throughout the trial. In a PRP-like setting, Pashler (1994b) used this method to confirm the importance of a response selection bottleneck. Here we adapt his approach to the hybrid AB–PRP paradigm.

The result is the following design. For the reasons already considered we wish to use all four T1–T2 task/modality combinations: UV–UV, SA–SA, UV–SA, and SA–UV. To avoid strategic task switching, however, these four should be run not in separate trial blocks, but randomized within each block. Now T1 unpredictably can be either SA or UV, and whichever it is, T2 also can be unpredictably SA or UV. Across trials all T1–T2 combinations will occur equally often, and at the same time, there is now no formal reason for shifts in preparatory state after T1 has appeared.

So far we have been considering strategic or rational changes in task readiness; i.e., those reflecting an actual change in the type of event that can occur. In the task switching literature, however, such ‘‘endogenous’’ readiness changes [e.g., those produced by an explicit task cue (Meiran, 1996)] are only a part of the empirical picture. At least as potent are ‘‘exogenous’’ changes driven by actual stimulus processing (e.g., Allport et al., 1994; Rogers & Monsell, 1995): The aftereffect of performing a trial of one task is a relative facilitation (increased readiness) on the following trial if this involves the same task, or equivalently, a relative impairment (decreased readiness or task switching effect) if it does not. With events of two very different types (SA and UV) both possible within one trial, such exogenous readiness changes might also be considered. Specifically, the task switching literature might imply the kind of result shown in Fig. 2B: After T1, there might be increased readiness for a subsequent T2 event of the same type, accompanied by decreased readiness for a T2 event of the opposite type. At long SOAs, indeed, such alterations in T2 performance (Fig. 2B, rightmost SOAs) would be closely analogous to ‘‘task switching’’ effects as they are traditionally studied, i.e., with the response to one stimulus closely followed by a second stimulus for the same or a different task.

Though such exogenous effects are evidently not ruled out by our proposed design, at least this design allows them to be evaluated. Again, the predicted changes are *reciprocal,* with decrements in performance for one event type accompanied by improvements in performance for the other. With complete randomization of event types, data are acquired for both SA and UV tasks at all SOAs, both as T1 and as T2. For this reason the reciprocal changes predicted by task switching models (Fig. 2) are clearly distinguished from the simple interference effects (Fig. 1) predicted by resource limitations.

Summary

In the remainder of this article we report two experiments using the proposed method for analyzing PRP–AB relations. In line with the previous literature on hybrid PRP–AB tasks, we consider combinations of SA and UV events. To allow separate assessment of task-specific and shared resource limitations, we use all combinations of SA–UV T1 and SA–UV T2 (cf. Treisman & Davies, 1973). To remove the impetus for strategic task switching, we use randomized events such that the possible set of events for T1 is exactly the same as the possible set of events for T2 (cf. Pashler, 1994b). As a consequence, both SA and UV data are acquired at each SOA, both as T1 and as T2 and independent of the other event occurring on that trial. The resulting data set provides a powerful evaluation both of the simple interference effects predicted by standard limited-resource models (e.g., Jolicoeur, 1998; Pashler, 1989) and of the reciprocal performance changes predicted by standard task switching models (e.g., Allport et al., 1994; Meiran, 1996; Rogers & Monsell, 1995).

EXPERIMENT 1

In Experiment 1, the auditory stimuli were three unmasked pure tones requiring a speeded on-line response. The task was effectively a three-alternative-forced-choice (three-AFC) version of Dell' Acqua and Jolicoeur's (1999), Pashler's (1989), and Ruthruff and Pashler's (unpublished) two-AFC tasks using tones. The visual stimuli were 10 masked single numerals requiring an unspeeded, off-line response. If SA and UV processes share no common processing resources, then dual-task costs would be predicted within, but not across task and modality (Figs. 1A and 1B). If there is only one, shared resource limitation, then equal dual-task costs could be predicted in the within and crossed conditions (Figs. 1C and 1D), or more realistically, data would resemble the pattern in Figs. 1E and 1F (or the reverse if resource demand is lower for the UV task). A result resembling the pattern found in

Figs. 1E and 1G, on the other hand, would suggest a combination of both shared and specific resource limitations.

Method

Participants

Twelve participants (six females), age 17–42 (mean = 30.6) years, participated in one 2-h session for pay. All were members of the Cambridge and area community and the CBU participant panel. All participants reported normal or corrected-to-normal visual acuity and normal hearing.

Design

The design was a 2 (T1 task/modality) × 2 (T2 task/modality) × 4 (SOA) factorial. T1 task/modality (SA or UV), T2 task/modality (SA or UV), and SOA (160, 360, 560, and 1500 ms) were all within-participant variables which varied randomly within blocks, with the constraint that each possible combination of these factors occurred equally often. Each participant performed 320 experimental trials in one session.

Stimuli and Apparatus

The visual stimuli were the numerals ‘‘0’’ to ‘‘9’’ inclusive. For each trial, the exact numeral(s) was(were) chosen independently by the computer in advance of the session. The numerals were black and presented in 18-point Geneva font. At this size, they subtended approximately 0.4° of visual angle in both height and width. The numerals were presented randomly in one of eight locations configured in a circle and equidistant from the black central fixation point in the center of a uniform gray field. The visual angle from the center of each possible numeral location to the center of the fixation point was approximately 2.64°. A backward pattern mask composed of several horizontal and vertical line segments positioned pseudorandomly within a 0.8-cm square (0.9° of visual angle) masked each presentation of a numeral. The presentation duration of the numerals was determined by participant’s identification performance on an initial practice block where each trial contained only a single masked numeral. Across participants, presentation times varied from 67 ms (with the mask presented for 67 ms) to 117 ms (with the mask presented for 17 ms).

The auditory stimuli were three pure tones, each 150 ms in duration. The frequency of the ‘‘low’’ tone was 333 Hz, the ‘‘medium’’ tone was 1000 Hz, and the ‘‘high’’ tone was 3000 Hz. No auditory masking stimuli were ever presented. Tones were presented through Macintosh speakers mounted in the monitor, immediately below the screen.

Experiments were controlled and timed using PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993) and a Macintosh Power Macintosh 8200/120 computer, with a 17-in. Macintosh color monitor. Participants initiated trials and made their responses using the keyboard. They viewed the display binocularly from a distance of approximately 50 cm under conditions of dimmed room illumination.

Procedure

In an initial 30 practice trials participants simply identified a single masked visual numeral. These trials were used to set the presentation duration for the numeral on the experimental trials. The experimenter then played all of the auditory tones for each participant telling them the correct pitch. This was followed by 30 auditory practice trials requiring speeded discrimination responses to single unmasked tones. Each participant then ran 32 practice trials with two stimuli (mixed SA–SA, SA–UV, UV–SA, and UV–UV) and last the 320 experimental trials.

Each experimental trial began when the participant pressed the spacebar. Immediately after the press, a fixation cross appeared and remained on the screen until the end of the trial. T1 was presented 800 ms after the onset of the fixation cross. Two targets (T1 and T2) were presented on each trial, separated by one of the four SOAs. Whenever a tone sounded, participants were instructed to make a speeded keypress indicating its pitch (low, medium, or high). Both speed and accuracy of responses were stressed. Participants pressed the ‘‘p,’’ ‘‘[,’’ or ‘‘]’’ keys, labeled ‘‘low,’’ ‘‘med.,’’ and ‘‘high,’’ respectively, with the middle three fingers of their right hand. To remove any experimenter demand characteristics, either order of response (i.e., T1 response then T2 response or T2 response then T1 response) was allowed on trials where both T1 and T2 were tones.

Participants were instructed to make unspeeded identification responses to the masked visual numerals. On trials with at least one visual numeral, 200 ms after the offset of T2 or 200 ms after any tone response was recorded (whichever was later), a sentence appeared prompting the participant to enter the numeral response(s). Participants used the numeral keys on the top row of the keyboard. Accuracy was stressed and participants were aware that their response times were not being recorded. The computer waited until the appropriate number of numeral responses had been recorded before proceeding to the next trial.

Participants were instructed to look at the fixation point throughout the trial and to use peripheral attention to identify visual numerals. No eye movement monitoring was performed for these participants; however, the experimenter watched all of the trials for each participant to ensure that the participants did not look down at their fingers, and away from the screen, when making their speeded responses.[5]

Results

All performance scores for T1 and T2 were calculated independently of whether the response to the other target was correct. However, all key aspects of the data are also found when making T1 or T2 performance conditional upon a correct response for the other target. T2 RTs for trials with two SA stimuli requiring the same response (e.g., T1 and T2 both low tones) were removed from all analyses. This was done under the assumption that normal response selection operations may not be performed if the participants simply decide to press the same key they had pressed immediately before as opposed to mapping from the stimulus to the correct response key. For trials with two SA stimuli, responses were scored as correct even if they were entered in the opposite order to presentation (i.e., T2 response and then T1 response). Such order reversals occurred very infrequently, and the few RTs that were reversed may well have been removed by the outlier elimination procedure. Only RTs for correct responses were included in the analyses. RTs were subjected to the Van Selst and Jolicoeur (1994b) modified recursive outlier elimination procedure with moving criterion. With this procedure fewer than 3% of all RTs were removed prior to analysis. For all figures, negative SOAs reflect T1 performance plotted as a function of the SOA backward from T2,

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[5] Eye monitoring was conducted on four additional participants while they performed the same experimental trials. On average, these four participants made eye movements on 1% of trials (minimum 0% to maximum 2%). Data from these four participants showed the same patterns as the data from the original 12 participants.

positive SOAs reflect T2 performance as a function of SOA forward from T1.

Visual Numeral Accuracy

T2 accuracy. As shown in Fig. 3A, T2 numeral identification accuracy in the within condition dropped markedly at the two shortest SOAs. In contrast, there was only a slight drop in the crossed condition. A 2 × 4 analysis of variance (ANOVA), with task condition (within/crossed) and SOA as within participant factors, produced a significant main effect of SOA, $F(3, 33) = 10.71$, $p < .001$, $MSE = 4.48$, a marginally significant effect of task within/crossed, $F(1, 11) = 4.65$, $p < .06$, $MSE = 10.06$, and most importantly, a significant SOA × task within/crossed interaction, $F(3, 33) = 3.65$, $p < .03$, $MSE = 5.26$, indicating that the drop in accuracy at short SOAs was larger in the within condition than in the crossed condition. The effects of SOA were also analyzed separately for the within and crossed conditions using one-way ANOVAs. T2 accuracy varied significantly across SOA in the within condition, $F(3, 33) = 11.24$, $p < .001$, $MSE = 5.32$, but not in the crossed condition $F(3, 33) = 1.67$, $p > .19$, $MSE = 4.42$.

T1 accuracy. When the visual numeral was presented as T1, participants averaged 61.2% correct in the within condition and 64.5% in the crossed condition (chance is 10%). A 2 × 4 ANOVA performed on visual T1 accuracy rates, with task condition (within/crossed) and SOA as within-participant factors, found no main effect of SOA, $F(3, 11) = 1.243$, $p > .32$, $MSE = 5.12$, no main effect of within/crossed, $F(1, 11) = 2.01$, $p > .18$, MSE, 5.30, and no SOA × within/crossed interaction, $F < 1$.

To summarize, for a UV T2 there was a clear drop in performance at short SOAs on within (UV–UV) trials, but not on crossed (SA–UV) trials. This difference in dual-task costs was found despite otherwise similar performance in the within and crossed conditions.

Auditory Tone RTs and Accuracy

T2 RTs and accuracy. The RTs to the unmasked tones are presented in Fig. 3B. A 2 × 4 ANOVA was performed on the T2 RTs, with within-crossed and SOA as within-participant factors. The analysis produced no main effect of within/crossed, $F < 1$, a significant main effect of SOA, $F(3, 33) = 17.89$, $p < .0001$, $MSE = 19134.05$, reflecting the fact that response times were markedly elevated at short SOAs, and a significant SOA × within/crossed interaction, $F(3, 33) = 6.49$, $p < .002$, $MSE = 14227.73$, demonstrating in part that the response slowing observed at short SOAs was reliably larger in the within condition than in the crossed condition, and the different pattern of RTs for the two conditions at long SOAs. The effects of SOA were also analyzed separately for the within and crossed conditions using one-way ANOVAs. T2 RTs varied significantly across SOA both in the within condition $F(3, 33) = 8.73$, $p < .0002$, $MSE = 18632.75$, and in

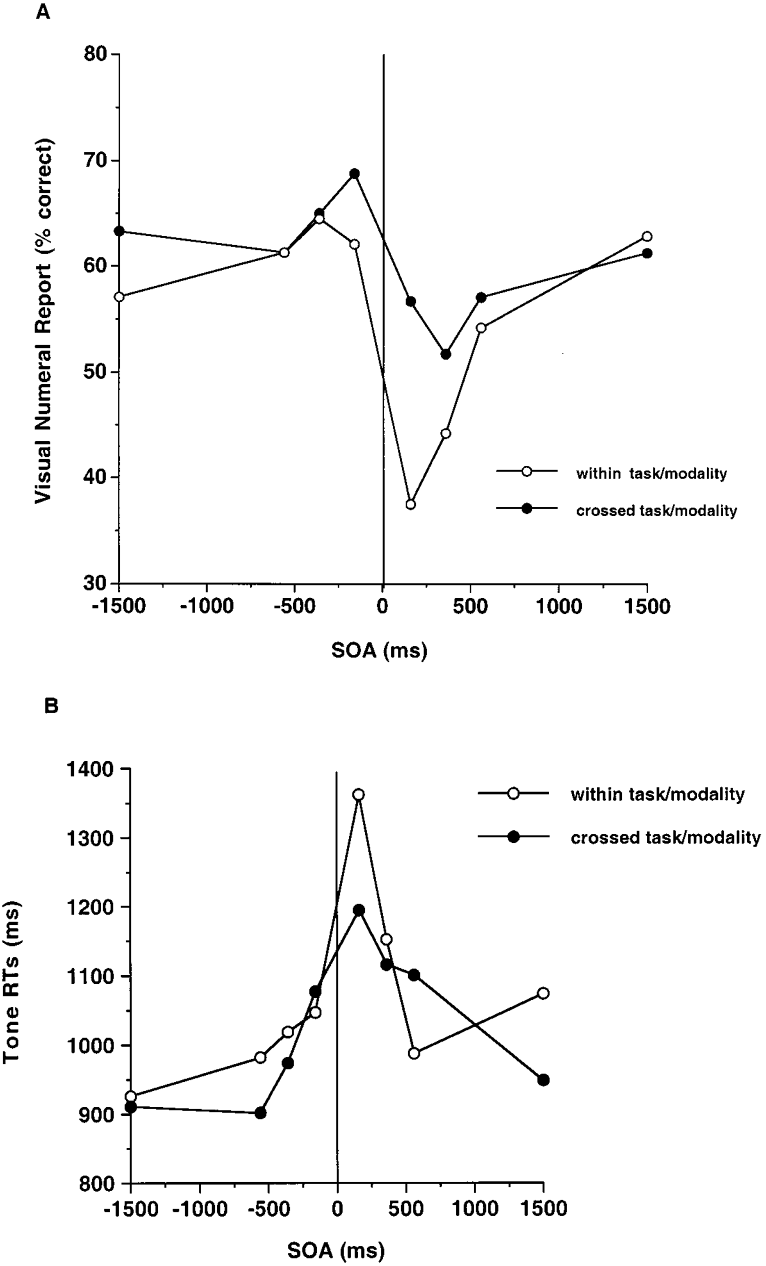

FIG. 3. Results from Experiment 1 as a function of SOA and within vs crossed task/modality. (A) Masked visual numeral accuracy rates. (B) Unmasked auditory tone RTs. (C) Unmasked auditory tone accuracy rates.

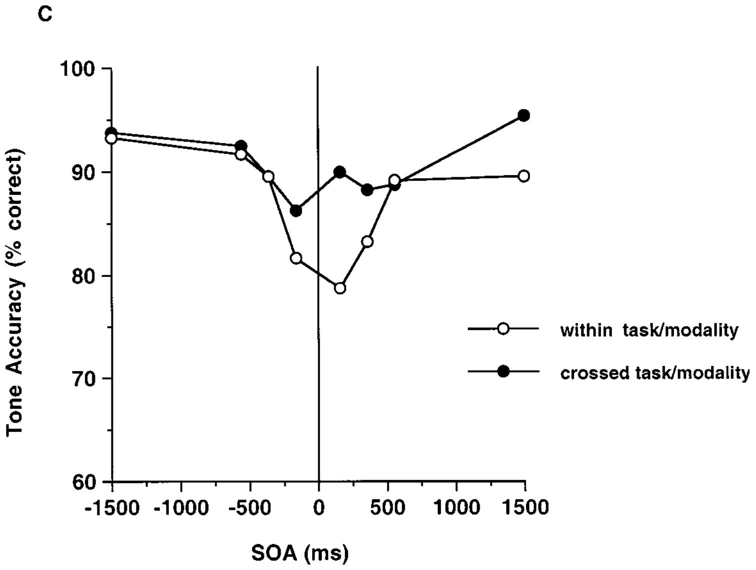

FIG. 3—*Continued*

the crossed condition, $F(3, 33) = 9.02$, $p < .0002$, $MSE = 14094.64$. For the within condition the slope of the RT function at short SOAs approximated the -1 slope that is one of the hallmarks of the traditional PRP effect (Pashler, 1994a). However, this was not the case for the crossed condition where the slope, although significant, was too shallow to approach -1.

It is worth noting that the slope of the RT function in the within condition (both targets SA) was reduced when trials requiring the same response for T1 and T2 (e.g., both ‘‘high’’) were retained in the analysis. With these trials included, mean RTs at the shortest SOA of 160 ms were almost exactly the same for the within and crossed conditions (1206 and 1196 ms respectively). The significant within/crossed by SOA interaction was still found, however, due to the fact that RTs in the within condition dropped off more quickly in the middle SOA range. Further data relevant to this point are presented in Experiment 2.

Accuracy rates for tone responses are presented in Fig. 3C. A 2 × 4 within-participants ANOVA as before was also performed on these data. The analysis revealed a main effect of within/crossed, $F(1, 11) = 8.77$, $p < .02$, $MSE = 3.21$, with higher T2 tone accuracy in the crossed condition compared to the within condition, a main effect of SOA, $F(3, 33) = 6.32$, $p < .002$, $MSE = 1.97$, where T2 tone accuracy rates were lowest at short SOAs, and a marginally significant within/crossed × SOA interaction, $F(3, 33) = 2.44$, $p < .09$, $MSE = 2.245$, where the effect of SOA was stronger in the within condition than in the crossed condition. One-way ANOVAs were performed on auditory T2 accuracy rates separately for the within and crossed conditions. There was a significant effect of SOA for the within condition, $F(3, 33) = 7.40$, $p < .0006$, $MSE = 1.73$, but no reliable effect of SOA for the crossed condition, $F(3, 33) = 2.07$, $p > .12$, $MSE = 2.49$. The results of the T2 auditory accuracy analyses support those of the T2 auditory RT analyses, giving no suggestion of speed–accuracy trade-offs.

T1 RTs and accuracy. A 2 × 4 within-participants ANOVA was performed on the T1 auditory RTs, with within/crossed and SOA as factors. There was no main effect of within/crossed, $F < 1$, or interaction between SOA and within/crossed, $F < 1$. However, there was a significant effect of SOA, $F(3, 33) = 3.69$, $p < .03$, $MSE = 26467.01$, which reflected the fact that RTs increased as SOA decreased. The finding may suggest that participants diverted some capacity to processing T2 before responding to T1, and therefore dual-task costs on T2 may be slightly underestimated. However, because there was no within/crossed by SOA interaction, any underestimation would be equal for within and crossed conditions.

A similar 2 × 4 within-participants ANOVA was also performed on the T1 auditory accuracy rates. Again there was a significant main effect of SOA, $F(3, 33) = 14.36$, $p < .0001$, $MSE = 1.34$, but no main effect of within/crossed, $F < 1$, and no SOA × within/crossed interaction, $F(3, 33) = 1.71$, $p > .18$, $MSE = .99$.

Discussion

In important respects, the data from Experiment 1 agreed with those reported by Pashler (1989) and Ruthruff and Pashler (unpublished). In particular, impairments in processing T2 were clearly stronger if both T1 and T2 came from the same task/modality, SA or UV. Against the simple view of only one, shared processing bottleneck contributing to both PRP and AB (Jolicoeur, 1998), these results provide strong evidence for a task-specific form of resource limitation.

In agreement with Jolicoeur and Dell' Acqua (1998, 1999), on the other hand, there was also clear evidence for cross-task interference. In particular, there was a substantial increase in RT when an SA T2 followed shortly after a UV T1 (Fig. 3B). Though this increase was smaller than that produced by an SA T1, it shows the importance of some resource limitation shared between UV and SA processing.

One ambiguity in the data concerns a UV T2 following an SA T1. In this case (Fig. 3A), a suggestion of interference at short SOA was not significant, reminiscent of the negligible effects reported by Pashler (1989) and Ruthruff and Pashler (unpublished). We pointed out above the restricted conclusions allowed by such negative results: Since resource demands are unknown for the two tasks, it may simply have happened that the SA task used here made only modest demands on any shared resource, leading to only modest interference with a UV T2. To investigate this possibility, response selection demands for the SA task were explicitly manipulated in Experiment 2.

A further important result in Experiment 1 concerns exogenous task switching. As shown in Fig. 2B, such switching in relative readiness for SA and UV tasks should have been shown by a pattern of reciprocal performance changes, in particular at long SOA when conditions most closely approached those of typical task switching experiments. In fact, there was no suggestion of such reciprocity: At long SOA, T2 performance was not better on within task/modality trials, as it should have been if T1 biased preparation or readiness toward a T2 from the same task. We return to this result under General Discussion.

Already, certainly, the data from Experiment 1 show the merit of our randomized SA–SA, SA–UV, UV–SA, and UV–UV design. Reconciling much of the conflict in the literature, the results resemble the theoretical pattern of Figs. 1E and 1G, implying that *both* separate and shared resource limitations contribute to PRP and AB phenomena.

EXPERIMENT 2

Experiment 2 used the same design as Experiment 1, except auditory stimuli were compressed speech words varying orthogonally in pitch (low, medium, or high) and word identity (‘‘mug,’’ ‘‘yes,’’ and ‘‘bad’’). In some trial blocks, participants made a speeded response indicating *either* pitch or identity; in others, participants made two speeded responses indicating *both* pitch and identity. Because response selection is a bottlenecked operation (Pashler, 1994a; Welford, 1952) and because subjects must make two independent response selections in the ‘‘both dimensions’’ condition (compared to only one response selection in the ‘‘single dimension’’ condition), the length of the response selection stage is lengthened in the both condition relative to the single condition (Fagot & Pashler, 1992).

Given the results of Experiment 1, and those of Jolicoeur & Dell’ Acqua (1998, 1999), we expected that UV digit identification would produce RT slowing at short SOAs for subsequent SA pitch or identity responses. The more important question concerned UV T2s. The experiment asked whether, with substantially increased response selection demand for an SA T1, there would be correspondingly increased interference with a UV T2.

Method

Participants

Twelve participants (9 females), participated in two 2-h sessions for pay. Participants were between 17 and 44 years of age (mean = 28.5 years) and were members of the Cambridge and area community and the CBU participant panel.

Design

The design was a 2 (one or two auditory response dimensions) × 2 (T1 task/modality) × 2 (T2 task/modality) × 5 (SOA) mixed factorial. Whether participants responded to one or both dimensions of the auditory stimulus was a blocked variable. In each session, there were three blocks, with order counterbalanced across sessions and participants. In the ‘‘single dimension: identity’’ block participants ignored the pitch and responded to the word’s identity. In the ‘‘single dimension: pitch’’ block participants ignored the word’s identity and responded to its pitch. In the ‘‘both dimensions’’ block participants responded to both identity and pitch. T1 task/modality (SA or UV), T2 task/modality (SA or UV), and SOA (160, 360, 560, 1160, and 3000 ms) were all within-participant variables which varied randomly within blocks, with the constraint that each possible combination of these factors occurred equally often. The 3000-ms SOA was included since it was expected that in the ‘‘both dimensions’’ condition the longest RTs would exceed Experiment 1’s longest SOA of 1500 ms. ‘‘Single dimension’’ blocks each had 100 trials, and ‘‘both dimension’’ blocks 200 trials, giving for each participant a total of 800 experimental trials across the two sessions.

Stimuli and Apparatus

The visual stimuli and apparatus were the same as those used in Experiment 1. The auditory stimuli were spoken words compressed to a duration of 150 ms. The words ‘‘mug,’’ ‘‘yes,’’ and ‘‘bad’’ were presented in ‘‘low,’’ ‘‘medium,’’ and ‘‘high’’ pitch, where word identity and word pitch varied orthogonally. These materials were prepared using SoundEdit 16 software. Digital vocal recordings were performed using an Apple microphone and a Power Macintosh AV computer. Recordings were done using 16 bits of resolution for amplitude at a sampling rate of 47 kHz. Recordings were taken of a female voice speaking the words in normal voice, and these were used for the ‘‘medium’’ recordings. Each word was spoken briefly and distinctly (in a staccato manner). Care was taken to keep voice inflection constant across all recordings. High and low recordings were created by shifting the pitch of the medium recording up or down until the low, medium, and high pitches were clearly distinct for each word. The digital recordings for each word were then set to the same amplitude and compressed to a duration of 150 ms without altering pitch. All sounds were presented using 16 bits of amplitude resolution during the experiment.

Procedure

The procedure was the same as that of Experiment 1, with the following exceptions. The first session began with 30 practice trials, in which participants simply identified a single masked visual numeral. These trials were used to set the presentation duration for the numeral on the experimental trials. Across participants, presentation times varied from 67 ms (with the mask presented for 67 ms) to 117 ms (with the mask presented for 17 ms). The experimenter then played all of the auditory words for each participant telling them the correct pitch. To consolidate learning of the three pitches, this was followed by 30 auditory practice trials requiring speeded pitch responses to single unmasked words. The session was then completed by the three experimental blocks, each preceded by 40 practice trials in that block’s condition. The second session was similar, except that initial numeral and pitch practice were omitted.

In ‘‘single dimension: identity’’ blocks, participants were asked to respond to the identity of each auditory word, ignoring pitch. Participants made their speeded identity responses by pressing the ‘‘q,’’ ‘‘w,’’ or ‘‘e’’ keys (for ‘‘mug,’’ ‘‘yes,’’ and ‘‘bad’’ respectively) with the middle three fingers of their left hand. In ‘‘single dimension: pitch’’ blocks, participants were asked to respond to the pitch of each auditory word, ignoring identity. They made their pitch responses by pressing the ‘‘p,’’ ‘‘[,’’ or ‘‘]’’ keys (for ‘‘low,’’ ‘‘medium,’’ and ‘‘high’’ respectively) with the middle three fingers of their right hand. In ‘‘both dimensions’’ blocks participants were instructed to make two speeded responses to each word, one indicating identity and the other indicating pitch, using the same keys as above.

In the ‘‘both dimensions’’ case, participants were allowed to make responses in either order (i.e., pitch then identity or identity then pitch). Similarly, on SA–SA trials participants were free to make all appropriate responses to T1 and T2 in any order. On a ‘‘both dimensions’’ SA–SA trial, for example, participants could report T1 and T2 pitch and then T1 and T2 identity or make responses in any other order, although one common strategy was to respond to both dimensions of T1 and then both dimensions of T2. Throughout the experiment, the examiner watched to ensure that participants did not look at their fingers when making speeded responses.

Results

Visual Numeral Accuracy

Again, performance scores for T1 and T2 were calculated independently of whether response to the other target was correct; but again, scoring only trials in which response to the other target was correct gave similar results. Figure 4A shows the accuracy of visual numeral identification for ‘‘single dimension’’ blocks. Figure 4B shows corresponding data for ‘‘both dimensions’’ blocks. Since an ANOVA showed no significant difference between conditions where participants judged only pitch or only identity of the auditory word, accuracy results have been collapsed across this factor.

T2 accuracy. As shown in Fig. 4A, T2 numeral identification accuracy for ‘‘single dimension’’ blocks dropped markedly at short SOAs, in both within and crossed conditions. A 2 × 5 ANOVA on the ‘‘single dimension’’ data was performed with task condition (within/crossed) and SOA as within-participant factors. The analysis produced a significant main effect of SOA, $F(4, 44) = 7.89$, $p < .0001$, $MSE = 101.98$, no main effect of within/crossed, $F < 1$, and no SOA by within/crossed interaction, $F < 1$, indicating similar loss of accuracy at short SOAs in the within and crossed conditions.

As shown in Fig. 4B, T2 numeral identification accuracy for ‘‘both dimensions’’ blocks dropped markedly at short SOAs, in both the within condition and the crossed condition, but the accuracy deficit was much deeper and later in the crossed case. A 2 × 5 ANOVA on data from the ‘‘both dimensions’’ blocks was performed with task condition (within/crossed) and SOA as within participant factors. The analysis produced a significant main effect of SOA, $F(4, 44) = 9.03$, $p < .0001$, $MSE = 182.49$, a significant main effect of within/crossed, $F(1, 11) = 5.96$, $p < .05$, $MSE = 462.48$, and a significant SOA × within/crossed interaction, $F(4, 44) = 7.44$, $p < .0001$, $MSE = 118.87$, reflecting the fact that the loss of accuracy at short SOAs was much larger and later in the crossed condition, when participants responded to both dimensions of the auditory stimulus, than in the within condition.

A within-participant ANOVA, with single/both dimension and SOA as factors, was performed to examine whether the T2 accuracy deficit in the

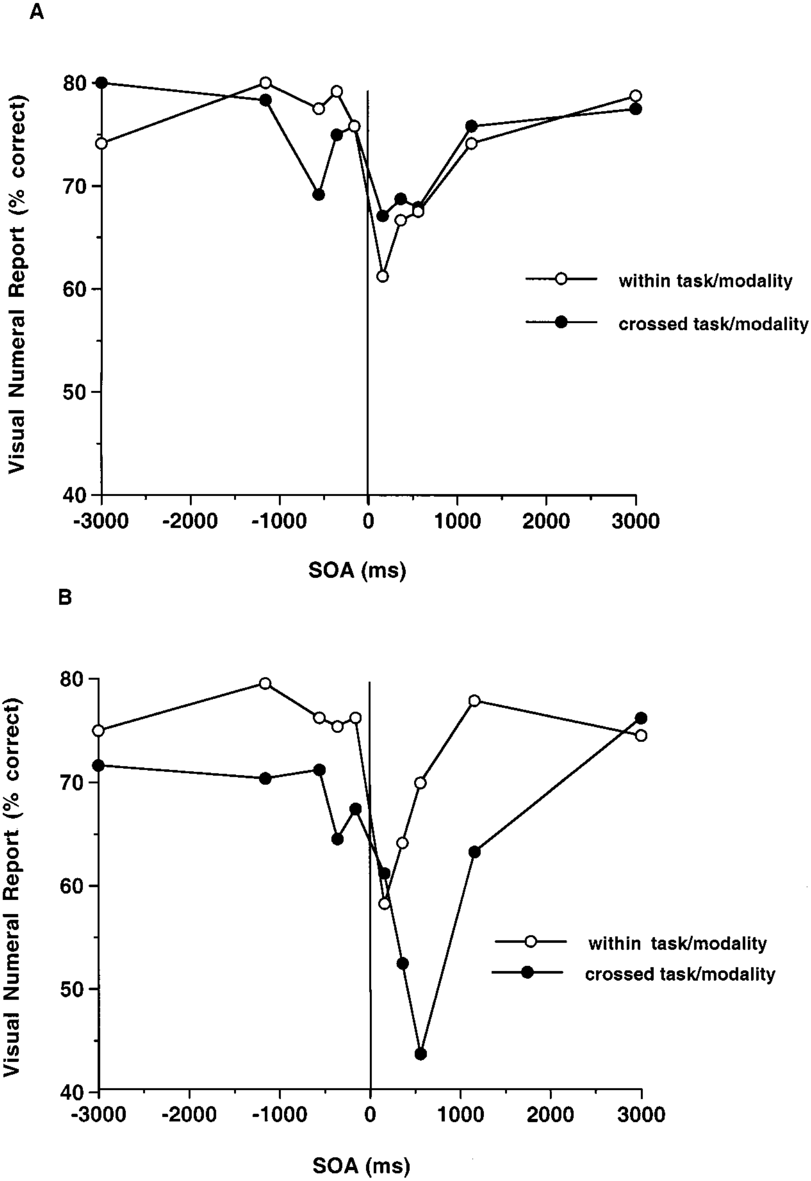

FIG. 4. Masked visual numeral accuracy rates from Experiment 2, as a function of SOA and within vs crossed task/modality. (A) ‘‘Single dimension’’ trials. (B) ‘‘Both dimensions’’ trials.

crossed (SA–UV) condition was larger when participants responded to both dimensions of the auditory T1 word. The analysis revealed a significant main effect of single/both dimensions, $F(1, 11) = 18.14$, $p < .002$, $MSE = 238.18$, a significant effect of SOA, $F(4, 44) = 9.97$, $p < .0001$, $MSE = 159.42$, and a significant single/both dimension by SOA interaction, $F(4, 44) = 3.29$, $p < .02$, $MSE = 145.81$.

A within-participant ANOVA, with single/both dimension and SOA as factors, was also performed on T2 accuracy rates in the within task (UV–UV) condition. This analysis revealed a significant main effect of SOA, $F(4, 44) = 8.33$, $p < .0001$, $MSE = 148.02$, but no main effect of single/both dimension, $F < 1$, and no SOA by single/both interaction, $F(4, 44) = 1.04$, $p > .39$, $MSE = 72.59$, indicating that the UV–UV T2 accuracy deficit at short SOAs was the same size in ‘‘single dimension’’ and ‘‘both dimensions’’ blocks. These results are as expected as there were no SA stimuli presented on these trials. However, the pattern of results from this analysis does show that participants did not have increased dual-task costs overall in the ‘‘both dimensions’’ blocks compared to the ‘‘single dimension’’ blocks, for example, due to changes in strategy or arousal.

T1 accuracy. For ‘‘single dimension’’ blocks, when the UV numeral was T1, participants averaged 78.2% correct responses in the within condition and 75.0% correct in the crossed condition. A 2 × 5 ANOVA, with task condition (within/crossed) and SOA as within-participant factors, found a marginally significant main effect of SOA, $F(4, 44)= 2.45$, $p < .06$, $MSE = 66.99$, a main effect of within/crossed, $F(1, 11) = 10.09$, $p < .01$, $MSE = 31.42$, and a marginally significant SOA by within/crossed interaction, $F(4, 44) = 2.17$, $p < .09$, $MSE = 62.15$. Of course, when a UV T1 was followed by an SA T2, the T2 response was always made first. The results suggest modest interference with UV reports in this case.

For ‘‘both dimensions’’ blocks, when the UV numeral was T1, participants averaged 76.5% in the within condition and 69.1% in the crossed condition. A 2 × 5 ANOVA, with task condition (within/crossed) and SOA as within-participant factors, found no main effect of SOA, $F(4, 44) = 1.04$, $p > .40$, $MSE = 85.38$, a main effect of within/crossed, $F(1, 11) = 27.82$, $p < .0003$, $MSE = 59.30$, where accuracy was better in the within condition than the crossed condition, but no SOA × within/crossed interaction, $F < 1$. Again the results suggest some interference with UV T1 reports following a complex, speeded ‘‘both dimensions’’ response to an SA T2.

Visual accuracy summary. A T2 accuracy deficit was found at short SOAs in both the within and crossed conditions. When a response was made to only one dimension of the auditory word, the two conditions produced similar T2 accuracy deficits. When responses were made to both dimensions of the auditory word, however, the T2 accuracy deficit in the crossed condition was much larger and later than the deficit in the within condition. This difference exists despite otherwise fairly similar accuracy levels on ‘‘single dimension’’ and ‘‘both dimensions’’ blocks.

Auditory Word RTs and Accuracy

All RTs were subjected to the Van Selst and Jolicoeur (1994b) modified recursive outlier elimination procedure with moving criterion. Fewer than 3% of all RTs were removed prior to analysis.

Data from ‘‘single dimension’’ blocks are of most interest and presented first. Mean RTs for pitch and identity responses were significantly different from each other (with identity discriminations having longer RTs than pitch discriminations). Accordingly, RT results are presented separately for pitch and identity responses. It should be noted that similar results in these two cases provide a replication of findings within this one experiment. Again, T1 and T2 responses were scored independently of whether response to the other target was correct and for scoring of T2 trials were excluded if T1 and T2 required the same response.

‘‘Single dimension’’ blocks: T2 RTs and accuracies. Figure 5A shows auditory RTs for pitch responses in ‘‘single dimension’’ blocks. A 2 × 5 ANOVA was performed on the T2 pitch discrimination RTs, with task condition (within/crossed) and SOA as within-participant factors. The analysis revealed a significant main effect of SOA, $F(4, 44) = 39.91$, $p < .0001$, $MSE = 16080.54$, no main effect of within/crossed, $F < 1$, and a significant SOA × within/crossed interaction, $F(4, 44) = 5.53$, $p < .01$, $MSE = 14416.73$. The within condition shows greater RT slowing at shortest SOA, followed by more rapid recovery when compared to the crossed condition. T2 pitch RTs were almost identical for within and crossed trials at the longest SOA, but T2 pitch RTs were much longer for within trials than crossed trials at the shortest SOA. The effects of SOA on pitch discrimination trials were also analyzed separately for within and crossed conditions using one-way ANOVAs. T2 accuracy varied significantly across SOA in the within condition, $F(4, 44) = 35.07$, $p < .0001$, $MSE = 15410.75$, where the RT slowing showed a typical PRP pattern with the characteristic -1 slope over the three shortest SOAs. T2 accuracy also varied significantly across SOA in the crossed condition, $F(4, 44) = 11.99$ $p < .0001$, $MSE = 15086.51$. In this case, also, RTs increased as SOA decreased, though even across short SOAs the slope was much shallower than -1.

Accuracy rates for ‘‘single dimension’’ auditory pitch responses are shown in Fig. 5C. T2 accuracy was high overall. A 2 × 5 within-participants ANOVA performed on the pitch accuracy rates produced no main effect of within/crossed, $F < 1$, no main effect of SOA, $F(4, 44) = 1.18$, $p > .33$, $MSE = 39.81$, but a significant within/crossed × SOA interaction, $F(4, 44) = 3.91$, $p < .009$, $MSE = 23.14$. In the within task/modality condition only, accuracy rates were reduced (93.33%) at the shortest SOA, in line with the corresponding increase in RTs.

Figure 5B shows auditory RTs for identity responses in ‘‘single dimension’’ blocks. A 2 × 5 ANOVA was performed as before, revealing a sig-

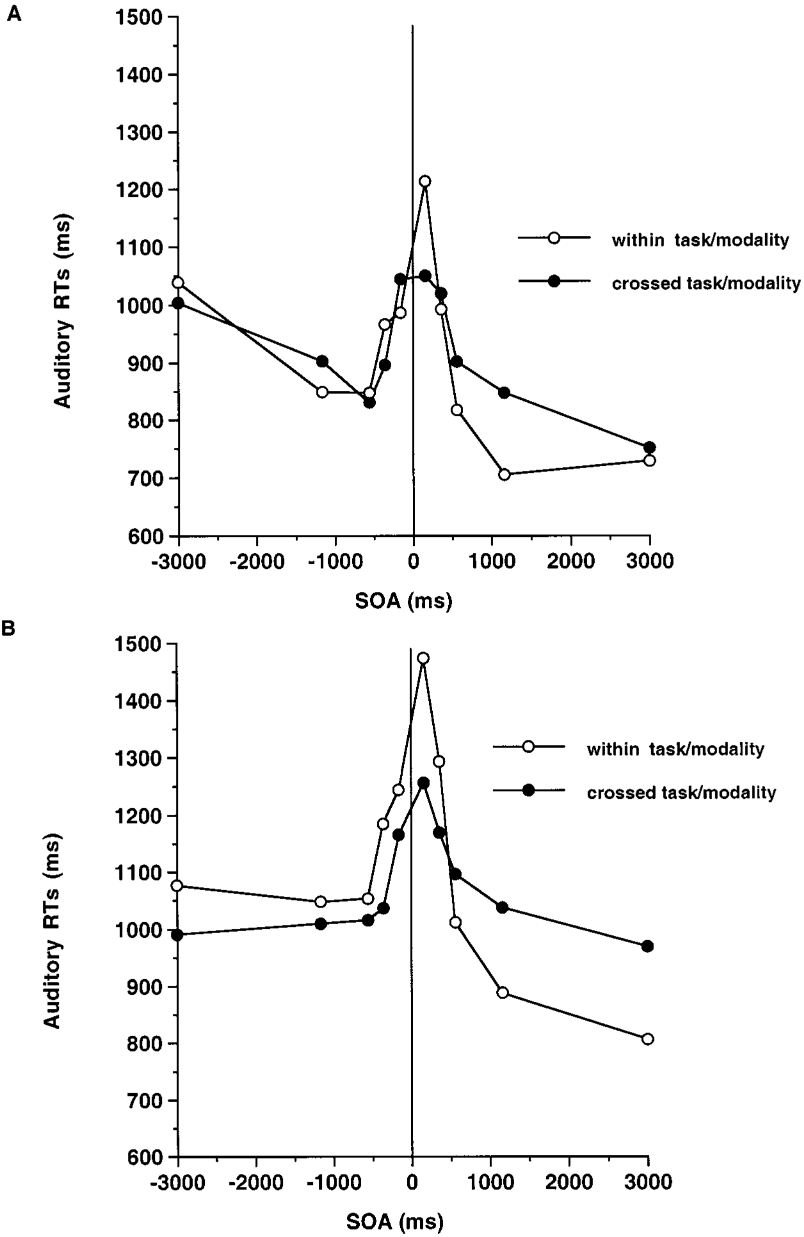

FIG. 5. ‘‘Single dimension’’ unmasked auditory results from Experiment 2 as a function of SOA and within vs crossed task/modality. (A) Pitch RTs. (B) Identity RTs. (C) Pitch accuracy rates. (D) Identity accuracy rates.

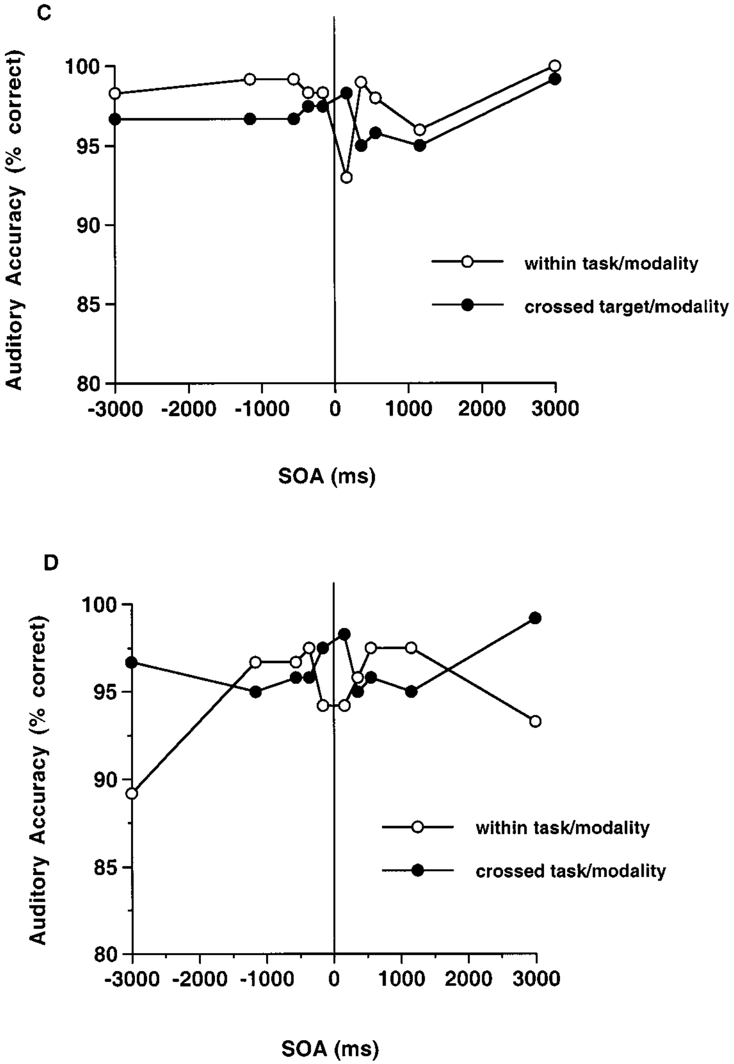

FIG. 5—*Continued*

nificant main effect of SOA, $F(4, 44) = 30.32$, $p < .0001$, $MSE = 30364.60$, no main effect of within/crossed, $F < 1$, and a significant SOA × within/crossed interaction, $F(4, 44) = 5.83$, $p < .001$, $MSE = 30361.73$. Again, the interaction indicates that the RT slowing at short SOAs was greater in the within condition. At longer SOAs, furthermore, T2 identity RTs were shorter in the within condition than in the crossed condition.

The SOA data were also analyzed separately for the within and crossed conditions using one-way ANOVAs. T2 RTs varied significantly across SOA in the within condition, $F(4, 44) = 27.05$, $p < .0001$, $MSE = 35021.72$, again showing the characteristic PRP pattern with -1 slope across shorter SOAs. T2 RTs also varied significantly across SOA in the crossed condition, $F(4, 44) = 5.86$, $p < .0007$, $MSE = 25704.61$, with RTs increasing as SOA decreased, but again the slope in this condition was considerably more shallow than -1.

Accuracy rates for ‘‘single dimension’’ auditory identity responses are shown in Fig. 5D. Again T2 accuracy was high overall. A 2 × 5 within-participants ANOVA produced no main effect of within/crossed, $F < 1$, no main effect of SOA, $F < 1$, but a significant within/crossed by SOA interaction, $F(4, 44) = 3.13$, $p < .03$, $MSE = 26.89$. Accuracy rates were higher in the crossed condition than in the within condition at both the shortest and the longest SOAs.

Recall that SA–SA trials where the same response was required for T1 and T2 (e.g., ‘‘high’’ and ‘‘high’’) were removed prior to the above analyses. If these trials are not removed, the RT pattern does change somewhat. The slope decreases for the within condition, but the within/crossed × SOA interaction still remains significant, $F(4, 44) = 3.56$, $p < .05$ $MSE = 15090.16$, for pitch trials, and $F(4, 44) = 7.10$, $p < .0002$, $MSE = 20232.80$, for identity trials, and RTs for within and crossed condition conditions still cross over at the same SOAs.

‘‘Single dimension’’ blocks: T1 RTs and accuracies. RTs for T1 ‘‘single dimension’’ pitch responses were analyzed using a 2 × 5 within-participants ANOVA with within/crossed and SOA as within-participants factors. No effects reached significance (within/crossed, $F < 1$; SOA, $F(4, 44) = 1.61$, $p > .18$, $MSE = 98226.49$; within/crossed by SOA, $F(4, 44) = 1.80$, $p > .14$, $MSE = 10587.49$). T1 accuracy rates for ‘‘single dimension’’ pitch discriminations were extremely high. A 2 × 5 within-participants ANOVA on these data revealed no reliable effects (within/crossed, $F(1, 11) = 4.23$, $p > .06$, $MSE = 19.70$; SOA, $F < 1$; within/crossed by SOA, $F < 1$.)

RTs for T1 ‘‘single dimension’’ identity responses were also analyzed using a 2 × 5 within-participants ANOVA. The analysis revealed a marginally significant main effect of within/crossed, $F(1, 11) = 4.73$, $p < .06$, $MSE = 38392.23$, where RTs were longer in the within condition than in the crossed condition. The analysis also produced a significant main effect of SOA, $F(4, 44) = 4.21$, $p < .006$, $MSE = 33266.70$, which reflects the increased RTs at short SOAs. However, this RT increase is present for both within and crossed trials, $F < 1$ for the interaction. T1 accuracy rates for ‘‘single dimension’’ identity discriminations were high. A 2 × 5 within-participants ANOVA on these data revealed no significant effect of within/crossed, $F < 1$, or SOA, $F(4, 44) = 1.13$, $p > .35$, $MSE = 47.01$, but a significant within/crossed by SOA interaction, $F(4, 44) = 3.78$, $p < .01$, $MSE = 25.72$, reflecting the lower accuracy rate (89.2%) in the within condition at the longest SOA. T1 pitch and identity RTs and accuracy rates suggest no important speed–accuracy trade-offs. However, the significant effect of SOA for T1 identity RTs suggests that, in this case, dual-task costs at short SOAs were reflected partially in the T1 data.

‘‘Both dimensions’’ blocks: SA–UV and UV–SA trials. In ‘‘both dimensions’’ blocks, two responses were made to each SA target. Results for SA–SA trials required rather different treatment from the others and are considered separately below. For SA–UV and UV–SA trials, i.e., trials with one SA and one UV event, SA scores were again calculated independent of whether the UV response was correct. RTs, however, were based on just those trials on which the conjoint response to the SA event was correct (i.e., correct responses to both pitch and identity).

Since participants were free to respond in either order (pitch then identity or vice versa), it does not seem useful to present separate data for pitch and identity responses. Instead, RT data in Fig. 6A are shown separately for the first and second responses on each trial, both timed from stimulus onset. By comparison with the ‘‘single dimension’’ RTs shown in Figs. 5A and 5B, responses took almost twice as long to complete on ‘‘both dimensions’’ trials (Fig. 6A, second response). This result provides strong evidence that, by comparing ‘‘single dimension’’ and ‘‘both dimensions’’ blocks, we successfully manipulated the length and/or difficulty of SA response selection. As in ‘‘single dimension’’ blocks (Figs. 5A and 5B, crossed task/modality trials), second response RTs were elevated by approximately 200 ms at short SOAs. While second response RTs are useful in showing the time to complete processing, first response RTs are less informative, as participants were free to employ any response ordering or grouping strategy they chose. In fact, the first response typically preceded the second by around 400 to 500 ms, the delay in comparison to ‘‘single dimension’’ RTs being consistent with some degree of response grouping. An ANOVA on T1 RTs, with within-participant factors response (first/second) and SOA, showed the inevitable effect of response, $F(1, 11) = 104.67$, $p < .001$, $MSE = 64579.81$, no significant effect of SOA, $F(4, 44) = 1.26$, $p > .30$, $MSE = 80596.78$, but a significant interaction, $F(4, 44) = 4.15$, $p < .01$, $MSE = 2623.04$. The effect of SOA was perhaps slightly more marked on the second response as compared to the first. A similar ANOVA on T2 RTs showed the inevitable effect of response, $F(1, 11) = 94.37$, $p < .001$, $MSE = 60360.42$, a significant effect of SOA, $F(4, 44) = 6.34$, $p < .001$, $MSE = 44485.13$, and no significant interaction, $F(4, 44) = 1.86$, $p > .10$, $MSE = 3903.16$.

SA accuracies for SA–UV and UV–SA trials (percentage of trials with both pitch and identity correct) appear in Fig. 6B. As in ‘‘single dimension’’ blocks (Fig. 5C and 5D, crossed task/modality), there was no evident loss of accuracy at short SOAs for T2, $F < 1$, or for T1, $F(4, 44) = 2.26$, $p > .05$.

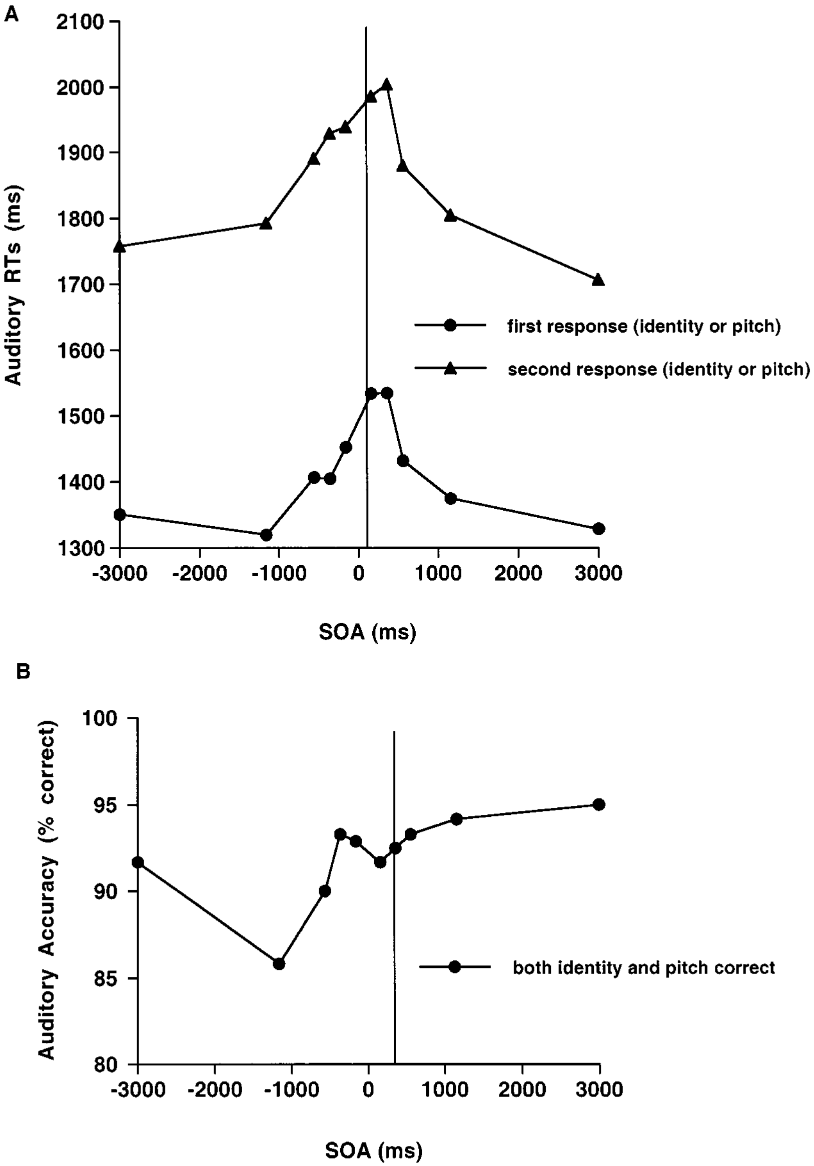

FIG. 6. ‘‘Both dimensions’’ unmasked auditory results from SA–UV and UV–SA trials in Experiment 2. (A) RTs as a function of SOA and first/second response on the trial. (B) accuracy rate (percentage of trials on which both responses were correct) as a function of SOA.

TABLE 1
Mean Response Time (in Milliseconds) at Each SOA for Each Response on SA–SA Both Dimension Trials

Response	160	360	560	1160	3000
First	1748	1583	1540	1489	1276
Second	2204	1977	1881	1814	1600
Third	3016	2749	2443	1911	1438
Fourth	3363	3093	2761	2408	1687

‘‘Both dimensions’’ blocks: SA–SA trials. For ‘‘both dimensions’’ SA–SA trials, participants were free to make their four SA responses in any order and to employ any strategy of serial or grouped responding. The resulting complex data are only of secondary interest here; we present a brief summary for completeness.

For analysis, we selected just those trials on which all four required responses were different. Of these, all four responses were correct on 77.8% of trials; only these were selected for analysis of RTs. As for SA–UV and UV–SA trials, we wished to obtain separate mean RTs for the first, second, third, and fourth responses on a trial. An added complication here is that any of these responses could be a response either to T1 or T2, so that instead of separating T1 and T2 data, we calculated just mean RTs for first, second, third, and fourth, responses at each possible T1–T2 SOA. On each trial, each RT was measured from onset of the stimulus (T1 or T2) it matched. Resulting mean RTs are shown in Table 1.

Since each value in Table 1 represents a mixture of responses to T1 and T2, with the exact mixture varying across participants and SOAs, only rather coarse conclusions can be drawn. At the shortest SOA, the first response followed its stimulus by a mean of 1748 ms, increasing to 3363 ms for the fourth response. As expected, all RTs declined as SOA increased, with the attendant opportunity to complete both responses to T1 before onset of T2. By an SOA of 3000 ms, all RTs had declined to a level roughly comparable to those seen on SA–UV and UV–SA trials. An ANOVA with the within-participant factors response (first, second, third, and fourth) and SOA showed the inevitable main effect of response, $F(1, 11) = 46.50$, $p < .001$, $MSE = 314606.02$, a main effect of SOA, $F(4, 44) = 24.95$, $p < .001$, $MSE = 334857.79$, and a significant interaction, $F(4, 44) = 14.50$, $p < .001$, $MSE = 59099.01$.

Discussion

The most important results from Experiment 2 concern UV T2s following ‘‘both dimensions’’ SA T1s. During the extended process of choosing two speeded responses to the auditory T1, there was a remarkable deficit in ability to identify a masked visual T2. This deficit built up over the first 500 ms following T1 and continued for more than 1000 ms. Such results provide overwhelming evidence for shared resources between SA and UV tasks: Whatever its nature, some process essential to unspeeded visual identification can be massively impaired by a demanding, concurrent SA task. In this respect, Experiment 2 confirms the previous cases of SA–UV interference reported by De Jong and Sweet (1994), Jolicoeur (1999a), and Jolicoeur and Dell' Acqua (1999).

At the same time, the findings from ‘‘single dimension’’ blocks largely replicated the results of Experiment 1, providing evidence for task-specific in addition to shared resource limitations. SA data were just as before: Even on crossed task/modality (UV–SA) trials, there was an increase in T2 RTs at short SOA, but this increase was even stronger in the within task/modality (SA–SA) case. In UV data the pattern was slightly different from that seen in Experiment 1: Short SOAs were associated with reduced T2 accuracy on both within (UV–UV) and crossed (SA–UV) trials, and though the trend was for greater interference in the within task/modality case, this time the difference was not significant. Overall, still, the pattern of ‘‘single dimension’’ data most closely resembled that shown in Figs. 1E and 1G, indicating a combination of task-specific and shared resource limitations.

Again the data may be examined for evidence of reciprocal changes in task preparation, in particular at long SOAs. UV data, as before, showed no hint of such reciprocity: At long SOAs, T2 performance was much the same whether T1 was SA or UV (Figs. 4A and 4B). For SA data the picture is more complicated. On the one hand, T2 performance at long SOAs can be compared for within and crossed task/modality conditions (Figs. 5A–5D). In this case, the only conspicuous result is that identity responses were faster (Fig. 5B) but less accurate (Fig. 5D) in the within task/modality case. Another relevant comparison, however, is between T1 and T2 responses; evidently (Figs. 5A and 5B), in the within task/modality case, T2 RTs ‘‘recovered’’ at long SOA to a value substantially below T1 RTs, to some extent reminiscent of the exogenous switch of task readiness shown in Fig. 2B. Two points may be made here. First, no such priming effect was evident in Experiment 1 (see Fig. 3B). Second, there is no suggestion of *reciprocal* readiness changes following an SA T1: Though an SA T2 may have been facilitated at long SOA (Figs. 5A and 5B; within task/modality), there was no suggestion of impairment for UV T2s (Fig. 4A; crossed task/modality). If anything, the data suggest some ‘‘costless’’ priming of its own task by an SA T1; as in Experiment 1, accordingly, there was no strong or reliable evidence for a conventional task switch effect.

With regard to the overall relationship between AB and PRP phenomena, Experiments 1 and 2 provide strong support for elements of both separate-limitation (Pashler, 1989) and shared-limitation (Jolicoeur, 1998) views. In line with the separate-limitation view, there is strong evidence that interference with T2 processing can be greater when T1 and T2 come from the same task/modality. But even when they do not, very substantial interference can be produced by increases in T1 processing demand.

GENERAL DISCUSSION

In this article we have addressed the relationship between underlying resource limitations in PRP and AB phenomena. In particular we have addressed the debate between separate- and shared-limitation views. We showed that, to obtain a separate measurement of both cross-task and shared resource limitations, a design is needed assessing all four possible task combinations: SA–SA, SA–UV, UV–SA, and UV–UV. Though partial designs used in previous work have provided evidence for either separate or shared limitations, typically they have not been able to rule out additional contributions from a limitation of the other type. Indeed, the two experiments conducted here with the full design show that both types of limitation are important: In part, the resource limitations underlying PRP and AB phenomena are specific to the different tasks involved, but at the same time, substantial cross-task interference can be seen under appropriately demanding conditions. An additional benefit of randomizing SA–SA, SA–UV, UV–SA, and UV–UV trial types is control over endogeneous switches in task set and ability to assess stimulus-driven or exogeneous switches. In fact, for the present task pairs the data gave little suggestion of task switching effects. Rather than reciprocal changes in SA and UV performance, the data showed a fairly simple pattern of T2 interference at short SOAs, just as expected if only conventional resource limitations contribute to the data. In the following sections, each of these main findings is considered in more detail.

Interpretation of Resource Limitations

To a large extent, the present work was motivated by two simple accounts of relations between SA and UV processing. At one extreme, the separate-limitation view proposed no significant resources shared between these two types of event (Pashler, 1989, 1994). At the opposite extreme, the shared bottleneck view proposed a single limit responsible for both SA–SA (conventional PRP) and UV–UV (conventional AB) interference. How then should we interpret evidence for both separate and shared limitations? As we mentioned at the outset, both SA and UV events undoubtedly involve multiple components. This is clear in conventional stage models of speeded tasks such as SA, with at least stimulus encoding, response selection, and response execution components. Though UV tasks are potentially simpler in that postencoding stages may have little influence on performance, still there is a need for assorted extravisual control processes such as establishing task-appropriate identification criteria, directing attention to digit as opposed to mask information, and so on. Such considerations leave open multiple possibilities for SA–UV interaction.

One major clue from the present results concerns the shared aspect of resource limitation. From the data of Experiment 2, we can conclude that the demands of the SA task on some *shared* resource are substantially greater when two separate features must be identified and two responses made. Is this a consequence of increased perceptual or response selection demand? The perceptual demand interpretation seems unlikely, since it is well known that, in pure visual AB experiments, T2 performance is exactly the same whether participants must identify one or two features of T1 (Jolicoeur, 1999c; Ward, Duncan, & Shapiro, 1996). In line with many other experiments, resource demands in unspeeded visual identification depend only on the number of attended objects, not the number of attended features from those objects (Duncan, 1984, 1993). Only when T1 responses are speeded does T2 performance decline with increased number of T1 features to be processed, either in the pure PRP case (Fagot & Pashler, 1992) or as in the present data when T1 is speeded but T2 is unspeeded (see also Jolicoeur, 1999c, for similar data from a speeded visual T1 followed by an unspeeded visual T2). The natural interpretation is that increased *speeded response selection demand* increases consumption of a resource *shared* between SA and UV events (see also Jolicoeur, 1998, 1999a). Though the attempt in unspeeded tasks is to avoid any influence of postperceptual processes, this attempt is apparently unsuccessful; some crucial component of these tasks remains highly sensitive to concurrent response selection demands.

This said, the other major clue from these and previous data concerns the task-specific element of resource demand. Undoubtedly, the different components of SA and UV events result in somewhat different resource requirements. In the conventional separate-limitation view (Pashler, 1989, 1994), two considerations are at the heart of this difference. First, SA and UV tasks are differentially sensitive to respectively response selection and perceptual encoding processes. Second, within the encoding stage they call on different, modality-specific resources. In the following sections, we consider possible contributions from each of these factors.

A stage model. Perhaps the simplest possible model consistent with the present data would envisage two forms of resource limitation. First would be a cross-modal resource involved in both UV and SA stimulus encoding. For this encoding resource, demands would be greater for the more difficult UV task. Also important in both UV and SA tasks, however, would be a resource limit arising in later processing stages. In speeded response selection tasks this resource might lead to largely serial processing, as in the conventional bottleneck model. In unspeeded identification tasks its contribution would be less certain: As in the Jolicoeur (1998) model one might propose involvement in some late consolidation of the visual percept for report, or alternatively, there might be involvement in nonvisual, control aspects of the UV task. For the present experiments, demands on this late-stage resource would be greater for the SA task.

Even with only two forms of resource limitation, this model could easily be fit to the data. Under appropriate conditions (Experiment 1; Experiment 2, ‘‘single dimension’’ cases), the UV task could be more sensitive to encoding than to late-stage resource limitations. At short SOAs, there would be some interference for a UV T2 following an SA T1, but stronger interference for a UV T2 following a UV T1. At the same time, increasing SA late-stage demands (Experiment 2, ‘‘both dimensions’’ case) could ultimately lead to any arbitrary level of UV T2 performance decrement. For the SA task the situation could be complementary: This time it would be late-stage rather than encoding resources that were most important. At short SOAs, there would be interference for an SA T2 following a UV T1, but stronger interference for an SA T2 following an SA T1. Though arbitrary, all these assumptions are plausible. They illustrate one way to fit a data pattern implicating both separate and shared resource limitations—with only two such limitations, differentially important in SA and UV tasks.

One interesting line of support for stage model comes from recent event-related potential (ERP) evidence. A familiar ERP component—the P300—is commonly taken to reflect the completion of stimulus identification or categorization (Donchin, 1981). In line with this, conventional PRP experiments show little or no change in T2 P300 latency even at short SOAs, when T2 responses themselves are substantially delayed (Luck, 1998). This is as we should expect if T2 slowing in the PRP reflects a response selection bottleneck, i.e., delay in T2 processing at a stage following stimulus categorization. In contrast to this result, at short SOAs, Arnell, Iverson, Larson, and Hurdelbrink (2001) found substantial P300 delays for an SA T2 following a UV T1. Though results are preliminary, the implication is that, in the UV–SA case, the predominant source of T2 delay is in encoding rather than response selection. Certainly such data suggest merit in the proposal of somewhat separate resource limitations for these two stages of processing.

Modality-specific limitations. Though the data can be fit by proposing only two forms of resource limitation, this is not to say that further differentiations are not important. In particular, the stage model might be augmented by further proposing that, to some extent at least, different perceptual resources are required for processing in visual and auditory modalities. As we mentioned above, such a proposal would be consistent with physiological evidence for attentional restrictions in early, modality-specific cortex (Desimone & Duncan, 1995). This extra element of specificity in the model could only add to its power in accounting for combinations of separate and shared resource limitations. For a UV T2, it should be easy to find conditions under which there was more interference from a UV T1 than from an SA T1. Competition for modality-specific perceptual resources would be the dominant factor as long as late-stage resource demands were relatively low (Experiment 1; Experiment 2, ‘‘single dimension’’ case). As before, however, increasing the late-stage demand of an SA T1 could in principle increase impairments in UV T2 performance to any arbitrary degree (Experiment 2, ‘‘both dimensions’’ case). SA data could also be explained straightforwardly. When an SA T2 followed an SA T1, there would be strong interference in both modality-specific perceptual processing and the response selection bottleneck.

An obvious test for modality-specific encoding resources is use of unspeeded tasks for within- and between-modality AB experiments. In many conditions, i.e., providing shared-resource demands are not too discrepant for UV and UA (unspeeded auditory) discriminations, there should be clear evidence for the postulated modality-specific resource limitations: A UV T2 should suffer more interference from a UV T1 than from a UA T1, while a UA T2 should show the reverse pattern. As we have mentioned, existing data on this question are contradictory (Arnell & Jolicoeur, 1999; Duncan et al., 1997; Treisman & Davies, 1973), leaving more work to be done. Meanwhile, it remains highly plausible that some degree of modality specificity as well as some degree of stage specificity contributes to the differential resource utilization of SA and UV tasks.

Other interpretations. Important though stage and modality distinctions may be, it is likely that the above simple models capture only a part of the relationship between SA and UV resource utilization. As we discussed above, there are actually many possible interpretations for a data pattern (cf. Figs. 1E and 1G) giving evidence for both separate and shared limitations. Though the above two models envisage rather discrete resource limitations, for example, an equally plausible possibility is a more continuous model in which processing events call on many different cognitive or neural elements, interference between concurrent events depending on overall similarity and thus overall overlap (Kinsbourne & Hicks, 1978).

The key general conclusion from our results is that PRP and AB phenomena are neither entirely the same nor entirely unrelated. Perhaps a more plausible overall view is that concurrent activities can interfere or interact for many reasons (Allport, 1980). In typical cases, PRP and AB experiments may sample from this pool of possible ‘‘resource limitations’’ in rather different ways. For example, when responses are speeded, stimuli are in different modalities, and encoding demands are modest, the predominant basis for interference may indeed lie in response selection. Contrarily, when tasks are unspeeded and the main source of error is stimulus identification, interference may predominantly arise in modality-specific perceptual systems. But these simple cases may be the exception rather than the rule; with modest increases in task demand or complexity, there can be major interference across more apparently distant cognitive domains.

Task Switching

In our data there was little evidence for task switching contibutions to the data, i.e., for reciprocal changes in UV and SA performance of the sort that might be attributed to alterations in relative preparedness for the two types of event. In part, this presumably reflects our use of a design giving no explicit motivation for endogenous or intentional switches: Because events were randomized, the identity of T1 gave no information concerning the forthcoming T2. Neither, however, was there evidence for exogenous task switching, or sequential carryover effects: Even at long SOAs, T2 performance showed no consistent benefit from a preceding T1 of the same type.

An important result in the task switching literature may help to explain this for our particular task combination. In general, ‘‘switch costs’’—deficits accompanying task alternation—are greater when switching between two tasks *both of which can be performed on the same input.* For example, costs are substantial when alternating between adding and subtracting 3s from two-digit numbers; they are much smaller or absent when alternating between adding 3 to numbers and giving antonyms to words (Jersild, 1927; Spector & Biederman, 1976). To a large extent, switches in relative preparation or dominance for two tasks seem to be important only in the case of significant conflict over how to process a presented stimulus; in the absence of such conflict, it may indeed be possible to maintain maximum preparedness for both tasks simultaneously. The present UV and SA tasks would represent an extreme case in point, affording no possibility of performing the wrong task on any given input. Plausibly this is the reason that task switching effects were negligible in these data.

Of course, this is not to say that such effects were similarly negligible in the many previous PRP, AB, and hybrid experiments that have used fixed-order, different-task designs for T1 and T2. Such experiments, indeed, have varied widely in how strongly each stimulus constrained the task to be performed on it. For the future, we suggest that our randomized design—in which the total set of stimulus and response alternatives is the same for T1 and T2—should have substantial utility both in minimizing the motivation for task switching and in assessing such switching when it occurs.

Conclusion

In this article we have considered the relationship between two forms of dual-task interference, the conventional PRP and AB phenomena. In previous work, hybrid PRP–AB experiments have led to conflicting, simple views—either that PRP and AB phenomena arise from quite separate resource limitations (Pashler, 1989) or that they are common reflections of just one such limitation (Jolicoeur, 1998). A direct comparison of hybrid tasks with corresponding pure PRP and AB cases shows that both views are incomplete: Though separate limitations undoubtedly contribute to the data, there are also shared limitations whose contribution can be made arbitrarily large by simple increases in demand. As so often in psychology, both conflicting views hold good in restricted regions of task space; the broader picture is that neither accounts for the full range of PRP/AB phenomena.

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