

Running Head: Attentional Blink and Task Switching

The attentional blink and task switching
within and across modalities

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Version of 12/12/2000

Chun, M. M., & Potter, M. C. (in press). The attentional blink and task-switching. To appear in K. Shapiro (Ed) Temporal constraints on human information processing. Oxford: Oxford University Press.

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Abstract

The attentional blink (AB) is a robust deficit obtained for a second visual target (T2) appearing within 200 - 600 ms of a correctly identified first target (T1). In most AB studies both targets appear among distractors in a rapid serial visual presentation (RSVP), and a key variable is the lag or SOA between the two targets. In the present chapter we review research bearing on the basis for the AB deficit and related deficits, including cross-modal versions of the AB procedure and tasks that require a task switch (a switch in target criterion) between T1 and T2. We conclude that the standard AB deficit is restricted to visual targets and can be distinguished from an additional deficit that results from a task switch between T1 and T2. The latter effect is found with cross-modal and auditory stimuli as well as visual stimuli, and is additive with the AB effect (when both targets are visual). We propose that the standard AB effect occurs at a different stage of processing than the more central task-switching deficit and shows features that distinguish it from the latter. The visual AB effect represents a limit in the speed with which visual targets — which are vulnerable to masking — can be consolidated into working memory or awareness: A second target may be lost while queuing for access to the consolidation process. We review studies that show a clear dissociation between AB and task-switching deficits, consistent with complementary findings of Allport and Hsieh (this volume) on criterion shifting in RSVP target search. The evidence suggests that there are multiple bottlenecks in processing which individually or together limit performance when two target stimuli must be processed close in time.

There are clear limitations in the ability to process perceptual information, but what is the nature of these limitations? This a fundamental enterprise of inquiry in the field of cognitive psychology. A classic debate concerns the locus of attentional bottlenecks along the information processing stream (Broadbent, 1958; Deutsch & Deutsch, 1963). According to these accounts, all sensory events that require a response must pass through some limited capacity bottleneck. However, it is also possible that multiple attentional bottlenecks exist throughout the information processing stream. As such, capacity limitations at one stage of the system may constrain performance independently of limitations at other stages of the system. Hence, an important goal for researchers is to dissect the human information processing stream by examining which tasks interfere with which.

The endeavor to analyze and understand the architecture of perceptual and cognitive processing relies heavily on the use of dual-task paradigms (Pashler, 1994). In dual-task paradigms, observers are presented with two tasks that must be performed concurrently or in rapid succession. For example, subjects could be asked to report two targets from a display (Duncan, 1980). Typically, interference occurs between the two tasks, and such performance decrements are revealing of the attentional demands of the tasks performed. In sum, dual-task interference illuminates capacity limitations within the information processing stream.

One of the most striking and compelling examples of dual-task interference is the attentional blink. In this paradigm, subjects are asked to identify and report two visual targets presented in rapid succession at various intervals (stimulus onset asynchronies, SOA) from each other. These targets appear amidst a rapid serial visual presentation (RSVP) sequence of visual distractors. The items are presented at rates of 8 to 12 items per second, pushing perceptual/cognitive processing mechanisms to the limit. While subjects are typically good at identifying and reporting the first target (T1) in such sequences, they exhibit a dramatic impairment in reporting the second target (T2) when it appears within half a second of the first (See Figure 1). This deficit has been called the "attentional blink" (AB, Raymond et al., 1992), and it has been observed in numerous labs using a variety of paradigms (Broadbent & Broadbent, 1987; Chun & Potter, 1995; Duncan, Ward, & Shapiro, 1994; Grandison, Ghirardelli, & Egeth, 1997; Jolicoeur, 1998; Maki, Frigen, & Paulson, 1997b; Seiffert & Di Lollo, 1997; Weichselgartner & Sperling, 1987). The AB paradigm is remarkable for several reasons. First, it is exceptionally robust, resulting in drops in target identification performance from 87% to 30% correct (e.g., Chun & Potter, 1995). Second, the temporal lag (SOA) manipulations allow researchers to map a precise time course of interference. Performance on T2 is typically lowest at Lag 2 and gradually improves with increasing lag, asymptoting at Lags 6 or 7 (500-700 ms after T1 onset). Finally, the paradigm is such that essentially any type of task can be presented during the blink, making it a versatile tool for examining dual-task interference. For example, Joseph, Chun, and Nakayama (1997) used this paradigm to demonstrate that attention is needed to consciously report "pre-attentive" orientation pop-out features. In this chapter, we will review many other variations of this AB paradigm.

Insert Figure 1 about here

The attentional blink demonstrates capacity limitations for consolidating visual information into working memory and awareness. A number of theories have been proposed to explain this phenomenon (e.g., Chun, 1997b; Chun & Potter, 1995; Jolicoeur, 1998, 1999a; Maki, Couture, Frigen, & Lien, 1997a; Raymond, Shapiro, & Arnell, 1992; Raymond, Shapiro, & Arnell, 1995; Shapiro & Raymond, 1994; Ward, Duncan, & Shapiro, 1996), and there is now substantial convergence among several of these (e.g., Shapiro,

Arnell, & Raymond, 1997b). We proposed that target processing in RSVP proceeds in two stages (Chun & Potter, 1995), expanding suggestions by Broadbent and Broadbent (1987) and Duncan (1980). According to the two-stage model, every RSVP event (at least at rates of 10 items/s or slower) is rapidly identified in Stage 1, allowing for immediate detection. Analysis in Stage 1 may be fairly sophisticated and complete, such that visual types (stimulus identities) may be momentarily activated for all items in an RSVP sequence (Luck, Vogel, & Shapiro, 1996; Potter, 1975, 1976, 1993, 1999; Shapiro, Driver, Ward, & Sorensen, 1997a). However, we proposed that these Stage 1 representations may be subject to rapid forgetting or erasure as subsequent RSVP stimuli are presented (Giesbrecht & Di Lollo, 1998). Successful target report requires further processing and consolidation of these initially activated target representations. This is achieved through Stage 2, a capacity limited operation. While Stage 2 is occupied with a target, a second target cannot be consolidated (Chun & Potter, 1995; Jolicoeur, 1998). Thus a T2 appearing at short lags during bottleneck processing for T1 is likely to be missed, producing the AB effect. The spared level of performance at Lag 1 suggests that both T1 and the immediately following item (whether a distractor or T2) are processed together (Chun & Potter, 1995; Raymond et al., 1992). When the following item is T2, then both targets are likely to be successfully processed, producing Lag 1 sparing as seen in Figure 1.

Other models of AB agree that items occurring during the blink are momentarily identified (Stage 1) and then are lost before entering a later stage of processing (Stage 2) that is limited in capacity (Shapiro et al., 1997b). These models differ, however, in how to characterize the limited-capacity process of Stage 2. Simply put, does the attentional blink reveal a single multi-purpose fundamental bottleneck that any type of information must pass through to be reported and used for action? Or is this attentional limitation restricted to visual targets? The answer to this question is important for understanding the locus of the attentional blink, and it is of broader significance for understanding the attentional capacity and architecture of information processing in general. Shapiro and Raymond (1994) proposed that the main source of interference in AB occurs as competition for retrieval between the two targets, as well as their trailing distractors, in visual short term memory (VSTM). Hence, the interference model proposes that the AB must be a visual effect. Chun and Potter (1995) proposed that initial interference is inherently perceptual (between T1 and the +1 item), but that resolving this perceptual interference to identify the target slows down other processing stages such as consolidation into working memory. This theory also predicts that AB should be strictly visual. Finally, Jolicoeur (1998) proposed that T1 report engages short term consolidation processes which consumes central resources. This theory predicts that AB does not have to be visual, as short-term memory consolidation processes may occupy central resources needed to consolidate any type of target, regardless of modality. In addition, this central mechanism has a late locus, sharing capacity with other important cognitive operations such as response selection (Jolicoeur, 1998, 1999a).

Thus, the main question confronting the field is whether dual-task performance in AB tasks can be described in terms of a central bottleneck or as an attentional limitation restricted to the visual modality. The most direct way to tackle this question is to investigate whether AB effects can be obtained for other modalities and especially between targets from different modalities. If the AB has a central locus, then it should be observed for the auditory modality and between visual and auditory modalities. If it is specific to the visual system, it should not be observed for the auditory modality, and also not for cross-modal targets.

While the logic is straightforward, the empirical evidence is decidedly mixed, at least when viewed superficially. We will review some existing work that examines AB for targets presented within and across the visual and auditory modalities. Then we will discuss why we think discrepancies exist between studies published to this date. We will conclude with a model that outlines an architecture of human information processing that can explain these discrepancies, as well as point to future issues that deserve further empirical investigation.

Dual-task interference for visual, auditory, and cross-modal targets.

Potter, Chun, Banks, and Muckenhoupt (1998) directly compared search performance for visual and auditory targets presented in rapid sequences. Subjects were asked to detect and report two letter targets embedded in a stream of digit distractors. Rapid auditory presentation (RAP) sequences were generated using compressed-speech versions of a set of letters and digits. Visual RSVP sequences were similar to those used in previous attentional blink studies (Chun & Potter, 1995). Each modality was tested across blocks within subjects. The results are illustrated in Figure 2. A robust AB effect was obtained for visual targets, replicating previous studies. In contrast, no auditory AB was observed. Performance was flat across lag, unlike the marked lag effect in visual search. This pattern was replicated across two experiments. In one experiment, target performance in each modality was equated for difficulty (Experiment 1, Potter et al.), by using slightly faster rates for visual stimuli (120 ms per item) than auditory stimuli (135 ms per item). In a second experiment, the two modalities were matched for rate of presentation (135 ms per item); this resulted in different baseline performance levels for the two modalities. In both experiments, visual AB was obtained and auditory AB was not. As Potter et al. stated it, "Auditory attention apparently does not blink" (p. 982). These results suggest that capacity limitations in the visual modality are separate from the auditory modality.

Insert Figure 2 about here

What about cross-modal interference at a later stage of processing? In an additional experiment, Potter et al. (1998) examined whether a target in one modality interfered with the processing of a target in a different modality. Based on the within-modality studies described above, one can expect that cross-modal interference would not be obtained. Indeed, this was the case. As shown in Figure 3, visual T1 targets did not interfere with auditory T2 targets and vice versa. This further confirms the hypothesis that the AB phenomenon is restricted to the visual modality, revealing capacity limitations that are specific to the processing of visual stimuli. These results argue against an architecture that proposes AB is caused by a central bottleneck that is located at a late, amodal stage of information processing.

Insert Figure 3 about here

Although a clear story emerges from the Potter et al. (1998) study, a number of studies from other labs revealed conflicting results. For example, Duncan, Martens, and Ward (1997) observed an AB pattern for auditory targets, as well as the expected within-modality AB for visual targets. Interestingly, they did not obtain cross-modal interference between the two modalities, consistent with Potter et al.'s study. Thus, at the very least, capacity limitations within each modality appear to be independent from each other. Still, an explanation is needed for why Duncan et al. observed auditory target interference while Potter et al. did not.

Further complicating matters, yet a different pattern of results was obtained in a series of experiments by Arnell and Jolicoeur (1999). In contrast to both Potter et al. and Duncan et al., Arnell and Jolicoeur observed visual AB, auditory AB, and cross-modal AB between visual and auditory targets. In addition, Jolicoeur and his colleagues (Jolicoeur, 1999b; Jolicoeur & Dell'Acqua, 1998) have demonstrated interference effects between visual and auditory tasks in a variety of other paradigms. This pattern of results provides strong evidence for a central locus of AB that is limited in capacity, producing interference for targets appearing within and across both visual and auditory modalities.

What could explain these serious discrepancies? We will consider a hypothesis based on the attentional demands of task switching, which appears to explain all of the existing published data. But first, let us review one alternative hypothesis. The alternative account concerns parametric factors such as the rate of stimulus presentation or overall task difficulty. Arnell and Jolicoeur (1999) have pointed out that Potter et al.'s (1998) study employed slower presentation rates than those used in the Arnell and Jolicoeur's study. As the rate of presentation is critical for observing the attentional blink, this could possibly explain the failure to observe auditory and cross-modal AB using Potter et al.'s protocol. Arnell and Jolicoeur (Experiment 5) manipulated presentation rate and demonstrated that the AB deficit was eliminated for auditory targets when slower rates (135 ms/item), comparable to that used in Potter et al., were used. However, rate cannot be the main explanation. First, even if rate is constant across studies, it cannot be a psychophysically equalizing factor because performance in RSVP and RAP tasks is dependent on many other variables such as the visibility or audibility of the stimuli. Second, in an unpublished experiment, Potter et al. were unable to observe auditory AB even when a faster rate of 120 ms per item was used (Figure 4; Lag Effect, $F < 1$), a rate at which Arnell et al. obtained an auditory AB effect.

Insert Figure 4 about here

Finally, Potter et al. obtained strong dissociations between the visual and auditory modalities even when the stimuli were controlled for a critical parameter, stimulus identification difficulty. There is extensive evidence showing that stimulus identification difficulty is an important factor in AB, as reviewed in Seiffert and Di Lollo (1997). (Note that AB is only influenced by the difficulty of processing patterned stimuli (Shapiro, Raymond, & Arnell, 1994)). Jolicoeur has additionally shown that the magnitude of AB correlates with the time it takes subjects to perform the T1 task (e.g., Jolicoeur, 1998, 1999a,b). Thus, in our view, it would have been difficult to obtain the observed all-or-nothing dissociation in the time course between visual and auditory modalities if the processing capacities for each modality were not independent of each other.

We propose instead that all of the existing published data on dual-target performance for visual, auditory, and cross-modal targets can be understood as reflecting one or both of two distinct effects: (1) a vision-specific AB effect, and (2) a task-switch deficit. Task-switch deficits occur in the AB procedure when subjects must switch from one perceptual set for T1 to another for T2. Such task-switch costs are distinct from the processing limitations that cause AB for visual targets. What is task switching? People's interactions with the environment are guided by internally generated task sets (Allport, Styles, & Hsieh, 1994), such as "search for a letter while ignoring the digits." Such task sets guide the observer's attention to incoming sensory information. Task switching occurs when the subject must discard the current task set and replace it with a new one. Such task switching incurs a severe cost in performance. As an example, consider a classic study by Jersild (1927; see also Spector & Biederman, 1976). Subjects were given lists of two-digit numbers and asked to perform an addition (or a subtraction) task on all of the numbers in the list. In the task switch condition, they had to alternately add and subtract a constant number from successive items. Subjects were significantly slower in the task switch condition, which produced large RT costs on the order of several hundred milliseconds per item.

Task switching is a high-level executive function (Allport et al., 1994; Meiran, 1996; Rogers & Monsell, 1995), with a relatively late locus in the information processing stream. It is likely to be amodal and may draw upon central resources used for other cognitive operations such as response selection and perhaps also short-term memory consolidation.

We argue that many findings that have been interpreted as auditory AB or cross-modal AB can be reinterpreted as reflecting task switch deficits. In contrast, Potter et al.'s

(1998) experiments presented a consistent task for T1 and T2. Subjects were asked to detect and report two letter targets (T1 and T2), ignoring all of the extraneous digit distractors. No auditory or cross-modal deficits were obtained under these conditions. However, Arnell and Jolicoeur (1999) employed a procedure that involved a salient switch in task set between T1 and T2. In their study, subjects were asked to monitor a stream of letters for the presence of a single digit (T1). Then the task switched to letter detection for the presence of the letter X. Not only was there a categorical switch in target set from digit to letters, subjects had to switch from ignoring the letter stream to attending to the stream of letters for the presence of the X probe. This produced deficits for secondary targets regardless of modality. Such conditions are optimal for observing task-switch costs (Allport et al., 1994; Meiran, 1996; Rogers & Monsell, 1995). For example, Allport et al. (1994) asked subjects to search for animal names among nonanimal names, and then to switch their search to nonanimals among animals. A significant deficit was observed for a target that occurred within 3 items of the task switch. Thus, in a target search task similar to that used in AB paradigms, a task switch can also produce deficits for secondary targets.

Thus, all of the published experiments to date that showed visual, auditory and cross-modal AB (Arnell & Jolicoeur, 1999; Jolicoeur, 1999b) may reflect capacity limitations for task switching, and such task-switch costs are distinct from the bottleneck responsible for AB of visual targets. This explains why no auditory or cross-modal AB was observed in Potter et al's study (1998, see Figures 2 and 3), which did not involve a task switch between T1 and T2. As more compelling evidence, Potter et al. replicated Arnell and Jolicoeur's results when a task switch was introduced between T1 and T2, using the same stimuli and apparatus that did not produce dual-task interference effects in the absence of a task switch. These results were obtained when the T1 task was to detect a digit among letters and the T2 task was to detect an X probe among letters. The results are shown in Figure 5; now a visual AB, auditory AB, and cross-modal interference effects were observed. Contrast this with Figure 6, which shows the results of a parallel experiment in which subjects did not switch tasks, but looked or listened for two letters among digits. Here, with no task switch, only the visual-visual condition showed a significant AB deficit. This provides strong support for the role of task switching as the decisive factor producing discrepancies between studies. Note that the task switching deficit and the visual AB effect appear to be additive: The visual AB effect in Figure 5 is larger than that in Figure 6.

Insert Figure 5 about here

Insert Figure 6 about here

A theoretical account

Based on these findings, we propose an architecture of human information processing that posits separate capacity limitations for the visual modality as well as an amodal central bottleneck. This is illustrated in Figure 7. First, the visual processing system is limited in capacity, and AB occurs as visual targets interfere with other visual targets appearing close in time (Broadbent & Broadbent, 1987; Chun & Potter, 1995; Duncan et al., 1994; Raymond et al., 1992). However, these processing limitations are restricted to the visual modality, such that visual targets do not interfere with auditory targets and vice versa in the absence of other task demands. AB interference between multiple visual targets is obtained only when two conditions are satisfied, and these two conditions reflect characteristics specific to the visual modality. First, there is high capacity for initial identification of the visual input if it is presented for about 100 ms an item, but these Stage 1

representations are ephemeral and subject to interference and substitution from subsequent visual events (Chun & Potter, 1995; Giesbrecht and Di Lollo, 1998; Potter, 1975, 1993, 1999). Second, if attention is given to one of the items—for example, T1—then it can be encoded and consolidated in Stage 2, but at the expense of the immediately following items. They will be processed in Stage 1 but must wait for Stage 2 processing of the earlier item to be completed. During the wait, the items following T1 may be lost, resulting in the AB deficit. In sum, both of these conditions, rapid identification that is subjected to visual or conceptual masking (Chun & Potter, 1995; Grandison et al., 1997; Moore, Egeth, Berglan, & Luck, 1996; Raymond et al., 1992; Seiffert & Di Lollo, 1997), and a limited-capacity, attention-demanding consolidation process, must be present to observe AB.

Insert Figure 7 about here

The characteristics of the auditory module are less clear. First, it is plausible to assume that there are capacity limitations for processing simultaneous or rapid sequential auditory events (e.g., Treisman & Davies, 1973). That is, auditory targets do interfere with each other, as suggested by the lower level of performance in the dual-target conditions versus the single-target condition baseline in the studies reviewed in this chapter (Arnell & Jolicoeur, 1999; Duncan et al., 1997; Potter et al., 1998). The question is whether these dual-target deficits for auditory stimuli are caused by modality-specific capacity limitations for auditory targets, and whether such limitations result in AB effects with a time course similar to that observed for visual targets. The evidence on auditory AB is mixed. Potter et al. did not observe AB lag effects for auditory targets; performance, although lower for a second target, was flat across lags. Arnell & Jolicoeur (1999) demonstrated auditory AB, but this can be interpreted as reflecting task-switching deficits, and hence as engaging a different capacity limitation to be described below. Finally, Duncan et al. demonstrated an auditory AB effect that is very similar to that observed for visual targets, although it was symmetrical for T1 and T2 at short intervals, unlike the visual AB. However, it is unclear how to characterize the nature of interference in Duncan et al.'s task. Although there were different sets of targets in the two channels which the subjects monitored, both were words, which involved no task switch. However, in the auditory case, the two channels differed in voice pitch. Hence, their task may have required a switch in perceptual set defined over pitch. We cannot fully determine whether switching one's auditory perceptual set from one pitch to another constitutes a "task switch," although we are inclined to interpret it as a task switch based on the fact that different features are used for selection. But further research is required on this issue, and new findings will help characterize the nature of capacity limitations for auditory stimuli.

One property of auditory processing that can be clearly distinguished from visual processing concerns masking properties and durability over time, critical factors for observing AB. In contrast to visual information, which is easily overwritten and replaced by subsequent visual events (Breitmeyer, 1984; Enns & Di Lollo, 1997; Sperling, 1960), auditory stimuli appear to be more resistant to such masking interference from subsequent auditory events. The echoic buffer preserves auditory information over 1 to 2 s, presumably because many properties of sound depend on temporally extended information. If auditory stimuli are not as easily backward-masked as visual stimuli, then one would not expect to obtain an auditory AB, inasmuch as visual AB is dependent on the erasure of T2 representations by subsequent masking stimuli (Chun & Potter, 1995; Giesbrecht & Di Lollo, 1998).

Information from the visual and auditory modalities converges to a central bottleneck of information processing, required for most overt behaviors (See Figure 7). Following Jolicoeur (1998, 1999a) and Pashler (1994), we will call this the central processor. Capacity limitations in the central processor are distinct from those that may

exist in the separate perceptual modalities. Interference at the central stage of processing leads to decrements in performance for any type of target, regardless of modality and regardless of task. The important question is what types of cognitive operations engage this central processor. Work by Jolicoeur and his colleagues (1998ab) have demonstrated that short-term consolidation engages this central processor, leading to interference for subsequent targets, including targets from different modalities. Thus, when subjects must encode information for later report, this causes interference with central processing of subsequent events (Jolicoeur & Dell'Acqua, 1998). Increasing the load of information that needs to be consolidated produces concomitant increases in interference for subsequent targets. According to Jolicoeur, the short-term consolidation mechanism is engaged whenever information about target stimuli must be encoded for subsequent report. This is consistent with the operations of Stage 2 in Chun and Potter's (1995) model, but the two-stage model postulates that AB is only observed when processing is slowed down by the attentional requirements of identifying and individuating a visual target that is immediately followed by a mask or distractor. If, instead, the target is followed by a blank interval of 100 ms, there is little or no AB for a subsequent target.

The central processor is used for other important cognitive operations. For example, speeded response selection is also controlled by this central processor. Hence, increased AB is obtained when the response to T1 must be made immediately rather than delayed until after T2 is presented (Jolicoeur, 1998). The number of response alternatives also affects this processor's capacity. As the number of alternatives increases for speeded response tasks, increased interference is observed (Jolicoeur, 1999b). These results lead to the conclusion that the psychological refractory period (Pashler, 1994), which is the result of a response selection bottleneck, shares the same central processor as short-term consolidation. This produces dual-task interference whenever either one of these cognitive operations is engaged.

To this list of central operations, we add the attentional demands of task switching. Task switching involves remapping of stimulus-response associations, and hence may share capacity with response selection mechanisms. Supporting a central locus, we obtained cross-modal dual-target deficits when a task switch was introduced (Potter et al., 1998).

We further propose that the AB should be distinguished from task-switching costs. There are several lines of evidence that point to a dissociation. Task-switch costs are standardly measured by an increase in RT when the next trial in a sequence requires a switch (Allport et al., 1994; Rogers & Monsell, 1995; Meiran, 1996). Such trials are separated by 1 s or more, well beyond the 500 ms range of AB interference. Using an RSVP version of a task-switch experiment in which the criterion that defines the target is changed unpredictably during a sequence, Allport and Hsieh (this volume) have shown that a task-switch deficit on the next target item occurs immediately. The task-switch cost was present regardless of whether there was an earlier target, and it diminished as a function of the number of nontarget distractors preceding the target, not as a function of the simple passage of time. Neither of these properties is true of AB. The AB is dependent on processing of T1 (Chun & Potter, 1995; Jolicoeur, 1998; Joseph et al., 1997; Luck et al., 1996; Raymond et al., 1992) and is largely gone at an SOA of 500 ms or greater, whether or not the interval between T1 and T2 is filled with distractors (as long as each target is followed by a mask).

Conversely, the AB can be obtained in the absence of a task-switch. Chun and Potter (1995) replicated all of Raymond et al.'s findings using a design that did not require a criterion shift between T1 and T2 (search for two letters amongst non-letter distractors). The AB appears to be restricted to the visual modality, as no AB was observed when the targets were auditory or cross-modal (one visual, one auditory). In contrast, task-switching deficits are found regardless of modality when a criterion shift is introduced between T1 and T2 (Potter et al., 1998).

Insert Figure 8 about here

Providing further direct support for a distinction between AB and task switching costs, Chun and Jiang (1999) demonstrated a double dissociation between AB and task switching using identical stimuli. Subjects performed shape discrimination tasks for targets comprised of overlapping visual shapes (See Figure 8). The two target shapes, which were colored white, appeared within an RSVP sequence of black distractors on a gray background. As usual, the lag between T1 and T2 was varied to assess the time course of dual-target interference. Each target was composed of two shapes, and subjects were asked to perform one of two tasks for each target. For the circle task, subjects were asked to attend to and report the orientation (up, left, right, or down) of the gap of the circle. For the diamond task, subjects reported the direction of elongation, which was always different from the circle.

There were two main conditions in the primary experiment. In the AB condition, the task was consistent between T1 and T2 (attend to the circle shape in T1 and the circle shape in T2). In the task-switch condition, the perceptual set was different for the two targets (attend to the circle shape in T1 and the diamond shape in T2). With respect to the robust AB effect obtained in the AB condition (poorer performance at shorter lags), the task switch condition produced a further 20% decrement in performance for T2 appearing within half a second of T1. Hence, task switching added a cost in performance because subjects had to go from attending to a circle while ignoring the diamond in T1 to attending to the diamond while ignoring the circle in T2. Such perceptual set reversals classically produce task switch costs (Meiran, 1996; Rogers & Monsell, 1995). In two additional experiments, Chun and Jiang dissociated AB and task-switch costs. Task-switch costs were observed without AB when the distractors were simplified to minimize target-distractor interference, known to be a critical factor for observing AB (Chun, 1997; Chun & Potter, 1995). This pattern was reversed when the target stimuli were manipulated such that the two overlapping shape stimuli did not compete for different responses. When these “neutral” targets were presented amongst interfering distractors, AB was observed without an additional cost for task switching. Hence, AB and task switching are doubly dissociable, consistent with our proposal that the capacity-limited mechanisms involved may be placed in different stages of information processing.

To summarize, we propose that visual AB reflects sequential processing limitations that are restricted to visual stimuli, although more central, amodal limitations may add to those of visual AB. Our model is consistent with Jolicoeur's proposal that a central bottleneck exists and that this operates over amodal representations of target events (Arnell & Jolicoeur, 1999b; Jolicoeur, 1999). We support the notion that the central processor is important for short-term consolidation, response selection, and long-term memory retrieval (Jolicoeur & Dell'Acqua, 1998; Jolicoeur, 1999a; Pashler, 1994). We add task coordination (switching) to this list of cognitive operations mediated by the central processor. Our account differs only in how to define the loci of the bottleneck process responsible for visual AB.

First, we suggest that Stage 2 either precedes or forms a distinct subcomponent of the central processor that is separate from the other bottleneck processes responsible for response selection and task switching. Otherwise, it would be difficult to obtain double dissociations between AB and task switching (Chun & Jiang, 1999). Also, such a distinction is consistent with the fact that AB can be observed without PRP and vice versa, a pattern that can be observed across published studies in the literature. Although the loci are distinct, it is important to note that the two processes form a single chain of information processing, which is why one can observe both effects within the same task (Jolicoeur, 1998, 1999a).

Second, Stage 2 differs from other central processes in its sensitivity to visual interference. The efficacy of Stage 2 and the subsequent interference effects it produces are tightly influenced by the degree of perceptual interference on T1 (Chun & Potter, 1995; Grandison et al., 1997; Moore et al., 1996; Raymond et al., 1992; Seiffert & Di Lollo, 1997). In contrast, manipulations of the target's perceptual integrity do not have direct impact on central processor operations such as response selection (Pashler, 1984; Pashler & Johnston, 1989). In addition, a visual T2 is uniquely vulnerable to any delay in entering the central processor (Chun & Potter, 1995; Giesbrecht & Di Lollo, 1998), such that it suffers a deficit from STM consolidation of T1 even without an additional delay due to task switching or response selection.

How can task switches be defined?

The notion of task switching is important for our framework and for distinguishing when dual-target interference (especially cross-modal interference) will occur. So it will be useful to operationalize what counts as a task switch.

All target search tasks are defined by a perceptual set for a particular target or class of targets. Task switches can be simply defined as a switch in perceptual set from one target to another. For instance, switching the category that defines a target (e.g., digit to letter) involves a task switch. However, an important condition is that switches in perceptual set should also involve a reversal in target-response and distractor-response mappings, for example, searching for a digit among letters (T1), and then searching for a particular letter (T2). The requirement to ignore the letters to detect T1 makes it more difficult to switch to that set in subsequent search for T2, as shown in Chun and Jiang's (1999) study described above.

We propose that there are performance "markers" that reveal whether a particular task involves a task switch or not. One useful heuristic is to examine whether subjects can effectively ignore the T1 task when two tasks are presented in succession. For instance, in a task where T1 is defined by luminance and the second target is defined as X probe detection, Raymond et al. (1992) and numerous other labs have shown that the T1 task can be effectively ignored with minimal interference on the T2 task. We argue that this is because the two tasks are different enough to allow this. Another example can be found in a study by Joseph et al. (1997). The T1 task was white letter detection, and the T2 task was orientation pop-out detection. The two tasks were very different, and subjects had no difficulty ignoring the T1 task to perform the T2 task alone in the control condition. Contrast these examples with Chun and Potter's task that involved no task switch. When searching for two letters amongst digits, subjects have great difficulty reporting just the second letter. Apparently this task requires subjects to register but then ignore the first letter, something they find almost impossible to do because of the high similarity between the two tasks. Another example involves a search for two colored letters. Although one may expect subjects to have no problem ignoring the first colored letter and reporting the second colored letter, there is in fact a significant interference effect from the "ignored" T1 (Chun, 1997a; Jiang & Chun, in press). That is, subjects are unable to filter T1 if it meets the search description required to detect T2 (see also Folk, Leber, & Egeth, 2000).

Note that we are not claiming that previous demonstrations of dual-task deficits in AB studies can all be interpreted in terms of task switching. For example, in Raymond et al.'s (1992) original study, there is clearly a visual AB component, as evidenced by the fact that the presence of AB was highly sensitive to perceptual manipulations (such as the insertion of a blank after T1). Also note the degree of task switching involved in that task was minimal. Even if the first target task was to detect a "white" letter, subjects could still focus attention on attending to letters. Thus, no reversal in categorical set was required in the Raymond et al. study, in contrast to the task employed by Arnell and Jolicoeur, which did impose a categorical set reversal between T1 and T2 (i.e., search for digit T1 among letters, then search for 'X' T2). Moreover, we propose that the visual AB effect is present even with a task switch: the two effects add, so that a visual "blink" is increased when there is a task switch.

Another useful marker for the presence or absence of task switching was first suggested by Potter et al. (1998): Lag-1-sparing is characteristic of AB, whereas the task-switching deficit is maximal at lag 1 (as observed in experiments reported by Potter et al. and also in Allport and Hsieh's studies in the present volume). Lag 1 sparing refers the relatively high level of performance for T2 when it appears immediately after T1 (see Figure 1). In a comprehensive literature review, Visser, Bischof, & Di Lollo (1999) demonstrated that the degree of Lag-1 sparing observed was dependent on the number of dimensional (category, modality, etc.) switches imposed between T1 and T2. For example, when no switches were imposed (as in Chun and Potter's search for two letters among digits task), 44 out of 46 experiments demonstrated lag-1 sparing. However, when a task required more than one type of switch, (e.g., digit to letter and identification to detection, as in Arnell and Jolicoeur (1999)), 29 out of 32 experiments failed to produce lag-1 sparing. Further details may be found in Visser et al., but the important conclusion is that lag-1 sparing is a sensitive index of the degree of task similarity between T1 and T2. The greater the similarity, the greater the lag-1 sparing observed. Thus, in a letter identification task consistent for T1 and T2 (Chun and Potter, 1995), lag-1 performance was similar to the asymptotic baseline performance. As an extreme example in the other direction, Joseph et al.'s task required a switch in location (center to periphery), task (letter identification to orientation pop-out detection), and category (letter to Gabor patch). This resulted in a monotonic function of T2 performance across lag, with the poorest performance at Lag 1. In still other cases (e.g., Potter et al., 1998) in which there was a task switch but the targets were both visual, there was an intermediate degree of lag-1 sparing.

Summary

Interference between two targets can occur at one or several distinct stages within the human information processing stream. Standard AB may be restricted to capacity limitations and stimulus masking properties that are specific to the visual modality, independent of capacity restrictions in other modalities. For both visual and auditory targets, interference may be obtained within modality and across modalities if the task taxes attentional demands of short-term memory consolidation, response selection, or task switching. In particular, we propose that the cognitive operation of task switching explains why and when dual-target interference occurs between auditory and visual target pairs in AB paradigms.

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Figure Captions

Figure 1. The attentional blink effect: Correct report of the second target (T2, given correct report of the first target, T1) as a function of lag; the stimulus onset asynchrony (SOA) was 100 ms. (From Chun & Potter, 1995, Experiment 1)

Figure 2. Correct report of T2 (given correct report of T1) as a function of lag, for visual stimuli (SOA = 120 ms) and auditory stimuli (SOA = 135 ms). Vertical bars show standard error of the mean. (From Potter et al., 1998, Experiment 1.)

Figure 3. Correct report of T2 (given correct report of T1) as a function of lag, for the two cross-modal conditions; the auditory stimuli had SOAs of 135 ms, the visual stimuli, 120 ms. Vertical bars show standard error of the mean. (From Potter et al., 1998, Experiment 3.)

Figure 4. Correct report of T2 (given correct report of T1) as a function of lag, for auditory stimuli (SOA = 120 ms). Vertical bars show standard error of the mean. (Unpublished experiment reported in Potter et al., 1998, p. 984.)

Figure 5. Correct report of T2 (given correct report of T1) as a function of lag, with two simultaneous sequences of visual and auditory items (SOA = 120 ms) and instructions to identify T1 and detect "X" (T2) in specified modalities, for (a) the groups with two visual or two auditory targets, and (b) the groups with one visual and one auditory target. Only trials on which an "X" was presented are included. Vertical bars show standard error of the mean. (From Potter et al., 1998, Experiment 4.)

Figure 6. Correct report of T2 (given correct report of T1) as a function of lag, with two simultaneous sequences of visual and auditory items (SOA = 120 ms), when the task was to report two letters among digit distractors. The results are shown separately for each of the four conditions, VV, AA, VA, and AV. Vertical bars show standard error of the mean. (From Potter et al., 1998, Experiment 5.)

Figure 7. Model of the structure of information processing to explain dual-target performance in visual, auditory, and cross-modal attentional blink, task switching, and short-term memory consolidation paradigms.

Figure 8. Illustration of paradigm to test AB and task switching using identical physical stimuli (From Chun & Jiang, 1999). A sample target stimulus is shown in the inset of the left panel; each target is composed of two shapes (circle and diamond). Two of these targets, colored white, were presented in an RSVP sequence of black distractors (left panel). The right panel shows correct report of T2 (given correct report of T1) as a function of lag for the AB, Task Switch, and Single target control conditions.

Figure 1

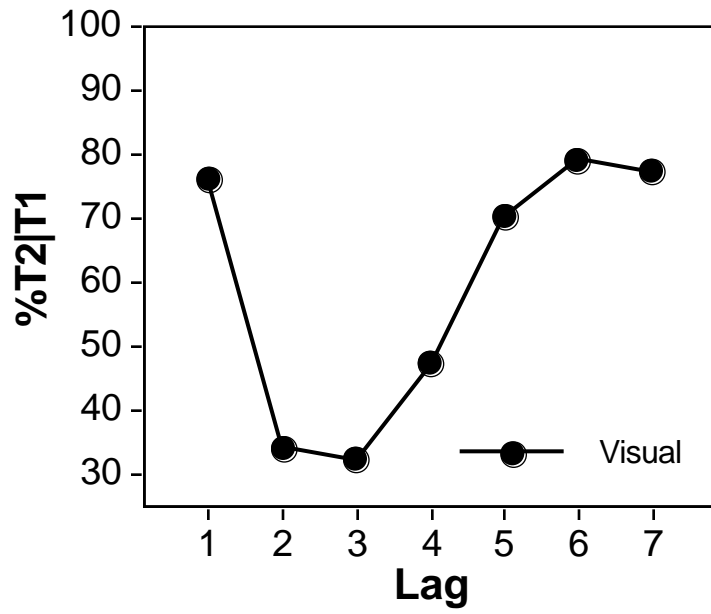


Figure 2

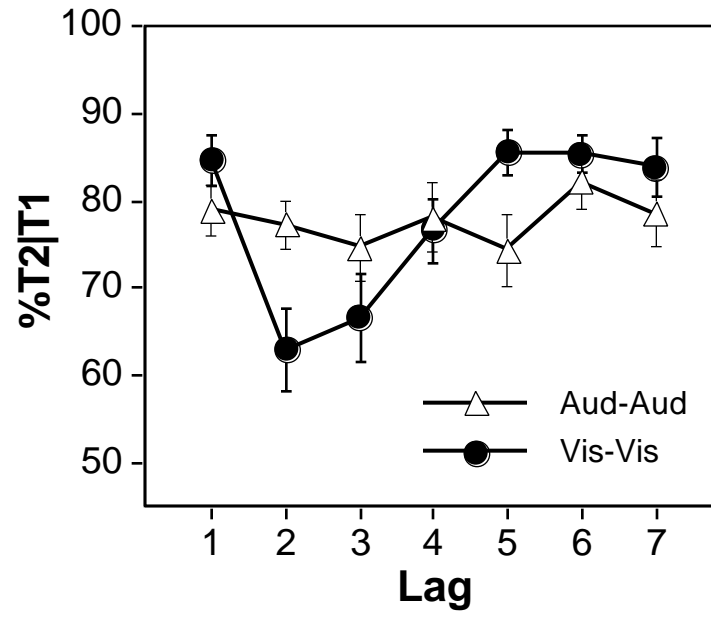


Figure 3

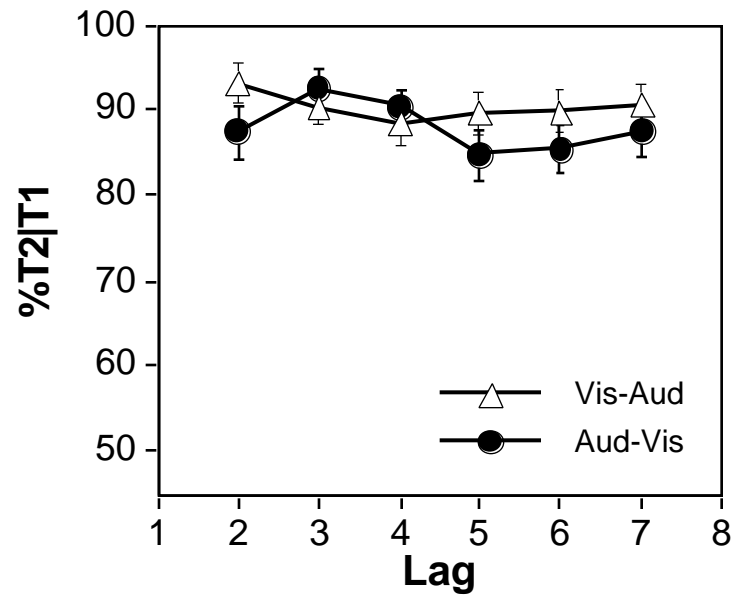


Figure 4

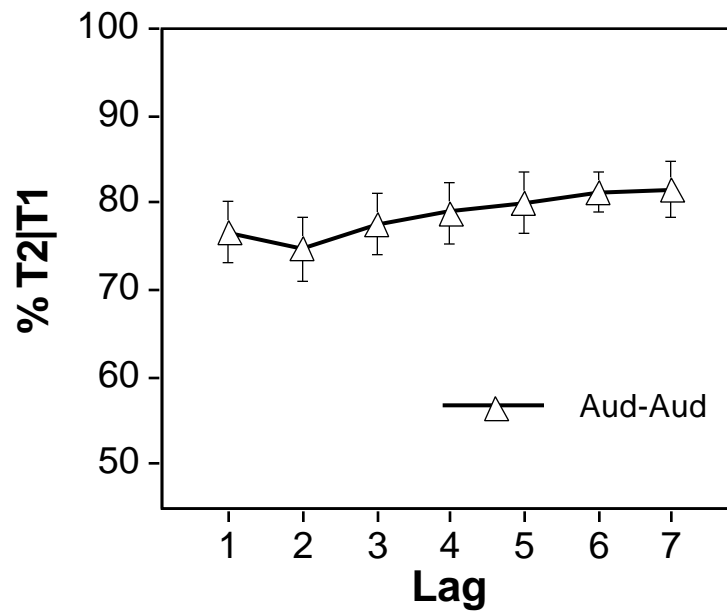


Figure 5

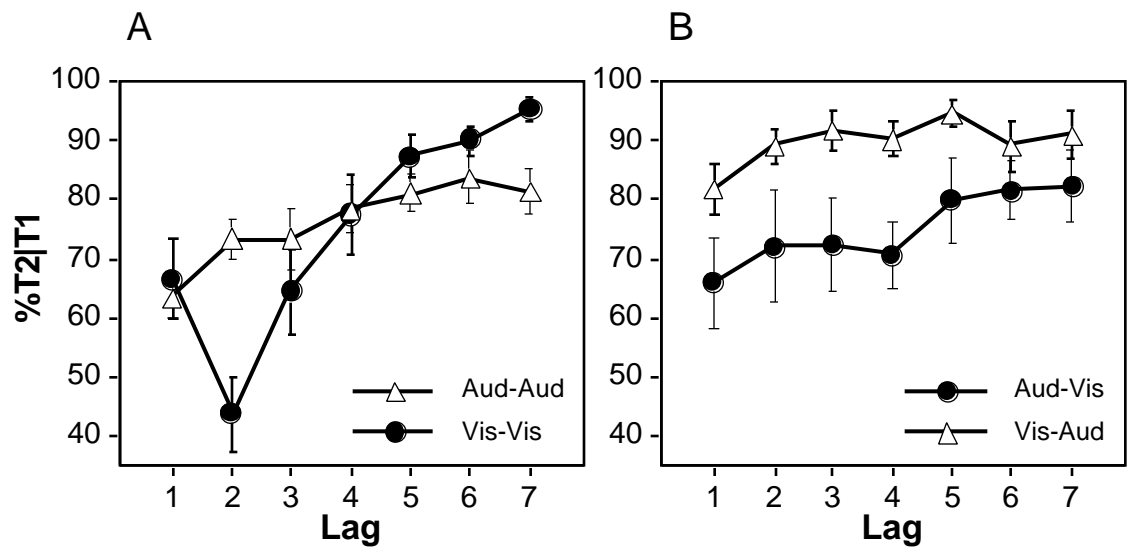


Figure 6

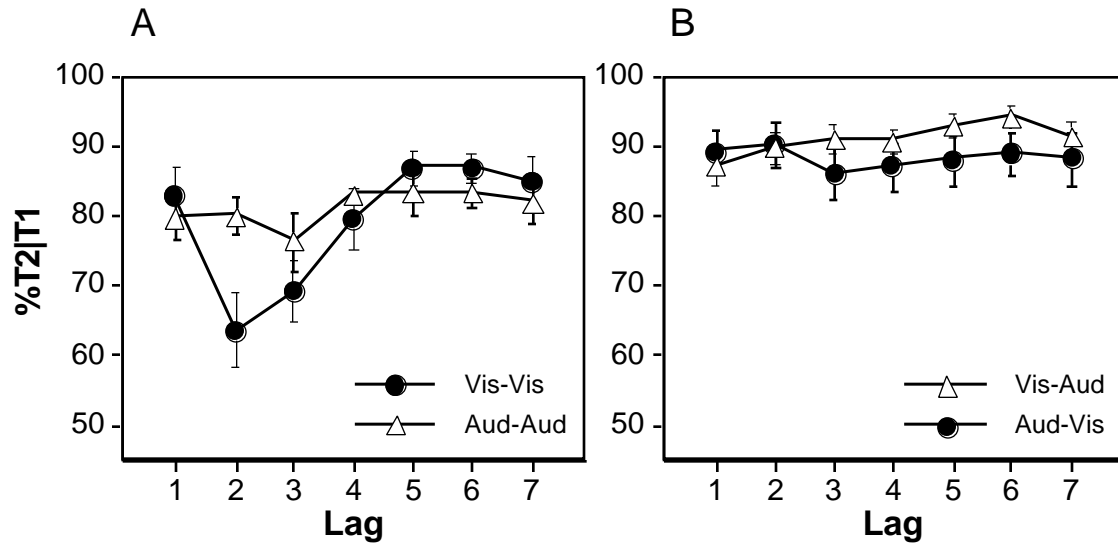


Figure 7

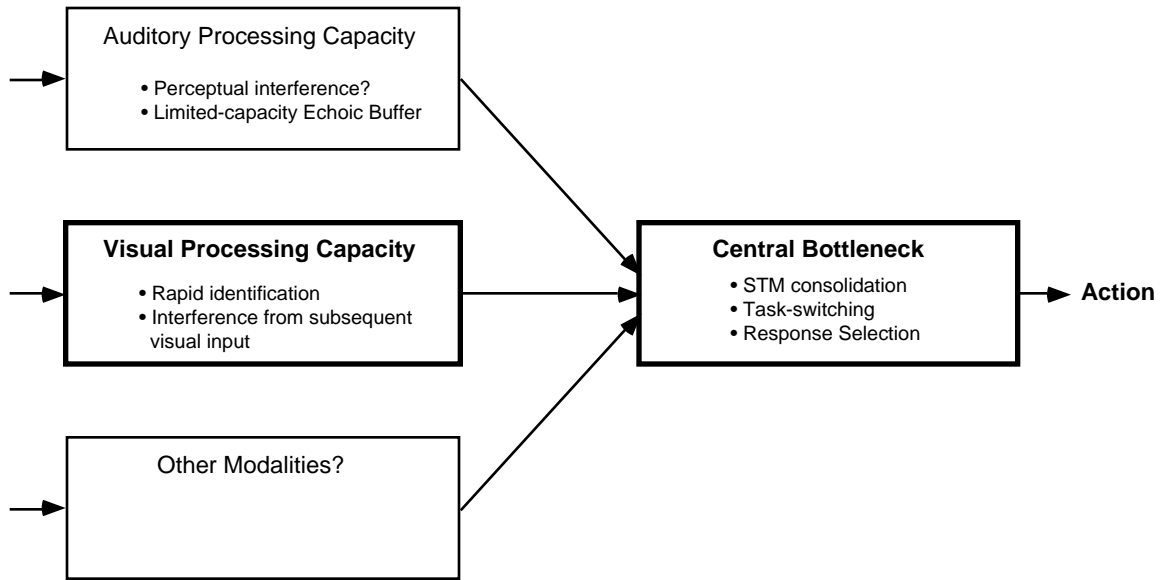


Figure 8

