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Online response-selection and the attentional blink: Multiple-processing channels

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Robust interference often arises when multiple targets (T1 and T2) are discriminated in rapid succession (the attentional blink or AB). The AB has been observed for a wide range of stimuli, and is often thought to reflect a central capacity limitation in working memory consolidation, attentional engagement, and/or online response selection. However, recent evidence challenges the existence of unitary bottleneck during postperceptual processing. Awh et al. (2004) found no AB interference when a digit target preceded a face target, presumably because these stimuli could be processed by means of separable processing channels. Using a modified AB procedure, recent studies have also demonstrated that speeded response selection of T1 leads to an AB effect for T2 identification, supporting the conclusion that response selection induces the same processing limitations that typically gives rise to an AB. The present research tests this hypothesis by examining the effects of response selection on the identification of faces. Although we replicated previous demonstrations that online response selection of a digit disrupts the identification of T2 letters, we found no interference in the identification of T2 faces. However, robust AB interference was once again observed when a speeded response to a T1 face was required, confirming that faces are not simply immune to central interference. These results dispute the existence of a unitary postperceptual capacity limitation that gives rise to the AB.

Studies of the attentional blink (AB) reveal strong limitations in the ability to process targets that are presented in rapid succession (Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992). The most common method used

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to study the attentional blink (AB) is known as *rapid serial visual presentation* (RSVP). In an RSVP paradigm, a stream of items is presented at fixation, at around 10 items per second, with each item serving as a mask for the preceding item. Two targets are embedded in the stream of items and the subject's task is to identify the first target (T1) and to either identify or to detect the presence of the second target (T2). T2 accuracy is then plotted as a function of the number of intervening items between T1 and T2 (usually referred to as T2 *lag*, hence lag 1 would mean that T2 was presented immediately after T1). In another method used to investigate the AB (the *two-target* paradigm), two targets are presented sequentially in different spatial locations, each followed by a mask. The subject's task is to identify or to detect both of the target items and T2 accuracy is measured as a function of the stimulus–onset asynchrony (SOA; Duncan, Ward, & Shapiro, 1994; Ward, Duncan, & Shapiro, 1997); previous research has shown that the RSVP and two-target paradigms probably tap the same attentional limitations (Ward et al., 1997).

A growing body of evidence suggests that the AB is due to postperceptual limitations in information processing. For example, event-related potential recordings (ERPs) have been used to assess the degree of semantic analysis during the period of time when items are missed because of the attentional blink (Luck, Vogel, & Shapiro, 1996; Vogel, Luck, & Shapiro, 1998). Semantic processing was operationalized by the amplitude of the N400 component. This component provides a sensitive index of the degree of semantic processing, because its amplitude corresponds directly to the degree to which the evoking stimulus mismatches the current semantic context (Kutas & Hillyard, 1980). Because a stimulus must be identified before semantic incongruence can be determined, the N400 response provides clear evidence that a word has undergone semantic processing. Luck et al. (1996) presented words both during and after the AB period, and found that the degree of semantic processing was equivalent, even though AB interference strongly impaired the overt report of which items were presented. Moreover, Vogel et al. (1998) measured the amplitude of the P1 component evoked by these words—a component that provides a sensitive index of early perceptual processing (Mangun & Hillyard, 1991)—and found that the amplitude of this component was equivalent during and after the AB period. These results demonstrate that strong AB interference can be observed even though early perceptual and semantic processing is unaffected; thus, AB interference operates at a relatively late stage of target processing.

This late-selection interpretation is also consistent with the pattern of accuracy as a function of lag in the RSVP procedure. T2 accuracy across lag position is usually nonmonotonic in RSVP tasks; T2 accuracy is lowest at intermediary lags, and relatively unaffected at lag 1 and lags exceeding 5 or

6. The preservation of T2 performance at lag 1 is typically referred to as lag 1 sparing and is thought to reflect the operation of a sluggish attentional gate (Chun & Potter, 1995; Potter, Chun, Banks, & Muckenhoupt, 1998). According to this hypothesis, processing takes place in *two stages* (Chun & Potter, 1995; Shapiro, Raymond, & Arnell, 1994). Stage 1 is involved with detecting or discriminating the target items from the distractors in an RSVP stream and Stage 2 is involved in consolidating the perceptual representations of the targets into a durable trace in working memory. However, because of capacity limitations, access to Stage 2 is limited by an attentional gate that closes after T1 has entered (Chun & Potter, 1995; Duncan, 1980; Sperling & Weichselgartner, 1995). If T2 arrives after the gate is closed then its perceptual trace remains in Stage 1, where it is susceptible to interference from backwards masking (Brehaut, Enns, & Di Lollo, 1999; Dell'Acqua, Pascali, Jolicoeur, & Sessa, 2003; Enns & Di Lollo, 1997; Giesbrecht, Bischof, & Kingstone, 2003; Giesbrecht & Di Lollo, 1998; Grandison, Ghirardelli, & Egeth, 1997). However, if T2 is presented in close temporal proximity to T1, as in the lag 1 condition, then T2 "sneaks" through the gate before it closes and benefits from Stage 2 processing along with T1. More recent models suggest that AB interference is not caused by T1 consolidation per se, but rather because attention cannot be rapidly engaged on T2 during or immediately following T1 identification (e.g., Nieuwenstein, Chun, van der Lubbe, & Hooge, 2005). In either case, a central processing limitation (T1 consolidation or a delay in the allocation of attention to T2) is thought to prevent the selection and consolidation of T2 when it is presented in close temporal proximity to T1.

While the process of T1 identification clearly plays a role in producing the AB, other postperceptual processes such as online response-selection also interfere with the consolidation of T2. For instance, Jolicoeur and colleagues have shown that if the T1 response is speeded in an RSVP paradigm—forcing the subject to select and execute an immediate response—then the AB is larger than if the response to T1 may be delayed until the end of the trial (Dell'Acqua, Turatto, & Jolicoeur, 2001; Jolicoeur, 1998, 1999a; Ruthruff & Pashler, 2001). These data make contact with research on the psychological refractory period (PRP), in which subjects are required to make a speeded response to two stimuli that are presented at a variable stimulus–onset asynchrony (SOA). Reaction times (RTs) to the second stimulus are typically slowed at shorter SOAs, suggesting that response-selection to the second stimulus is delayed until response-selection to the first stimulus is complete (Pashler, 1984, 1994; Welford, 1952).

While some notable exceptions have been observed (Hazeltine, Teague, & Ivry, 2002; Schumacher et al., 2001), the PRP effect has been shown to apply across a variety of experimental conditions, including tasks involving bimodal stimulus and response requirements, mental rotation, making two speeded responses to the same object, and retrieving items from long-term memory (Carrier & Pashler, 1995; Fagot & Pashler, 1992; Pashler, 1990; Rohrer & Pashler, 2003; van Selst & Jolicoeur, 1994). Thus, the modulation of the AB by T1 response selection, in combination with PRP studies demonstrating the generality of the response selection bottleneck, suggest that online response-selection can interfere with the process of selecting and consolidation T2 into working memory. On this account, T2 processing must wait for both T1 identification and for the completion of response-selection to T1 (Jolicoeur, 1998, 1999a; Ruthruff & Pashler, 2001). The strong form of this model posits that T1 identification and response-selection may be viewed as two components of a single central bottleneck; any increase in the duration of this central stage of processing will result in increased dual-task interference (Ruthruff & Pashler, 2001).

MULTICHANNEL HYPOTHESIS OF THE AB

The models of the AB reviewed thus far make the prediction that interference arises because multiple stimuli presented in rapid succession compete for limited postperceptual resources. That is, an AB should be evident if T2 is presented during the process of T1 identification or during the selection of a response to T1, which will in turn impair selection of T2 and leave it susceptible to backwards masking (Chun & Potter, 1995; Duncan et al., 1994; Jolicoeur, 1999a; Raymond, Shapiro, & Arnell, 1995; Ruthruff & Pashler, 2001; Ward, Duncan, & Shapiro, 1996). Indeed, the observation of an AB across an impressive range of stimulus categories and modalities strongly supports the existence of a central, amodal bottleneck in postperceptual processing as the locus of AB interference (e.g., Arnell & Jolicoeur, 1999; Arnell & Larson, 2002; Jolicoeur, 1999b; Joseph, Chun, & Nakayama, 1997; Ross & Jolicoeur, 1999).

However, recent evidence argues against a unitary central resource that gives rise to the AB. For example, the AB in an unspeeded two-target (digit–letter) paradigm was eliminated when the T2 letter was substituted for a picture of a face (Awh et al., 2004). This result cannot be attributed to insufficient masking or T2 difficulty, as the AB was not observed when multiple types of mask stimuli (and exposure durations) were used to induce a range of T2 accuracy levels (and to allow for object-substitution masking; Giesbrecht et al., 2003; Giesbrecht & Di Lollo, 1998). The lack of an AB for faces preceded by digits suggests that these two stimuli do not compete for a single postperceptual process that supports target discrimination. However, additional experiments showed that if T1 was a face and T2 a letter, then the AB effect was restored. Similarly, T1 faces followed by T2 faces also produced an AB, demonstrating that face stimuli are capable of placing sufficient demands on postperceptual processing to induce an AB.

The asymmetric effect of stimulus ordering on the AB may be reconciled if there are multiple processing channels supporting the discrimination of T2 during the AB. For instance, Farah and colleagues have distinguished a "holistic" or "configural" processing mode for faces, and a "feature-based" or "parts-based" mode for processing other stimuli (such as letters and digits; Farah, Wilson, Drain, & Tanaka, 1998). On this account, discriminating faces is special because face identity is highly dependent on the configuration of the individual features contained within a face, not just on the shape or form of the individual features. While strong evidence exists supporting a configural processing mode for faces, the individual features within the faces also play a clear role in face recognition. Gauthier and Tarr (2002) used "Greebles"—artificially generated stimuli that are known to evoke configural processing—to show that observers are sensitive to changes in the individual features of a given greeble. Thus, the data suggest that the discrimination of faces relies on both configural and feature-based modes of visual processing.

If these assumptions about face processing are correct, then a multichannel model of stimulus identification accounts for the pattern of interference observed when face stimuli are used in an AB paradigm (Awh et al., 2004). When digits and letters are used for T1 and T2, they compete for access to the same feature-based processing mechanisms, rendering T2 susceptible to the AB. In contrast, if T1 occupies the feature-based system, a face T2 may still be discriminated based on information from the configural processing channel. The AB is restored when T1 is a face and a T2 is a letter because faces engage both feature and configural processing channels, thereby occupying the feature-based channel necessary for the discrimination of T2. This theoretical account makes the strong prediction that T2 stimuli should be identified during the AB as long as either the feature-based or configural channels are not engaged by the processing demands of T1. This prediction is supported by experiments showing an AB when faces were used as T1 and as T2, and also when faces were coupled with greebles, stimuli that should also compete for both feature-based and configural processing channels (Awh et al., 2004).

PRESENT STUDY

The results of Awh et al. (2004) suggest that multiple visual processing channels can support discrimination during the AB. However, the studies supporting this model all used masked T1 and T2 stimuli that required unspeeded responses. Recall that two factors may influence the duration of the postperceptual bottleneck giving rise to the AB; the identification of T1, and the online selection of a response to T1. Thus, while the use of masked stimuli ensured that both T1 and T2 were in temporal competition for attentional selection and consolidation into working memory, T1 response selection should have minimally interfered with the T2 processing because T1 required an unspeeded response.

In the present study, we tested the multiple channel model of the AB when the duration of T2 interference was modulated by the online selection of a response to T1. We first established an experimental procedure that yielded robust AB interference by requiring a speeded response to an unmasked T1. Using this paradigm, we show that increasing the duration of T1 response-selection leads to an increase in the duration of the AB, replicating previous findings showing that a speeded response to a masked T1 modulates the AB (Jolicoeur, 1998, 1999a). After establishing a robust AB using this paradigm, we examined the effects of online response selection to T1 on the processing of a face-stimulus T2. No AB for faces was observed, questioning the existence of a unitary central processing bottleneck induced by the online selection of a response to T1.

EXPERIMENT 1

Methods

Subjects

Four subjects were recruited from the University of Oregon community; each subject participated in four experimental sessions, with each session lasting approximately 2 hours. The experimental sessions were held on separate days and subjects were monetarily compensated for their participation ($6 an hour). Subjects received additional monetary compensation based on their performance during the experimental sessions (see later). All subjects reported normal or corrected to normal vision.

Apparatus, stimuli, and general procedures

Figure 1 depicts the sequence of events on an experimental trial. All stimuli were presented on a PC with a 17-inch colour monitor with a resolution of 800 × 600 pixels and the vertical refresh rate of 85 Hz. The T1 stimulus was a number (1, 2, or 3) and the T2 stimulus was a letter of the alphabet (no letters were excluded); both number and letter stimuli subtended a visual angle of approximately 1° in height and 0.5° in width based on a viewing distance of 50 cm. The fixation point was a small black

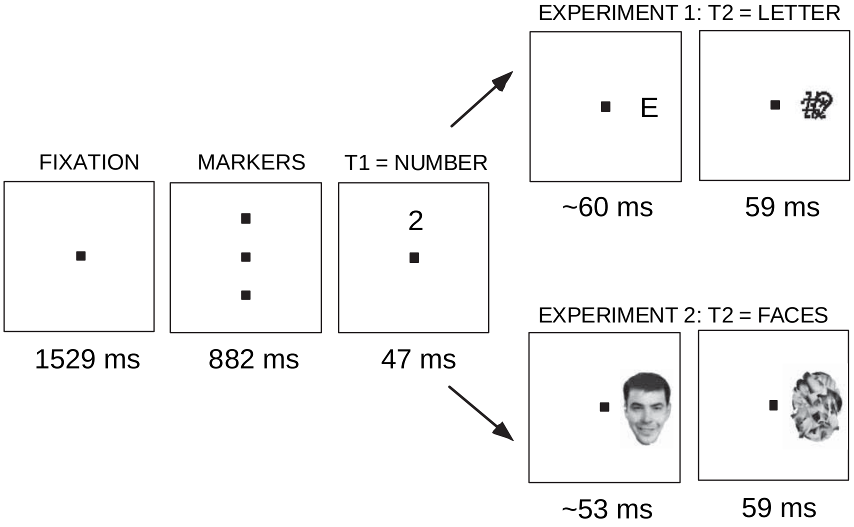

Figure 1. Sequence of events on a sample trial for each of the two experiments. The first target was always a number (1, 2, or 3), and the second target was either a letter (Experiment 1) or a face (Experiment 2). The second target was always followed by a stimulus-appropriate pattern mask.

square that subtended a visual angle of approximately 0.2°. The stimuli were black and presented on a mid-grey background. T1 was presented randomly 1.5° above or below fixation and was not masked. T2 was randomly presented 1.5° to the left or right of fixation and a pattern mask was presented immediately after the offset of T2. There were three possible T2 masks, each consisting of multiple overlapping typological symbols such "&", "%", and "#" (see Figure 1 for an example).

Subjects pressed the "Enter" key on the keyboard to initiate each trial, after which the fixation point was presented in the centre of the screen for 1529 ms before two placeholders were presented for 882 ms in each of the two possible T1 locations. T1 was presented for 47 ms above or below the fixation point in one of the location marked by the placeholders, and T2 was presented to the left or the right of fixation at a randomly selected SOA of 0 ms, 59 ms, 118 ms, 176 ms, 236 ms, 294 ms, 354 ms, 412 ms, 472 ms, or 529 ms. T2 exposure duration was independently determined for each subject (see later). Each SOA was equally represented within a block of trials. Responses to T1 were made using the first three fingers of the right hand placed over the "1", "2", and "3" keys on the number pad of a standard PC keyboard. Responses to the T2 letter stimuli were always unspeeded and subjects could alter their response to T2 until they were satisfied with their answer. More specific details concerning each of the experimental conditions are given in later sections.

T2 exposure staircase procedure. To ensure that T2 accuracy was not at ceiling, the T2 exposure duration was determined on a within subject basis at the beginning of each experimental session using a staircase timing procedure. Subjects were presented with both T1 and T2 (with T2 followed by a mask) at the 0 ms SOA; unspeeded responses to both T1 and T2 were required. If subjects responded correctly to both T1 and T2, the T2 exposure duration was reduced by one monitor refresh cycle (~ 11.76 ms). If subjects responded incorrectly to T2, the exposure duration was increased by two monitor refresh cycles (responding incorrectly to T1 and correctly to T2 resulted in no change). The mean exposure duration over the last block of trials (30 trials/block) was used as the exposure duration for T2 during that experimental session. This procedure produced a group mean exposure duration of 60ms (standard deviation: ± 13 ms), corresponding roughly to 70–80% T2 accuracy at the 0 ms SOA.

Point system. To ensure that subjects were adequately motivated to comply with task instructions, we developed a points system to reward the subjects monetarily for task compliance. As is typical of AB experiments, subjects were asked to respond to T1 as accurately as possible. In some cases, (see later) the speed of T1 responses was also emphasized. Therefore, the point system was weighted towards producing an appropriate response to T1 (when a T1 response was required), with a secondary emphasis on accurate T2 performance. Feedback was given for T1 and T2 accuracy at the end of every trial, in addition to the number of points earned on each trial. The exact point values are described later in the descriptions of the corresponding experimental conditions; subjects received an extra dollar for every 100 points they accumulated above a baseline of 1200 points/session.

Experimental conditions

Control task. In the control task, T1 and T2 were always presented, but a response was only required to T2. Subjects received 3 points for a correct response, and lost 3 points for an incorrect response. This condition was designed to assess T2 accuracy with minimal identification and response-selection requirements induced by T1 processing. However, any perceptual interference induced by the presentation of T1 should still be evident. Thus, T2 accuracy in this condition served as a baseline against which to compare other experimental conditions in which the identification and response-selection demands of T1 were directly manipulated and expected to affect T2 processing.

Dual-task unspeeded. In the dual-task unspeeded condition, subjects were required to respond to both T1 and T2; however, they could delay both of the responses until after the end of the trial and they were free to report T1 and T2 in any order. Subjects were awarded 5 points for a correct T1 response and deducted 5 points for an incorrect T1 response. Three additional points were awarded for the correct report of T2; however, no penalty was assessed if T2 was incorrect. No AB was expected in this condition because T1 was not masked and a speeded response to T1 was not required. Therefore, subjects could schedule T1 identification and response-selection during a temporal interval that did not lead to interference with the postperceptual processing of T2 (e.g., Giesbrecht et al., 2003; Giesbrecht & Di Lollo, 1998; Jolicoeur, 1998, 1999a; Ward et al., 1997).

Dual-task speeded, compatible T1 response. The trial structure and point system in the dual-task speeded condition were the same as in the unspeeded condition with the exception that a speeded response to T1 was required. To ensure that subjects were responding as quickly as possible to the first stimulus, we performed a T1 *deadline* procedure during each of the four experimental sessions. In the deadline procedure, only T1 was presented and subjects were required to respond as quickly as possible. The T1 deadline was defined as the mean RT plus twice the standard deviation of the RTs over the last block of trials (30 trials/block). This value was then was used as a response deadline during the ensuing blocks of dual task trials. Dual-task trials on which the T1 response was emitted after the deadline were treated as T1 errors and discarded from further analysis.

Dual-task speeded, incompatible T1 response. The trial structure in the dual-task speeded incompatible response condition was the same as in the speeded compatible condition with the exception that the T1 stimulus–response mapping was altered. That is, if T1 was the digit “1”, then subjects were required to respond by pressing the “3” key on the number pad with their ring finger. When T1 was a “2”, subjects pressed the “1” key, and when T1 was a “3”, subjects pressed the “2” key. Altering the stimulus–response mapping of T1 should lengthen the central bottleneck stage of T1 processing that has been shown to mediate the AB (Jolicoeur, 1998, 1999a). The same deadline procedure described for the earlier speeded compatible condition (except with an incompatible T1 response mapping) was used to ensure subjects were responding as quickly as possible on the dual-task incompatible trials.

Experimental sessions

There were 30 trials in each experimental block in all conditions. During the first experimental session (Day 1), subjects performed six blocks of the T2 exposure duration fading procedure, five blocks each of the compatible and incompatible T1 deadline procedures, three blocks of the control condition, and one block each of the dual-task unspeeded, speeded compatible, and speeded incompatible conditions. In each of the remaining sessions (Days 2–4), subjects performed three blocks of the control condition, seven blocks of the dual-task unspeeded condition, and seven blocks each in the compatible and incompatible speeded conditions. In addition, at least two blocks of the T2 exposure duration fading procedure and the T1 deadline procedures were run (prior to the respective dual-task condition). Additional blocks of data were acquired for the T2 exposure and T1 deadline conditions if the standard deviations of the estimated parameters were high or if the results were inconsistent with performance on previous days. Subject means in the control condition were computed across all four experimental sessions; however, data collected during the first experimental session in the unspeeded, speeded compatible, and speeded incompatible conditions were discarded (one block each).

Results and discussion

The mean T1 accuracy collapsed across SOA was 99%, 90%, and 83% in the unspeeded, speeded-compatible, and speeded-incompatible response conditions, respectively. Mean T1 RTs (± standard deviations) in the speeded-compatible and speeded-incompatible conditions were 388(43) ms and 464(28) ms, respectively (see Table 1). Paired *t*-tests between the speeded-compatible and incompatible conditions revealed a marginally significant

TABLE 1
T1 reaction time and accuracy data across all three experiments

T1 response type	*T1 deadline (ms)*	*T1 deadline errors*	*Total T1 errors*	*Mean T1 RT (ms)*
Experiment 1				
Compatible	497	5%	10%	388
Incompatible	640	6%	17%	464
Unspeeded	NA	NA	1%	1112
Experiment 2				
Incompatible	645	5%	14%	467
Experiment 3				
Three alternative	783	14%	27%	576
Two alternative	624	7%	16%	463

effect of response compatibility on accuracy, $t(3) = 2.75$, $p = .07$, and a significant effect on RT, $t(3) = 5.02$, $p < .05$, confirming that manipulating the T1 stimulus–response mapping significantly increased the duration of T1 processing.

To test for the presence of any significant differences in the T2 accuracy across experimental conditions, we first performed a two-way repeated measures analysis of variance (ANOVA) with experimental condition (control, unspeeded, speeded-compatible, and speeded-incompatible) and SOA (0–529 ms) as within-subject factors. There was a significant main effect of experimental condition, $F(3, 9) = 14$, $p < .005$, and accuracy improved as SOA increased, $F(9, 27) = 15, p < .001$. Accuracy in the different experimental conditions also differed as a function of SOA, $F(27, 81) = 4.1$, $p < .001$, suggesting the presence of a significant AB in at least one of the conditions.

Given the presence of significant Condition × SOA effects in the overall T2 accuracy data, we next performed separate two-way repeated measures ANOVAs to compare each experimental condition with the control condition. As depicted in Figure 2, there was no main effect of the

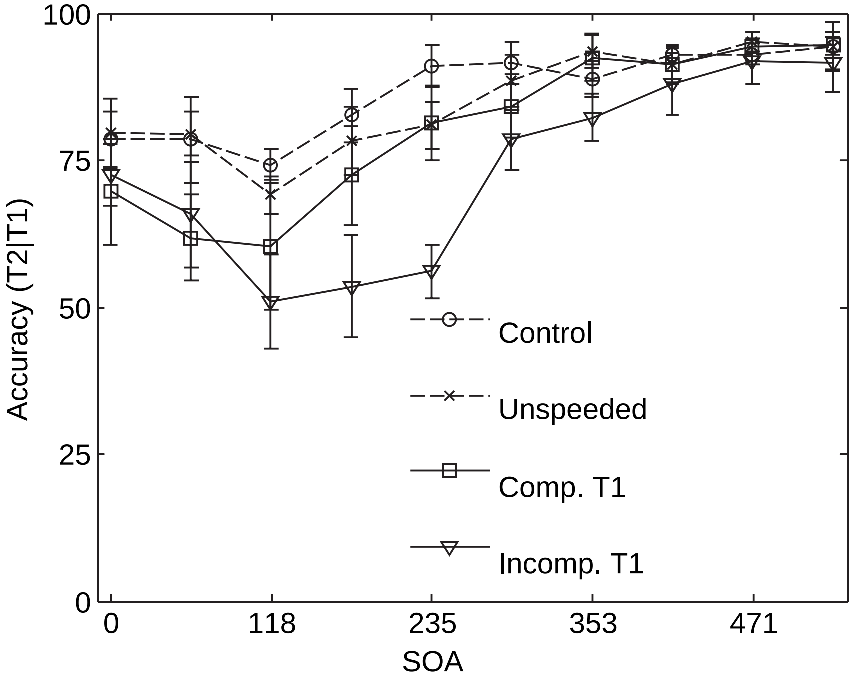

Figure 2. T2 accuracy during Experiment 1 on trials where T1 responses were correct. Error bars are ±1 SEM across subjects.

unspeeded versus the control condition on T2 accuracy, $F(1, 3) = 2$, $p > .25$. However, there was a main effect of SOA, $F(9, 27) = 12.2$, $p < .001$, and the interaction between condition and SOA was significant, raising the possibility that a small AB was present in the unspeeded condition, $F(9, 27) = 2.27$, $p < .05$. However, paired *t*-tests (uncorrected for multiple comparisons) revealed that the control and the unspeeded conditions only differed at SOAs of 236 ms and 472 ms, $t(3) = 7.07$, $p < .01$ and $t(3) = -4.1$, $p < .05$, respectively. The restricted range over which the conditions differed, coupled with a null main effect of condition, leads us to conclude that there is at best a very modest AB in the unspeeded condition.

Shown in Figure 2 are the control and the speeded-compatible conditions. In contrast to the unspeeded condition, the pattern of T2 accuracy impairment in the speeded-compatible task yielded a significant main effect of condition, $F(1, 3) = 12.1$, $p < .05$, of SOA, $F(9, 27) = 9.5$, $p < .001$, and a significant interaction between condition and SOA, $F(9, 27) = 3.15$, $p < .01$. Similarly, a comparison of the control and the speeded-incompatible conditions, depicted in Figure 2, also revealed significant main effects of condition, $F(1, 3) = 33.5$, $p < .01$, of SOA, $F(9, 27) = 12.67$, $p < .001$, and a significant interaction between condition and SOA, $F(9, 27) = 8.7$, $p < .001$. A separate two-way ANOVA was performed to directly compare the size of the AB in the speeded-compatible and speeded incompatible conditions (Figure 2); while the main effect of condition was only marginally significant, $F(1, 3) = 7.3$, $p = .07$, the main effect of SOA was significant, $F(9, 27) = 13$, $p < .001$, as was the interaction, $F(9, 27) = 3.8$, $p < .005$. This interaction between the speeded-compatible and speeded-incompatible conditions confirms that the magnitude of the AB was increased as a function of increased reaction time to T1.

The data presented in Figure 2 demonstrate that producing a speeded response to T1 can lead to a robust AB, even in the absence of a T1 mask. Furthermore, the magnitude of the AB is amplified when the difficulty of T1 response-selection is increased. Presumably, increasing in the duration of the response-selection stage of T1 processing causes a corresponding delay in T2 consolidation, with longer delays leaving T2 more vulnerable to backwards masking (Jolicoeur, 1998, 1999a).

In Experiment 2, we substituted a picture of a face for the letter T2 used in Experiment 1, and tested for an AB by comparing a speeded-incompatible condition with a control condition. We chose the speeded-incompatible condition because it produced the largest AB in Experiment 1, thus providing the strongest test of the multiple channel hypothesis with respect to interference induced by the online selection of a response to T1.

EXPERIMENT 2

Methods

Subjects

Four new subjects were recruited from the University of Oregon community; each subject participated in two experimental sessions, with each session lasting approximately 2 hours. The experimental sessions were held on separate days and subjects were monetarily compensated for their participation ($6 an hour). Subjects received additional monetary compensation based on their performance during the experimental sessions (as in Experiment 1). All subjects reported normal or corrected to normal vision.

Apparatus, stimuli, and general procedures

All experimental equipment, stimuli, and procedures were identical to those in Experiment 1 except where noted.

In Experiment 2, we substituted the T2 letter stimuli used in Experiment 1 with three greyscale pictures of faces that were contained within an imaginary rectangle with a height of 5.5° and a width of 4° (based on a viewing distance of 50 cm). The faces were masked with scrambled versions of the same three face pictures. The mean T2 exposure duration (as set by the fading procedure) across all four participants and sessions was 53 ms (standard deviation: ± 14 ms). Each of the three face stimuli were mapped onto the “z”, “x”, or the “c” keys.

Only the control (report T2 only) and the speeded-incompatible dual-task conditions were run using the T2 face stimuli. During both experimental sessions, subjects first performed six blocks of the T1 deadline procedure and the T2 exposure duration fading procedure; then they performed six blocks in the control condition, and ten blocks in the speeded-incompatible condition. As in Experiment 1, each block consisted of 30 trials, and each of the 10 SOAs was equally represented within each block of experimental trials.

Results and discussion

T1 accuracy and RT, collapsed across SOA, did not vary significantly compared to Experiment 1, $t(6) = 0.87$, $p > .4$, and $t(6) = 0.21$, $p > .8$, respectively; see Table 1), and the mean T2 exposure duration for the face stimuli used in Experiment 2 was similar to the T2 exposure duration in Experiment 1, $t(6) = 0.85$, $p > .4$. In addition, T2 accuracy did not differ significantly between Experiment 1 and Experiment 2 at the 0 ms SOA in the control condition, suggesting that the T2 fading procedure achieved the same base level of discrimination difficulty for letter and face stimuli, $t(6) = 0.27$, $p > .7$. The similarity between T2 exposure duration and accuracy at the 0 ms SOA suggests that the fading procedure was successful in equating T2 discrimination difficulty in Experiment 1 (using letters) and in Experiment 2 (using faces).

Depicted in Figure 3 are the results from the control and speeded-incompatible conditions in Experiment 2. As indicated by the degree of overlap between the two lines on the graph, a two-way repeated measures ANOVA revealed only a significant main effect of SOA, $F(9, 27) = 3.2$, $p < .01$; the main effect of condition was not significant, $F(1, 3) = 2.4$, $p = .22$, nor was the interaction between condition and SOA, $F(9, 27) = 1.5$, $p = .18$.

To directly compare the T2 accuracy data in Experiments 1 and 2, we used a mixed factor three-way ANOVA with experimental condition (control vs. speeded-incompatible) and SOA (0–529 ms) as within-subject factors, and T2 identity (letter vs. face) as a between-subjects factor. There was a significant three-way interaction between experimental condition, SOA, and T2 stimulus

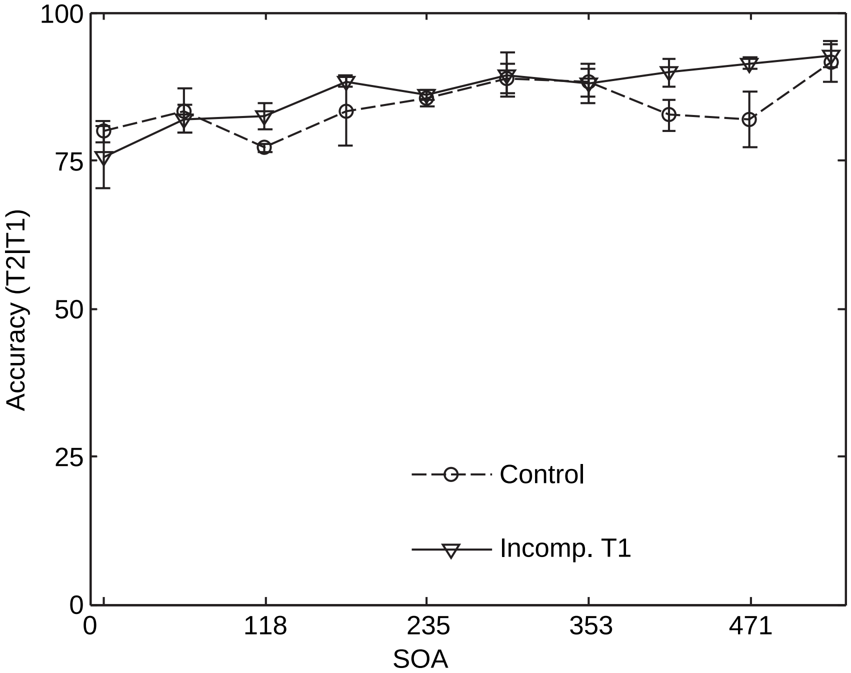

Figure 3. (a) T2 accuracy during Experiment 2 on trials where T1 responses were correct. In contrast to Experiment 1, no significant AB interference was observed. Error bars are ±1 SEM across subjects.

type, $F(9, 54) = 5.6$, $p < .001$, because T2 accuracy was significantly lower in the speeded-incompatible condition from Experiment 1.

To further establish the sensitivity of our paradigm to detect an AB, we binned the T2 accuracy data as a function of quartile response time to T1 (RT1). We reasoned that if online response selection were indeed responsible for inducing the AB observed in Experiment 1, then T2 accuracy should vary directly with the duration of RT1. To provide the strongest possible test, we compared T2 accuracy on trials in which RT1 was in the first quartile with T2 accuracy on trials in which RT1 was in the fourth quartile (on a within-subject basis). We first confirmed that RT1s in the first and fourth quartiles were statistically different by using a mixed-factors ANOVA with experiment as a between-subjects variable and RT1 quartile as a within-subjects variable. First quartile RT1s were significantly faster than fourth quartile RT1s, $F(1, 6) = 131.6$, $p < .001$, and there was no interaction, suggesting a constant difference between first and fourth quartile RT1s in Experiments 1 and 2, $F(1, 6) = 0.28$, $p > .6$. Next, we performed separate two-way repeated measures ANOVA on the T2 accuracy data from Experiments 1 and 2 to assess the effects of RT1 latency. The T2 accuracy data from Experiment 1 are depicted in Figure 4: The AB was larger when RT1 was slow versus when RT1 was fast, resulting in a main effect of RT1 quartile on T2 accuracy, $F(1, 3) = 59.1$, $p < .005$. The main effect of SOA was also significant, $F(9, 27) = 6.8$, $p < .001$; however, the interaction between SOA and RT1 quartile was only marginally significant, $F(9, 27) = 2.0$, $p = .08$. In contrast, the corresponding data from Experiment 2 in which T2 was a face; only the main effect of SOA was significant, $F(9, 27) = 2.3$, $p < .05$; main effect of quartile, $F(1, 3) = 0.008$, $p = .94$; interaction, $F(9, 27) = 1.0$, $p = .45$. However, a pairwise repeated measures *t*-test revealed that accuracy was lower in the fourth quartile compared to the first quartile at the 59 ms SOA, $t(3) = 3.2$, $p < .05$. To directly compare the magnitude of quartile effects between the studies, we performed an ANOVA with T2 identity as a between subjects factor and RT1 quartile and SOA as within subjects factors. There was a significant interaction between RT1 quartile and T2 identity, $F(1, 6) = 21.7$, $p < .005$, and a significant three-way interaction between T2 identity, RT1 quartile, and SOA, $F(9, 54) = 2.2$, $p < .05$. These results show that even if there was a small amount of interference for face T2 stimuli at the 59 ms SOA, the magnitude of AB interference was substantially larger in Experiment 1 compared to Experiment 2.

The absence of an AB with number T1 stimuli and face T2 stimuli is consistent with the notion that a speeded response based on featural information does not induce an AB when T2 can be discriminated based on configural information. However, an alternate explanation posits that no AB is observed for a face T2 because configural information is not subject to a central response-selection bottleneck. To test this possibility, we ran an

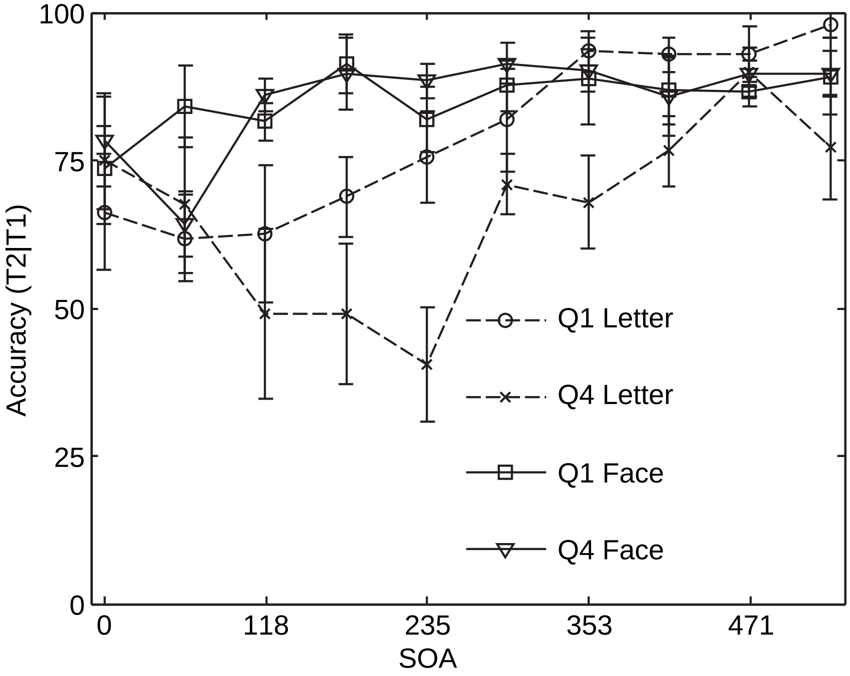

Figure 4. T2 accuracy data plotted as a function of T1 RT quartile. T2 discrimination is significantly worse for letters when T1 RTs are slow compared to when they are fast; however, no such effect of T1 RT on accuracy is observed for faces in Experiment 2. Error bars are ±1 SEM across subjects.

additional experiment in which both T1 and T2 were faces. The multiple-channel hypothesis predicts that robust AB interference should be observed because both stimuli require configural processing and should therefore compete for a common processing resource.

EXPERIMENT 3

Methods

Subjects

Four new subjects were recruited from the University of California, Irvine community; each subject participated in one practice session and two experimental sessions, with each session lasting approximately 2 hours. The experimental sessions were held on separate days and subjects were monetarily compensated for their participation ($10 an hour). Subjects received additional monetary compensation based on their performance during the experimental sessions (as in Experiments 1 and 2). All subjects reported normal or corrected to normal vision.

Apparatus, stimuli, and general procedures

All experimental equipment, stimuli, and procedures were identical to those in Experiment 2 except where noted.

In Experiment 3, we substituted the T1 number stimuli used in Experiments 1 and 2 with three greyscale pictures of faces. The T1 faces were always of the opposite gender as the T2 faces (counterbalanced across subjects), but were otherwise similar. No mask was presented following the T1 stimulus and each of the three T1 face stimuli were mapped onto the "j", "k", or the "l" keys. There was no "incompatible" condition because the T1 face stimuli were arbitrarily mapped to the response keys (unlike the numbers in Experiments 1 and 2, which were more naturally mapped to numbers on the response keypad). However, the same T1 RT deadline procedure employed in the previous experiments was also used to encourage fast responses in Experiment 3. The T2 face stimuli were mapped onto the "a", "s", and "d" keys. The mean T2 exposure duration (as set by the fading procedure) across all four participants and sessions was 48 ms (standard deviation: ± 9 ms).

Results and discussion

T1 accuracy was slightly lower in Experiment 3 compared to Experiment 2, $t(6) = 2.25$, $p < .05$, and T1 RTs were longer, $t(6) = 3.1$, $p < .01$ (Table 1). Mean T2 exposure duration was not significantly different across experiments, $t(6) = 0.85$, $p > .4$. T2 accuracy as slightly lower in Experiment 3 compared to in Experiment 2 at the 0 ms SOA in the control condition, $t(6) = 3.4$, $p < .01$. However, overall T2 accuracy in the control condition was not significantly different between the two experiments, suggesting that the T2 exposure staircase procedure was successful in roughly equating task difficulty, $t(6) = 0.46$, $p > .3$.

Figure 5a depicts the results from the control and speeded response conditions in Experiment 3. In contrast to Experiment 2, a large AB was observed when both T1 and T2 were faces. A two-way repeated measures ANOVA revealed a significant main effect of SOA, $F(9, 27) = 19.3$, $p < .001$, a significant main effect of condition, $F(1, 3) = 96.5$, $p < .005$, and a significant interaction between condition and SOA, $F(9, 27) = 3.5$, $p < .01$.

To directly compare the T2 accuracy data in Experiments 2 and 3, we used a mixed factor three-way ANOVA with experimental condition (control vs. speeded response) and SOA (0–529 ms) as within-subject factors, and T1

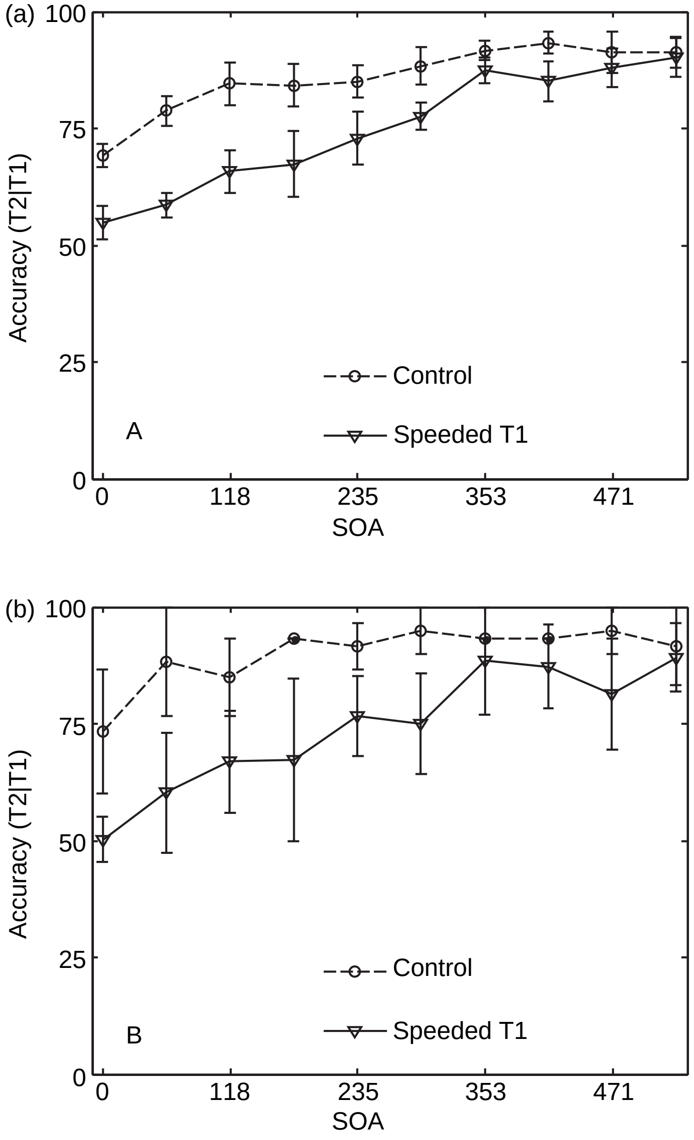

Figure 5. T2 accuracy during Experiment 3 on trials where T1 responses were correct. (a) In contrast to Experiment 2, there was a significant AB observed when both T1 and T2 were faces. (b) T2 accuracy when only two T1 stimuli were used; both subjects showed an AB, even though T1 RTs were significantly reduced in the two alternative version of the task (see Table 1 and text). Error bars are ±1 SEM across subjects.

identity (number vs. face) as a between-subjects factor. There was a significant three-way interaction between experimental condition, SOA, and T1 stimulus type, $F(9, 54) = 2.3$, $p < .05$, indicating that T2 accuracy was significantly lower when both T1 and T2 were faces.

A significantly larger AB was observed in Experiment 3 (faces for T1 and T2) compared to Experiment 2 (number T1, face T2). However, RTs to T1 were longer overall in Experiment 3 than in Experiment 2, raising the possibility that the difference in T2 accuracy across experiments was caused by a prolonged T1 response selection stage in Experiment 3, not by a qualitative difference in T2 processing induced by a change in the T1 stimulus type. To test this possibility, two of the subjects that participated in Experiment 3 came back for an additional day of testing in a version of the task in which there were only two face alternatives for T1. With only two T1 alternatives, RTs were similar to the RTs observed in Experiments 1 and 2 (see Table 1). Importantly, both subjects continued to show a large AB even when T1 RTs decreased, arguing against the possibility that the large AB observed in Experiment 3 is due solely to prolonged T1 response selection (Figure 5b).

GENERAL DISCUSSION

Most traditional models of the AB posit that interference is observed when there is a failure to consolidate the perceptual representation of T2 into a durable working memory store (see later for a discussion of other models). At least two factors mediate the success of T2 consolidation: (1) Concurrent demands on attending to and consolidating items into working memory, and (2) making an online response selection to T1.

Previous studies have shown that AB interference induced by an inability to consolidate multiple items into working memory is significantly attenuated when T1 and T2 do not compete for the same processing channels. This release from AB interference supports the existence of multiple processing channels that are capable of supporting target discrimination (Awh et al., 2004). However, this previous report leaves open the possibility that concurrent response selection will interfere with the selection and consolidation of T2, regardless of the type of information available to support discrimination. In the present study, we directly tested this possibility. In Experiment 1, we established a robust pattern of AB interference using a two-target (digit–letter) paradigm that required a speeded response to an unmasked T1. The magnitude of the AB varied directly with the duration of T1 response selection (Figure 4), confirming that T2 discrimination is impaired by the online selection of a response to T1 (Jolicoeur, 1998, 1999a; Ruthruff & Pashler, 2001). In Experiment 2, the same experimental procedures were employed, but the T2 stimulus was a picture of a face. No AB was observed, suggesting that the online selection of a response to T1 does not invariably interfere with T2 consolidation when multiple processing channels are available to support discrimination. Finally, the results of Experiment 3 show that when both T1 and T2 are faces, and thus compete for the same processing channel, that robust AB interference is restored.

Thus far, our discussion has focused primarily on the hypothesis that AB interference results from a bottleneck in the consolidation of new information in working memory. Recent evidence, however, has called into question whether a consolidation limit provides an adequate explanation of the AB effect. For example, Nieuwenstein et al. (2005) found that the duration and size of the AB effect was significantly attenuated when T2 was cued in advance by a distractor that shared one of the target-defining properties. This result contradicts the notion that T2 is missed because of a sluggish process for consolidating the first target, because there is no reason why cueing T2 should affect the efficiency of T1 consolidation. Thus, Nieuwenstein et al. suggested that AB interference is caused by a delay in attentional engagement, such that T1 processing slows the subjects' ability to direct attention to T2. From this perspective, T2 is missed because the mask for that stimulus has already been presented when attention is finally engaged (see also Bowman & Wyble, 2007; Di Lollo, Kawahara, Shahab Ghorashi, & Enns, 2005; Nieuwenstein, 2006; Olivers, van der Stigchel, & Hulleman, 2007; Olivers & Watson, 2006). By contrast, when T2 is cued in advance, the slow process of orienting to T2 is sufficient to enable accurate encoding into working memory. Our results do not provide a means of distinguishing whether the AB effect is due to competition for consolidation or slow attentional engagement. Nevertheless, our data provide theoretical constraints that are relevant for either account of AB interference. Regardless of which processing limit is responsible for AB interference (i.e., ongoing T1 consolidation or sluggish attentional engagement), our data suggest that it is not a stimulus-independent, central resource for visual perception.

The key pattern in these data is that when the same T1 task was required, the AB effect for T2 letters was significantly stronger than that for T2 faces. Given that the face and letter tasks were equally difficult (by virtue of the staircasing procedure), significant differences in the size of the AB effect for these two stimuli is an example of a structural alteration effect (Wickens, 1980). Structural alteration effects are demonstrated when changes in task requirements (i.e., the type of T2 stimulus) lead to a reduction in dual task interference even though the difficulty of the individual tasks is not changed. Structural alteration effects provide evidence that distinct constellations of processing structures are invoked by the components of a dual task procedure. Related to this point, Jackson and Raymond (2006) recently reported that they had observed a small AB effect for T2 faces, even though their T1 discrimination may not have elicited configural processing. This result alone, however, does not offer a firm conclusion regarding the multiple channel hypothesis, because they did not compare the size of the AB effect for faces with the effect that emerges when T2 is discriminated based on featural cues.[1] The present study (as well as Awh et al., 2004) provided precisely this comparison and documented a strong interaction between AB effect size and whether the T2 stimulus could be discriminated based on configural cues. Thus, the evidence argues against a central bottleneck account of AB interference.

We present our multichannel hypothesis in terms of the common "featural/configural" distinction that is derived from the face processing literature (e.g., Farah et al., 1998). However, the notion of multiple visual information processing channels does not depend on a specific set of labels for the dichotomy and we are open to the possibility that future research will further clarify the characteristics that influence the independence of concurrent processing streams. Nevertheless, the observation that the degree of interference depends on the type of visual information being processed is sufficient to call into question the existence of a unitary postperceptual capacity limitation that gives rise to the attentional blink.

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[1] In addition, it should be noted that the study by Jackson and Raymond employed faces as distractors even in the condition that was intended to test the effect of featural processing demands on T2 processing. Given that previous research emphasizes the role of distractors in defining the processing demands in the AB paradigm (e.g., Raymond et al., 1992; Shapiro et al., 1994), the presence of face distractors clouds the interpretation of the modest AB effect reported by Jackson and Raymond (2006).

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