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The Time Course of Competition for Attention: Attention Is Initially Labile

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Competition for attention between 2 written words was investigated by presenting the words briefly in a single stream of distractors (Experiment 1) or in different streams (Experiment 2–6), using rapid serial visual presentation at 53 ms/item. Stimulus onset asynchrony (SOA) was varied from 0 to 213 ms. At all SOAs there was strong competition, but which word was more likely to be reported shifted markedly with SOA. At SOAs in the range of 13–53 ms the second word was more likely to be reported, but at 213 ms, the advantage switched to the first word, as in the attentional blink. A 2-stage competition model of attention is proposed in which attention to a detected target is labile in Stage 1. Stage 1 ends when one target is identified, initiating a serial Stage 2 process of consolidation of that target.

It is known that when two or more visual stimuli are presented together, they compete for processing resources (e.g., Bundesen, 1990; Duncan, 1980; Kahneman, 1968; Kahneman & Treisman, 1984; Pashler, 1998). What happens when two stimuli are presented successively? Apparently there is competition when the time interval between them is short. For example, when viewers attempt to detect and identify two targets in a rapid serial visual presentation (RSVP), the second target (T2) is frequently missed when it appears 200–500 ms after the onset of the first target (T1; Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992; Weichselgartner & Sperling, 1987). Chun and Potter (1995) proposed a two-stage model of the attentional blink in which detection and identification of T1 takes place rapidly in the first stage so that targets presented for about 100 ms are normally identified; however, if an identified target is to be reported, a second, serial stage of processing is required to consolidate the target in short-term memory (see also Jolicœur & Dell'Acqua, 1998). If T2 appears while T1 is occupying Stage 2, it will be processed only in Stage 1 and will have to wait for Stage 2 to become available. Because information in Stage 1 is volatile and subject to interference from subsequent stimuli, T2 may be momentarily detected and identified but may be forgotten before it can enter the second stage (evidence that an unreported T2 is nonetheless identified has been provided by Luck, Vogel, & Shapiro, 1996; Maki, Frigen, & Paulson, 1997; and Shapiro, Driver, Ward, & Sorensen, 1997).

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Curiously, however, a T2 that follows immediately after T1 (at a lag of one, corresponding to a stimulus onset asynchrony [SOA] of about 100 ms) is often spared: The attentional blink is attenuated or eliminated (e.g., Chun & Potter, 1995; Raymond et al., 1992). Potter, Chun, Banks, and Muckenhoupt (1998) termed this effect *Lag 1 sparing* and suggested that it was more likely to be observed when the target criterion is the same for T1 and T2, that is, when there is no switch in perceptual set between the two targets. To explain Lag 1 sparing, several investigators (Broadbent & Broadbent, 1987; Chun & Potter, 1995; Raymond et al., 1992; Shih, 2000; Weichselgartner & Sperling, 1987) have suggested that an attentional gate is opened by the detection of T1 but that the gate's closing is inexact or sluggish, so a stimulus that immediately follows T1 enters Stage 2 with T1, and the two are processed together. When the following item is T2 (at Lag 1), both are processed successfully. Raymond et al. (1992) extended this model by suggesting that when the following item is a distractor, it interferes with the processing of T1, leading to the abrupt closing and locking of the attentional gate for a time and thus causing the attentional blink. They reported evidence consistent with this interpretation: When a blank followed T1 (instead of a distractor), the attentional blink on T2 was reduced or eliminated (a result replicated by Chun & Potter, 1995), presumably because processing of T1 is completed rapidly when there is no immediate visual interference. The two-stage model of Chun and Potter gave a similar account of Lag 1 sparing; in their model, Stage 2 processing is initiated by a transient attentional response when a potential target is identified in Stage 1. The timing of the attentional response is such that both T1 and the following stimulus are processed together in Stage 2.

Visser, Bischof, and Di Lollo (1999) reviewed the attentional blink literature to determine the conditions under which Lag 1 sparing is found. They confirmed Potter et al.'s (1998) hypothesis that Lag 1 sparing occurs only when there is no substantial shift in perceptual set between T1 and T2. They proposed a modification of the inexact gate model: Task set operates as a filter for stimuli that are consistent with the search set, such that only consistent stimuli enter the attentional window opened by T1, and then only if they appear within a short time period after T1 (Visser, Bischof, & Di Lollo, 1999, used both gate and window metaphors to describe the initiation and end of an attentional episode in response to detection of a target; the notion of a window of time captures the concept of a temporal interval). If detection of T2 requires a significant shift in set, it will not enter the attentional window at Lag 1 and will not show a benefit. An important difference between the original inexact gate model and Visser et al.'s model is that, in the latter case, a distractor that follows T1 will not be processed together with T1 because the distractor does not match the filter. This aspect of the Visser et al. model conflicts with a number of other theories of the attentional blink in which the distractor immediately following T1 is thought to be processed together with T1, creating the conditions for an attentional blink (Chun & Potter, 1995; Raymond et al., 1992; Raymond, Shapiro, & Arnell, 1995; Shapiro, Raymond, & Arnell, 1994). If Visser et al.'s model is correct, a new account is needed for the negative effect on T2 of a distractor following T1, relative to a blank. We suggest here that visual masking by the distractor in Stage 1 (not Stage 2) is responsible for slowing the initial processing of T1, delaying its identification and entrance to Stage 2 and hence delaying the Stage 2 processing of T2.

The attentional blink is defined as a difficulty in reporting T2 when T1 is relatively easy to report. Because an attentional blink is expected only when T1 has been detected and encoded, in many studies T2 performance is measured conditional on correct report of T1. In most attentional blink studies, rates of presentation (typically about 100 ms per item) are such that performance on T1 is high. In the present study, we asked what happens to report of T1 and T2 under conditions in which report of a single target is well below ceiling and when much shorter SOAs are included. We made three major changes in the standard method: In all but the first experiment, stimuli appeared in two simultaneous streams, each with one target; items were presented for 53 ms each (with no interstimulus interval); and the SOA between the two target words varied between 0 and 213 ms. In brief, we found that report of the targets as SOA varied indicated a changing ability of the two targets to attract processing resources and revealed that they competed at all SOAs in the range we examined.

A New Model of Early Attention: The Two-Stage Competition Model

To encompass the results of the present studies using very short SOAs between targets, we propose a model of early attention that we term the two-stage competition model. We outline the model here and consider it in more detail in the final discussion. The model is an extension and modification of the Chun and Potter (1995) two-stage model of attention. In Stage 1, each stimulus (distractor or target) begins to be analyzed; if properties are detected that make the stimulus a likely target, it attracts additional processing resources, increasing the probability that it will be identified. If T2 appears before T1 has been identified, T2 will begin to attract resources to itself, and the two targets will compete in Stage 1 for a limited pool of resources. Crucially, if T2 arrives very soon after T1, it will benefit from the previous detection of T1, accruing resources faster than if an attentional gate had not been opened by detection of T1 (see Shih, 2000, for a similar suggestion). Whichever of the targets is identified first will enter a central bottleneck, the second stage of processing necessary for short-term consolidation and report, as in the Chun–Potter two-stage model. The other target may be identified subsequently, but it will wait in Stage 1 and may be forgotten as further distractors follow it. Which target will be identified first will depend on both the length of time the target has been processed and the resources available during that time.[1] The item that directly follows a target in the same stream will perceptually mask the target, limiting further perceptual processing (although not necessarily limiting higher level, postidentification processing).

Relation to the Interference Model of the Attentional Blink

The two-stage competition model is similar in some respects to the *interference model* of Shapiro et al. (1994; see also Raymond et al., 1995), which was inspired in part by simultaneous search theories of Duncan and Humphreys (1989) and Bundesen (1990).[2] In the first stage of the model, each item in the RSVP sequence is given a perceptual description that is matched for similarity to the templates for the targets. (In a typical experiment, T1 is specified by a particular characteristic, such as being a white letter among black letters, and the task is to report the identity of that letter; T2, termed a probe, is a black *X* that the viewer reports as present or absent.) If the similarity to the target or probe specification is sufficiently high, the item enters a second stage, representation in visual short-term memory (VSTM), where it is assigned a weighting based both on its similarity to one of the target templates and on the available capacity in VSTM (the total weighting in VSTM is limited, so later items may be represented in VSTM with diminished weights or may not be admitted to VSTM). The item directly following the target also enters VSTM because of its proximity to the target (as in the inexact gate model), although its weighting is low unless it happens to be similar to the target or probe. The probe and its following item, in turn, may also enter VSTM, although they will enter with lower weights or may be excluded because VSTM capacity has already been expended on the target and following item.

Next, a retrieval process selects items from VSTM to report on the basis of their relative weightings and also their mutual similarity: Similarity is likely to increase selection mistakes. At short SOAs, the probe may lose the competition for selection. Because weights decay over time, as the SOA between the target and probe increases, the weight of the target will diminish or the target will have been expunged from VSTM (perhaps because it has been passed on to a report stage), enabling the probe to have a higher weight in VSTM and thus allowing it to be retrieved and reported. Descriptions of the model do not make clear whether a target can be selected from VSTM at the retrieval and report stage and then held for subsequent overt report, in parallel with probe detection and processing; without such a possibility, it would be difficult to explain the high success rate for reporting both target and probe at long SOAs.

[1] Whether two targets can both enter Stage 2 together under certain conditions (as has been proposed to account for Lag 1 sparing) is considered in the final discussion.

[2] We do not discuss an earlier model, the inhibition model of Raymond et al. (1992), because those authors largely replaced it with their interference model.

The chief similarities between the two-stage competition model and the interference model are that both have a stage at which two targets compete for resources and both separate one or more early stages of processing from a later stage (or stages) of processing. However, in the competition model the two targets mutually compete at short SOAs, whereas in the interference model T1 is successfully processed on most trials, and only T2 suffers from the competition. The competition in the interference model occurs in VSTM or in access to VSTM, as well as in later retrieval from VSTM, whereas in the competition model the competition is for processing resources required for identification and occurs in Stage 1; the target that is first identified enters Stage 2 for consolidation in short-term memory. In the competition model, there is no stage corresponding to VSTM. It should be noted that in most previous contexts (e.g., Bundesen, 1990; Duncan & Humphreys, 1989; Luck & Vogel, 1997; Phillips, 1983), VSTM has been assumed to represent only a single visual array that has been presented simultaneously, and it is not clear that information in VSTM can be built up from successive inputs from a single spatial location, as the interference model proposes. The interference model does not elaborate on stages following VSTM, and there is nothing corresponding to a serial component in the model, whereas a serial Stage 2 is a central characteristic of the competition model (and the Chun–Potter model).

Similarity plays somewhat different roles in the two models. In the interference model, the similarity of the perceived target (or probe) to its target specification and its dissimilarity to distractors (especially those that immediately follow the target and probe and that are likely to be in VSTM with the target and probe) determine initial weight, weight in VSTM, and hence likelihood of retrieval from VSTM; similarity within VSTM may also create confusion at the time of retrieval. The competition model, following the Chun–Potter two-stage model, proposes that target–distractor similarity has two effects: a global effect on the ease with which targets can be discriminated from distractors (which affects the setting of the threshold for initial target detection; the threshold is set lower when targets look very different from distractors) and a local effect, the masking effect of the item immediately following each target.[3]

In the interference model, T1 is always strongly represented in VSTM by virtue of arriving first, because VSTM is empty at that point; in the competition model, detection of T1 attracts resources, but when T2 arrives before T1 has been identified, it begins to attract resources away from T1.[4] In the interference model, it is competition to enter VSTM and competition within VSTM for retrieval that causes the attentional blink; in the competition model, it is the monopolizing of the consolidation stage by T1 (at longer SOAs) that allows T2 to be overwritten or forgotten in Stage 1. With respect to the experiments reported in this article, it is not clear what predictions the interference model would make; perhaps, like the Chun–Potter two-stage model, the interference model could be extended to account for the present results.

Relation to Bundesen's (1990) Theory of Visual Attention (TVA)

Bundesen (1990; see also Bundesen, 2002) presented an influential theory of visual attention designed to account for search of and memory for a simultaneously presented visual array. He proposed a computational model of attentional selection that takes into account stimulus variables such as number of targets present, number of distractors present, perceptual similarity of distractors to targets, and SOA between the array and a subsequent visual mask. The theory proposes that there is a limited-capacity short-term memory store; entrance into this store occurs when an item in the visual field is perceptually categorized (e.g., as a red object), provided that the store is not already full. Processing occurs in parallel over the whole field, but processing capacity is limited so that items are in competition for categorization. The theory predicts which items and how many items will be successfully reported from a given array on the basis of the number of targets and distractors, their similarity, and the duration of the array, as well as other variables such as the characterization of the targets. This theory has successfully modeled a wide range of results in search and other experiments in which a single, simultaneous array is presented on each trial.

The theory has not, however, been extended to serial presentation of stimuli, as in previous studies of the attentional blink and the present experiments. Although the two-stage competition model shares the notion of parallel, competitive processing with TVA, few of the variables that are central to TVA are relevant to the present experiments. We compare only one versus two targets, we do not vary similarity, and we do not vary the duration (SOA to the mask) of targets. Selective attention to a specific location in the visual field (as in Experiment 6) is a variable that has been incorporated in TVA. On the other hand, TVA does not consider the SOA between targets (which is always zero, because the arrays are simultaneous), whereas SOA is the key variable in the present experiments, nor does TVA consider the differential effect of presenting one versus two streams of stimuli. Thus, although it is very possible that TVA could be fruitfully extended to sequential presentation, at present TVA is not directly relevant to the present experiments and does not provide a model of the results.

Introduction to Experiment 1 and the Subsequent Experiments

In Experiment 1, we investigated a question about Lag 1 sparing: Does sparing of T2 result from its directly following T1 or from its following at an SOA of about 100 ms, or are both conditions necessary? In previous research, these two factors were confounded: Sparing occurred when T2 directly followed T1 and the SOA was about 100 ms. To address this and related questions, in Experiment 1 we presented two target words in a single stream at 53 ms/item; the distractors were strings of ampersands and percentage signs. The targets appeared at SOAs of 53, 107, and

[3] In the Chun–Potter model, the similarity of the following distractor increased the duration of Stage 2 because both the target and the following item entered Stage 2 and had to be discriminated; in the competition model, similarity of the following distractor affects visual masking, such that visual similarity increases masking and slows or prevents identification of the target.

[4] In the interference model, there is no stage that corresponds to identification of the target as distinct from detection, although the identity of the to-be-reported target (if not the probe, to which the response is only present or absent) must become known at some stage, perhaps only after retrieval from VSTM.

213 ms, thus dissociating Lag 1 and an SOA of about 100 ms. To investigate still shorter SOAs, in the subsequent experiments we presented the words in separate streams, one above the other. Short SOAs allow one to address not only the Lag 1–SOA confound but also other questions about the early stages of attention: Is attention fully fixed on a target the moment it appears, or does attention take time to become fixed? Does the first of two potential targets always have an attentional advantage (as in the attentional blink), or is T2 able to attract attention if the SOA is short?

Experiment 1: A Single Stream With Two Targets

In Experiment 1, we presented two target words in a single stream of distractors, at 53 ms per item. The SOAs were 53, 107, and 213 ms. (Throughout, durations are rounded to the nearest millisecond; the durations are multiples of the 75-Hz refresh rate of the monitor.) At an SOA of 53 ms (Lag 1), the second word served as the mask of the first word; otherwise, all words were preceded and followed by rows of ampersands that served as masks. Because the duration of each word was only 53 ms, we expected that accuracy on the first word would be below ceiling, but we still expected to find a second-word deficit at an SOA of 213 ms. The design permitted us to determine whether sparing of T2 is restricted to Lag 1 (the immediately following target) or is determined by SOA. If the SOA is critical, such that any target arriving within about 100 ms of the onset of T1 can be processed successfully, then sparing should be evident at both Lag 1 and Lag 2. If lag itself is critical, then only an immediately following target should benefit, not one that follows an intervening distractor (note that Raymond et al., 1992, hypothesized that it is the arrival of a distractor immediately after T1 that initiates the attentional blink). In that case, sparing of T2 would be observed at an SOA of 53 ms (Lag 1) but not at 107 ms.

Method

Participants. The 12 participants were members of the Massachusetts Institute of Technology community who volunteered and were paid. All participants spoke English as their first language.

Stimuli and apparatus. The target stimuli were 120 pairs of four- or five-letter lowercase nouns (60 pairs of each length), ranging in noun frequency (combining singular and plural forms) from 13 to 1,901 per million (Francis & Kucera, 1982). Words in a given pair were matched for frequency and length but were otherwise randomly paired. The font was lowercase Courier 20 bold. When viewed from the normal distance of 45 cm, the four-letter words subtended 2° horizontally and 0.55° vertically. The distractors consisted of rows of percentage signs (as long as the words on that trial), alternating with rows of ampersands. The words and distractors were black on a light gray background; the room was normally illuminated. Participants viewed the stimuli binocularly. The stimulus sequences were presented on a Power Macintosh 7500/100 computer equipped with a 17-in. monitor with a refresh rate of 75 Hz. We used MacProbe software (Hunt, 1994).

Design and procedure. A within-subject design was used, with three SOAs between the two words: 53, 107, and 213 ms. Which of the two words appeared first was counterbalanced across participants. On a random half of the trials the first word was preceded by three distractors, and on the other half it was preceded by four distractors, each presented for 53 ms. The distractor that immediately preceded and followed each word was always a row of ampersands except at an SOA of 53 ms, when the second word immediately followed the first. There were a total of 120 trials. Half of the word pairs in each condition were composed of four-letter words and half of five-letter words, counterbalanced over SOA. The order of the trials was randomized; the same random order of the word pairs was used for all participants.

A trial began with a central fixation plus sign for 507 ms, a blank of 107 ms, and then a stream of distractors. The distractors, percentage signs alternating with ampersands at 53-ms intervals, continued for 160 or 213 ms before the first word and for 267 ms after the second word.

One hundred milliseconds after the offset of the stream, a dialog box appeared with two blank fields, one above the other. The participant typed the two words in the respective fields. Participants were encouraged to type a response even if they believed they were simply guessing but to leave a blank if they had no idea; the correct words were presented for 2 s as feedback when the participant clicked *OK* to finish his or her report of the words. Almost all participants reported that on some or most trials they felt that they were guessing, but often the word they typed was correct. The next trial began 40 ms after the offset of the feedback words. There were 18 practice trials using a different set of words.

Analysis. Because our main interest was in the relative attention given to the first versus the second of the two words at various SOAs, the main analysis of variance (ANOVA) was performed on the proportion of correct words reported in each of six conditions (3 SOAs × First or Second Word). Each word was scored separately as correct (all letters correct) or incorrect, so there were 240 scores per participant.

Results and Discussion

The results are shown in Figure 1. In the ANOVA, there were main effects of SOA, $F(2, 22) = 14.37$, $p < .001$, and of first or second word, $F(1, 11) = 5.17$, $p < .05$. Strikingly, there was a marked crossover interaction between SOA and first or second word, $F(2, 22) = 29.09$, $p < .001$. As expected, there was a large attentional blink at an SOA of 213 ms, with the first word reported very accurately and the second word much less so. Performance at an SOA of 107 ms showed the pattern that has been termed Lag 1 sparing (although it was in fact Lag 2 in this experiment), in that

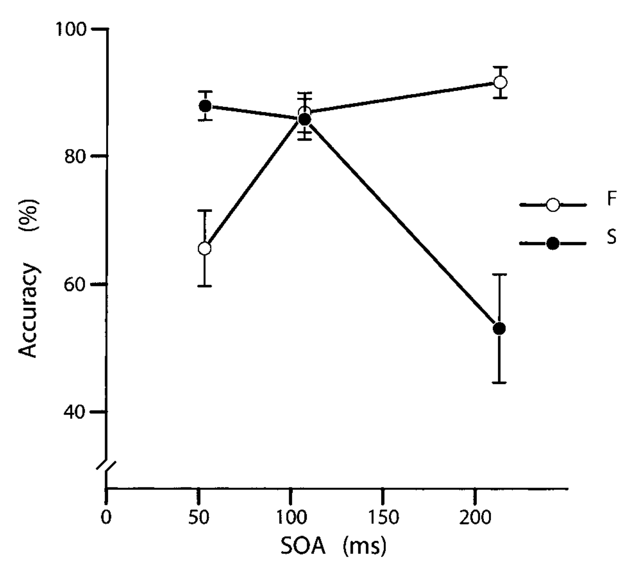

Figure 1. Experiment 1: Percentages of trials on which a given word was reported correctly at stimulus onset asynchronies (SOAs) of 53, 107, and 213 ms, separately for the first word (F) and second word (S). Error bars represent standard errors.

the two target words were both reported rather accurately. At an SOA of 53 ms, however, the sparing of the second word was accompanied by a marked deficit for the first word. This pattern, reported here for the first time, was the reverse of the attentional blink observed at an SOA of 213 ms.

The original inexact gate model (Chun & Potter, 1995; Raymond et al., 1992) proposed that Lag 1 sparing is due to the imprecise closing of an attentional gate through which pass both T1 (which initiates the opening of the gate) and a T2 that follows very closely in time, allowing both T1 and T2 to be represented and processed together in a following stage (VSTM in Raymond et al., 1992, 1995, and Stage 2 in Chun & Potter, 1995). To account for successful T2 performance at an SOA of 107 ms in the present experiment, the attentional window must stay open for about 150 ms (assuming that it opens at the onset of T1) and must therefore take into Stage 2 not only T1 and T2 but also the intervening distractor. When T2 follows T1 at an SOA of 53 ms, the open window would again take in both targets along with one distractor (the one following T2). Thus, T1 and T2 should be processed equally successfully at both SOAs.

However, at an SOA of 53 ms (Lag 1) T1 did rather poorly relative to T2, whereas at 107 ms (with an intervening distractor) both T1 and T2 were processed fairly successfully. The original inexact gate model gives no account of why performance on T1 would be so markedly different at the two SOAs, keeping in mind that the order of the items in Stage 2 is considered to be poorly preserved (Chun & Potter, 1995). The result is, however, consistent with the two-stage competition model, which predicts that two targets compete for processing resources in Stage 1, before either has been identified. The advantage of T2 over T1 at an SOA of 53 ms is consistent with the model's claim that detection of T1 attracts processing resources but that resources take time to accrue to T1 (i.e., the attentional gate opens sluggishly). When T2 appears shortly after T1 it can attract resources more rapidly than T1, because T1 has in effect initiated a transient attentional episode. The improvement in report of T1 at an SOA of 107 ms is expected, inasmuch as T1 has an extra 53 ms of processing before T2 begins to attract resources from T1.

It is worth noting that there is evidence for competition between T1 and T2 at Lag 1 (with an SOA of about 100 ms) in many attentional blink studies, and in fact T2 is often reported more accurately than T1. For example, in Chun and Potter's (1995) Experiment 1, at Lag 1 T1 was reported on 67% of the trials and T2 on 82%. Chun and Potter noted, moreover, that the probability of reporting T1 was somewhat lower in the Lag 1 condition than at longer lags, and the perceived order of the two targets was frequently reversed, again suggesting that there is some competition between T1 and T2 at an SOA of 100 ms; whether the competition is in Stage 2 (as Chun and Potter suggested) or in Stage 1 (as the two-stage competition model claims) is unclear.

There is, however, another possible explanation of the T2 advantage (and the T1 disadvantage) at Lag 1 in the present experiment. At Lag 1 T2 is the item that masks T1, and a word may well be a more effective perceptual mask of another word than is a row of ampersands.[5] Because perceptual backward masking is likely to be more marked at a short SOA such as 50 ms than at a longer one such as 100 ms (Loftus & Ginn, 1984; Potter, 1976), this masking differential would have been expected to be more marked in the present experiment (at 53 ms/item) than in earlier blink experiments in which the Lag 1 SOA was about 100 ms. As shown later, however, this masking interpretation is unlikely to account fully for the present results, because a similar pattern was observed in the following experiments in which T1 and T2 appeared in different spatial streams so that T1 was followed by a distractor at Lag 1 as well as the other lags.

Experiment 2: Two Words in Separate Streams

The use of two simultaneous streams of stimuli enabled us to fix the duration of each stimulus while investigating SOAs both shorter and longer than the stimulus duration, including a simultaneous (0-ms SOA) condition. The simultaneous condition provides a benchmark for competition between first and second words when they are presented asynchronously. In a number of studies, an attentional blink has been demonstrated when the two targets have been presented in different spatial positions at varying SOAs of about 100 ms or greater (e.g., Breitmeyer, Ehrenstein, Pritchard, Hiscock, & Crisan, 1999; Duncan, Ward, & Shapiro, 1994; Joseph, Chun, & Nakayama, 1997; Juola, Duvuru, & Peterson, 2000; Shih, 2000; Visser, Zuvic, Bischof, & Di Lollo, 1999). Thus, we expected to find a similar second-word deficit at the longer SOAs in the present experiment. Little or no Lag 1 sparing has been found, however, when the two targets are in different locations, suggesting that attention takes some time to switch between spatial locations (Shih, 2000; Visser, Bischof, & Di Lollo, 1999; see also Barriopedro & Botella, 1998, and Weichselgartner & Sperling, 1987). In that case, one would expect a very different pattern at short SOAs from that of Experiment 1.

Method

In Experiment 2, as shown in Figure 2, the word pairs appeared in separate streams at SOAs of 0, 40, 107, and 213 ms; a stream of distractors preceded and followed each target. The method was otherwise the same as that of Experiment 1, except as noted.

Participants. The 7 participants were drawn from the same pool used in Experiment 1; none had participated in that experiment.

Design and procedure. The word pairs were the 120 pairs used in Experiment 1, along with 20 additional pairs. The words were presented in two streams, one just above and the other just below the position of the fixation mark. When viewed from the normal distance of 45 cm, the four-letter words subtended 2° horizontally and 0.55° vertically, as before; the two words together subtended 1.5° vertically and were separated by a space of 0.4°. As mentioned, SOAs of 0, 40, 107, and 213 ms were used; SOA was crossed with the spatial position (upper or lower) of the first word (except at the 0-ms SOA). There were 140 trials, 20 in each of the seven conditions. The word sets in each condition were counterbalanced across participants so that a given word pair appeared equally often in each of the seven conditions.

The sequence of a typical trial is shown in Figure 2 (omitting the stream of distractors after the second word). The trial began with a central fixation plus sign for 507 ms, followed by a blank of 107 ms (as in Experiment 1) and then two streams of distractors, just above and below the preceding location of the fixation sign. The distractors, percentage signs alternating with ampersands at 53-ms intervals, continued for 213 ms before the first word. The dual stream continued after the first word and for 267 ms after the second word. When the first word appeared, a distractor (the row of percentage signs) was presented in the other stream (except in the simul-

[5] We thank a reviewer for pointing out this possibility.

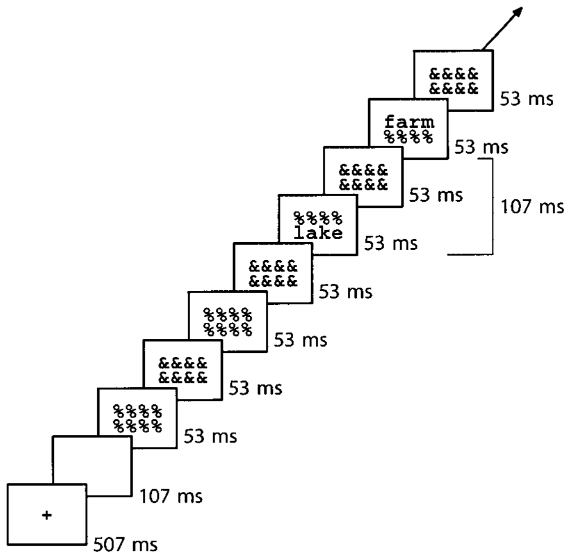

Figure 2. Sequence of events in Experiment 2. The duration of each word was 53 ms, the stimulus onset asynchrony (SOA) varied from 0 to 213 ms, and an ampersand mask followed each word. An SOA of 107 ms is shown; the sequence of alternating ampersands and percentage signs continued for 267 ms after the second word (not shown).

taneous condition). Each word was followed by an ampersand distractor and further distractors until the end of the sequence. Each of the two words was also immediately preceded by ampersands, except in the 40-ms SOA condition, in which the second word partially overlapped in time with the first word (an overlap of 13 ms). In this condition, the second word was preceded by percentage signs for 40 ms. In the stream with the first word, ampersand distractors followed the word for 40 ms while the second target remained in view, and then ampersands appeared in both streams for 53 ms and the alternating distractors continued for 267 ms after the second word.

One hundred milliseconds after the offset of the last distractor, a dialog box appeared as in Experiment 1, and the participant typed in the two words as before, followed by feedback. There was a 500-ms pause before the next trial began. There were 21 practice trials.

Analysis. The main ANOVA was performed on the proportion of correct words reported in each of 24 conditions (3 SOAs × First or Second Word × Upper or Lower Position × Four-Letter or Five-Letter Word). Performance in the 0-ms SOA (simultaneous) condition is shown in the figures but was not included in the analysis. Each word was scored separately as correct or incorrect, so there were 280 scores per participant (240 without the simultaneous condition).

Results and Discussion

The results are shown in Figure 3, as a function of SOA and first versus second word. Overall performance was lower in this experiment than in Experiment 1, presumably because there were two streams to monitor instead of one. As in Experiment 1, however, there was a marked crossover interaction between first versus second word and SOA. In the simultaneous condition, 55% of the words were reported; at an SOA of 40 ms, a similar average of 53% of the words was reported, but the first word was reported on 37% of the trials, whereas the second word was reported on 69%. In the ANOVA of the nonsimultaneous conditions, neither of the main effects reached conventional levels of significance (first or second word, $p = .139$; SOA, $p = .053$). The interaction between SOA and first or second word was highly significant, $F(2, 12) = 11.63$, $p < .01$. As Figure 3 shows, the marked disadvantage for the first word at an SOA of 40 ms, $F(1, 6) = 10.72$, $p < .05$, was greatly reduced at an SOA of 107 ms (*ns*) and became a marginally significant advantage at an SOA of 213 ms, $F(1, 6) = 3.71$, $p < .11$, whereas the opposite pattern was obtained for the second word.

The main effect of the upper or lower position of a given word was only marginally significant ($p = .072$), but there was an interaction between SOA and upper or lower position, $F(2, 12) = 4.09$, $p < .05$. There was a substantial advantage of the upper over the lower word at an SOA of 40 ms that was somewhat reduced at longer SOAs. There was no interaction between upper or lower position and first or second word, nor was there a three-way interaction.

Lag 1 sparing? With respect to Lag 1 sparing, the pattern was similar to that of Experiment 1: Both the first and second words did relatively well at an SOA of 107 ms, but the sparing of the second word at an SOA of 40 ms was coupled with markedly poor report of the first word. The magnitude of the attentional blink for the second word at an SOA of 213 ms was considerably smaller than the blink in Experiment 1, whereas the reverse effect at an SOA of 40 ms in the present experiment was even greater than that at 53 ms in Experiment 1. (Thus, the second-word advantage at 53 ms in Experiment 1 was not due to perceptual masking by T2, or it would not have been obtained in Experiment 2, in which each word was masked by ampersands.)

At first blush, the marked advantage of the second word at an SOA of 40 ms suggests a form of attentional capture by sudden onset (e.g., Yantis, 1993; Yantis & Egeth, 1999). The conditions were not optimal for attentional capture, however, because the second word was presented in an ongoing stream of stimuli rather than in a previously empty location. The similarity of the pattern to that in Experiment 1 (one stream) also argues against attentional

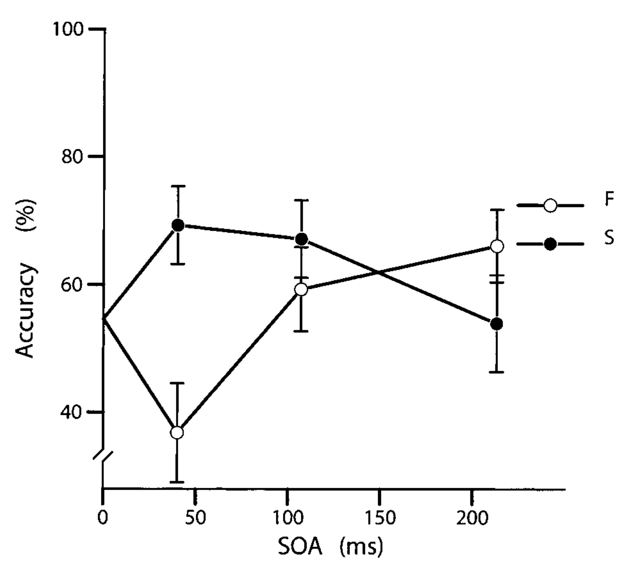

Figure 3. Experiment 2: Percentages of trials on which a given word was reported correctly at stimulus onset asynchronies (SOAs) of 0, 40, 107, and 213 ms, separately for the first word (F) and second word (S). Error bars represent standard errors.

capture in the present experiment; in the one-stream case, attention is already centered on the stream in which the second item appears. Moreover, if attentional capture were responsible for the second-word advantage, one would expect the same effect at longer SOAs, and clearly that did not occur in either experiment.

The function relating SOA and accuracy in reporting the first word was U shaped, as in many studies of backward masking and metacontrast (see Breitmeyer, 1984). Unlike those studies, however, in the present experiment each of the two targets was itself masked by immediately preceding and following distractors at all SOAs. We revisit this question of backward masking in the discussion of Experiment 6.

Does a switch in the spatial location of a second target eliminate Lag 1 sparing? Potter et al. (1998; see also Chun & Potter, 2001) proposed that a task switch (such as a change in modalities, or switching from one target cue for T1 to a different cue for T2) requires processing time, exaggerating the attentional blink at early lags, particularly Lag 1. They suggested that the failure to obtain Lag 1 sparing in a visual search task was an indicator of some form of task switching. Visser, Bischof, and Di Lollo (1999) reviewed the evidence on Lag 1 sparing and reached a similar conclusion. As mentioned earlier, they looked at studies in which the two targets were in different spatial locations and found that there was little or no Lag 1 sparing in such cases (e.g., Breitmeyer et al., 1999; Visser, Zuvic, et al., 1999). Visser, Zuvic, et al. (1999) concluded that "the presentation of a target triggers the opening of an attentional gate that is tied to the spatial location of that target" (p. 436). In the present experiments, however, we found Lag 1 sparing at an SOA of 107 ms (typical of the SOA of Lag 1 in previous studies) when the targets were in different spatial locations, contradicting this conclusion, although Lag 1 sparing was greater when there was only one stream (Experiment 1) than when there were two streams.[6] In any case, as we argue here, sparing of the second of two targets at an SOA of about 100 ms is best regarded as just one point in the changing fortunes of T1 and T2 as SOA increases from zero to the point at which one of the two targets is identified and begins to be consolidated.

The two-stage competition model proposes that processing of a given item is interruptable at an early stage but not at a later stage. This claim correctly predicts the shift from a second-word advantage to a first-word advantage as SOA increases from 40 ms to 213 ms. As SOA increases, processing of T1 is increasingly likely to have reached the point of identification by the time T2 appears (or will reach it before T2 because of its head start), triggering the second stage, during which processing is no longer interruptable. In the next experiment we focused on still shorter SOAs to map out the time course of this attentional shift from first to second word.

Experiment 3: Very Short SOAs Between Two Words

The finding that the second of two words is more readily reported than the first at an SOA of 40 ms led us to investigate even shorter SOAs. In Experiment 3, we used SOAs of 0, 13, 27, and 40 ms. The words (shown for 53 ms each) partially or completely overlapped in time. The competition model proposes that T2 can attract processing resources away from T1 in the first stage of processing, but whether this effect would materialize at an SOA as short as 13 ms was not clear. As in Experiment 2, the simultaneous condition served as a baseline; there, the two target words were in competition as soon as they appeared.

Method

Except as specified, the method was the same as that of Experiment 2.

Participants. The 7 participants were drawn from the same pool used in the previous experiments; none had participated in the earlier experiments.

Stimuli, design, and procedure. The 140 word pairs were the same as those in Experiment 2. The distractors consisted of two rows of percentage signs (as long as the words on that trial), alternating with rows of hatch signs. Except for the simultaneous condition, the two words partially overlapped in time; as in Experiment 2's 40-ms-SOA condition, while the first word was in view the other stream was filled with a distractor until the second word appeared. Each word was followed by a row of ampersands for 53 ms. Unlike the earlier experiments, no further stream of distractors followed the ampersand mask.

Results and Discussion

The main results are shown in Figure 4, as a function of SOA and first versus second word. In the simultaneous condition, 66% of the words were reported; in the nonsimultaneous conditions, 62% of the words were reported: 55% of the first words and 70% of the second words. In the ANOVA of the nonsimultaneous conditions, the second word was reported correctly more often than the first word, $F(1, 6) = 19.90$, $p < .01$. This bias tended to increase as SOA increased from 13 to 40 ms, although the interaction was not significant, $F(2, 12) = 2.66$, $p = .11$. In planned comparisons, the first–second difference was analyzed separately at each SOA, and all three comparisons were significant: 13 ms, $F(1, 6) = 6.89$, $p < .05$; 27 ms, $F(1, 6) = 122.13$, $p < .001$; and 40 ms, $F(1, 6) = 7.30$, $p < .05$. The only other significant main effect was an advantage for the upper over the lower word, $F(1, 6) = 11.98$, $p < .02$, but there was no interaction of upper or lower position with first or second word, or SOA.

The marked benefit for the second word at an SOA of 40 ms replicated the finding in Experiment 2; what is notable is that a second-word advantage was observed even at an SOA as short as 13 ms. This finding gives further support to the competition model's claim that processing of a first target is interruptable at an early stage.

The fact that average performance was similar for simultaneous (0-ms SOA) presentation of two words and for SOAs of 13–40 ms suggests that the two words competed for limited processing resources at all SOAs between 0 and 40 ms, but when one word appeared slightly in advance of the other the relative advantage of

[6] A possible explanation of the difference between the present experiments and those reviewed by Visser, Bischof, and Di Lollo (1999) is that the participants in the present experiments knew that T2 would be in the other stream. In a further experiment that was similar to Experiment 2 except that the two words appeared in the same or different streams with equal and random probability (there was no simultaneous condition), viewers tended to do better on T2 when it was in the same stream as T1, as if they conservatively maintained attention on the stream in which T1 appeared. T1 was always better than T2 when the words were in different streams, but T2 was better than T1 in the same-stream condition except at 213 ms, when there was a marked attentional blink for T2.

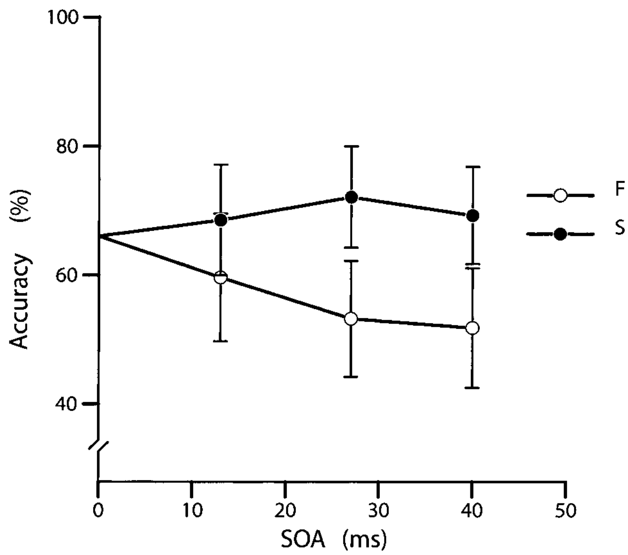

Figure 4. Experiment 3: Percentages of trials on which a given word was reported correctly at stimulus onset asynchronies (SOAs) of 0, 13, 27, and 40 ms, separately for the first word (F) and second word (S). Error bars represent standard errors.

the two words was altered in favor of the more recent word. In the next experiment, we addressed the question of the extent to which the two words in the present experiments were actually interfering with each other.

Experiment 4: One or Two Words

The crossover pattern seen in Experiments 1 and 2 (Figures 1 and 3) and the pattern seen in Experiment 3 (Figure 4) suggest that there was mutual interference or competition between the two words at all SOAs between 0 and 213 ms. In Experiment 2, performance in all conditions was well below ceiling, and the average performance at each SOA including zero was similar, supporting the competition model's assumption that the two words competed for limited processing resources. In Experiment 4, we tested the competition model's prediction that deleting one of the words would improve performance on the remaining word using SOAs of 0, 40, 107, and 213 ms as in Experiment 2. An alternative to the competition model is that attention is divided in advance between the two streams (or haphazardly assigned to one stream or the other on a given trial); were this the case, then omission of one of the words should (on average) have no beneficial effect on performance on the other word. A random one third of the trials had two words, and the other two thirds of the trials had just one word; thus, participants could not anticipate whether there would be two words or one on a given trial. McLaughlin, Shore, and Klein (2001) provided a similar rationale for intermixing trials at different levels of difficulty.

Method

The method was similar to that of Experiment 2, except that there were 210 trials instead of 140 (70 with two words and 140 with one word).

Participants. The 14 participants were drawn from the same pool as that in previous experiments; none had participated in the earlier experiments.

Design and procedure. A random half of the trials from Experiment 2 (70 trials), counterbalanced for SOA, whether the first word was in the upper or lower location, and word length, were replaced by two trials, each with one of the two words. The removed word was replaced by a row of distractors (percentage signs). Thus, two thirds of the trials had just one word, which was equally likely to be in the upper or lower position and to occur at the serial position equivalent to the (nominal) first word or the second word at each (nominal) SOA (0, 40, 107, or 213 ms). Among the 14 participants, half saw a given set of 70 word pairs in the two-word condition, and half saw that set in the one-word condition. Within each group, each pair of words (separate or together) was counterbalanced for SOA and first or second order, as in the previous experiments. In all other respects, the method was the same as that of Experiment 2. In particular, a dialog box with two blank fields appeared after the trial, whether there had been one word or two on that trial. Feedback after each trial indicated which word or words had been presented. Practice trials included a mixture of one-word and two-word trials, and participants were informed that there would sometimes be one word and sometimes two. Because the trials were ordered randomly, participants could not anticipate when (during a trial) or where (upper or lower position) the first word would appear, nor could they anticipate whether it would be followed by a second word.

Results and Discussion

The main results of Experiment 4 are shown in Figure 5. In general, the results of the two-word condition were very similar to those of Experiment 2, although the crossover occurred between the SOAs of 40 and 107 ms rather than between the SOAs of 107 and 213 ms. Thus, uncertainty about whether there would be one word or two did not have a major effect on performance on the

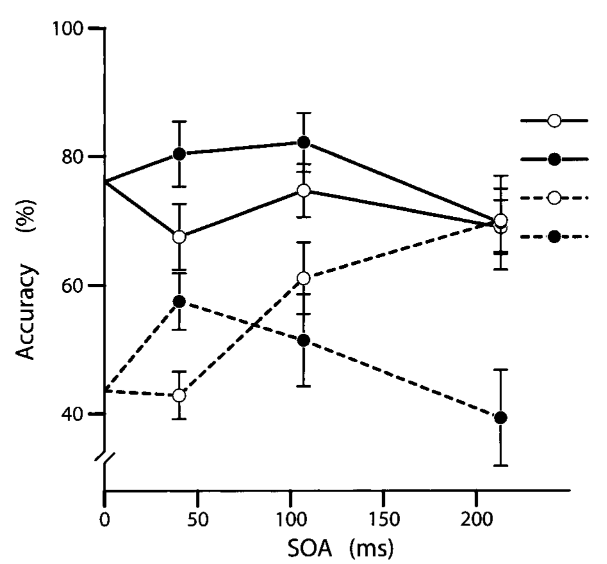

Figure 5. Experiment 4: Percentages of trials on which a given word was reported correctly at stimulus onset asynchronies (SOAs) of 0, 40, 107, and 213 ms, separately for the first word (F) and second word (S). The two top curves represent the one-word condition, in which the SOA and first (1F) versus second word (1S) designations were nominal, corresponding to the serial position of a given word in the stimulus stream. The two lower curves (2F and 2S) represent the two-word condition and can be compared with Figure 3. Error bars represent standard errors.

two-word trials. In contrast, overall accuracy in the one-word condition was markedly higher, as predicted, and no crossover was observed. For the simultaneous condition, 76% of the words were reported in the one-word condition and 44% in the two-word condition. An ANOVA of the conditions with SOAs greater than zero showed a main effect of one versus two words, $F(1, 13) = 121.77$, $p < .001$, with 74% of the words reported correctly on one-word trials and 54% of each of the words on two-word trials. There was also a main effect of SOA, $F(2, 26) = 4.55$, $p < .05$. There was an interaction between one versus two words and first or second word, $F(1, 13) = 7.34$, $p < .05$, as well as an interaction between SOA and first or second word, $F(2, 26) = 20.16$, $p < .001$.

It is important to note that these main effects and interactions were qualified by a three-way interaction among first or second word SOA, and one versus two words, $F(2, 26) = 7.81$, $p < .01$ (see Figure 5). Separate analyses of the one-word and two-word conditions were then carried out. The analysis of the two-word conditions showed no main effect of SOA or of first versus second word; however, as in Experiment 2, there was a strong interaction between these variables, $F(2, 26) = 18.86$, $p = .001$. At an SOA of 40 ms the second word was more likely to be reported ($p < .01$), whereas at longer SOAs the first word was increasingly likely to be reported, at the expense of the second word (107-ms SOA, *ns;* 213-ms SOA, $p < .01$).

The analysis of the one-word conditions showed effects of nominal SOA, $F(2, 26) = 4.46$, $p < .05$; nominal first versus second word, $F(1, 13) = 6.62$, $p < .05$; and their interaction, $F(2, 26) = 3.37$, $p = .05$. The pattern of these effects was different from the interaction observed for the two-word trials: Report of the nominal second word (which always had a later serial position than the nominal first word) was better than or equal to report of the nominal first word, with no crossover. Strikingly, however, the second-word advantage at an SOA of 40 ms was as marked in the one-word condition ($p = .001$) as in the two-word condition, raising the question of whether the second-word advantage we observed was somehow spurious. In the one-word condition, the stimulus difference between the first and the second word was as follows: The nominal first word appeared 213 ms after the onset of alternating distractor arrays and was immediately preceded by ampersands, whereas the nominal second word appeared after 213 ms plus 40 ms of percentage-sign distractors (see the description of the method of Experiment 2). These small differences between the context of nominal first and second words, at a nominal SOA of 40 ms, might have accounted for the small second-word benefit in the one-word condition. Before discussing the significance of the results of Experiment 4, we report the results of an experiment designed to eliminate some of the contextual cues that may have differentiated first and second words.

Experiment 5: One or Two Words With Variable Onset

In Experiment 4, there were significant differences between nominal first and second words in the one-word condition that might have been due to the serial position of the words or a minor difference in context, exacerbated by the fact that the serial position of the first word was always the same. In Experiment 5, the serial position of the actual or nominal first word was varied, the distractors were sequences of digits and keyboard symbols selected randomly for each distractor pair (the distractors in the two streams were the same), and an SOA of 53 ms was substituted for the 40-ms SOA to make the timing of item alternations uniform (eliminating the minor context difference in Experiment 4 at an SOA of 40 ms). In other respects, Experiment 5 was a replication of Experiment 4.

Method

Participants. The 14 participants were drawn from the same pool as that in previous experiments; none had participated in the earlier experiments.

Design and procedure. The design and procedure were the same as those in Experiment 4, except as follows. The distractors were random sequences of four or five items (the same length as the words on a given trial) sampled from the digits 2–9 and the keyboard symbols @, #, $, &, %, and *; the distractors in the two streams were identical and each distractor pair was a new random sample from this set of 14 symbols. As before, distractors and words were presented for 53 ms. In Experiment 5, the number of distractors preceding the first word (or the nominal first word in the one-word condition) varied from four to eight, counterbalanced over the other conditions. Thus, the single words in the nominally first position appeared from 213 to 427 ms after the onset of the dual stream, and those in the nominally second position appeared from 267 to 640 ms after the onset of the stream. (In the 0-ms-SOA condition, the word or words appeared between 213 and 427 ms after the onset of the two streams.) As before, there were always five distractors after the second word (even when the second word was in fact deleted and only the first word was presented), except that when the two words were simultaneous, only four distractors followed. The final change from Experiment 4 was that an SOA of 53 ms was substituted for the 40-ms SOA to synchronize events in the two streams.

Results and Discussion

The main results of Experiment 5 are shown in Figure 6. As in Experiment 4, performance on the one-word trials was much more accurate than performance on the two-word trials, but unlike Experiment 4 there was no significant first–second-word difference in the one-word condition. The two-word condition showed a highly significant interaction between SOA and first or second word, with the same pattern seen in Experiment 2 and the two-word condition in Experiment 4. The overall level of performance was lower in Experiment 5 than in Experiment 4, probably because of the random-string distractors and the uncertainty about the serial position of the first word.

For the simultaneous condition (SOA = 0 ms), 63% of the words were reported in the one-word condition and 34% in the two-word condition. An ANOVA of the conditions with SOAs greater than zero showed a main effect of one versus two words, $F(1, 13) = 46.44$, $p < .001$, with 57% of the words reported correctly on one-word trials and 42% of each of the words on two-word trials. There was a main effect of the number of distractors before the first word (or nominal first word), $F(4, 52) = 4.99$, $p < .01$, with poorer performance when there were eight distractors before the first word; this effect interacted with SOA, $F(8, 104) = 2.19$, $p < .05$. There was no apparent pattern to this interaction, and the number of distractors did not interact with any other variables. There were also main effects of SOA, $F(2, 26) = 3.62$, $p < .05$, and the first or second position of the word, $F(1, 13) = 19.61$, $p = .001$. There was an interaction between one

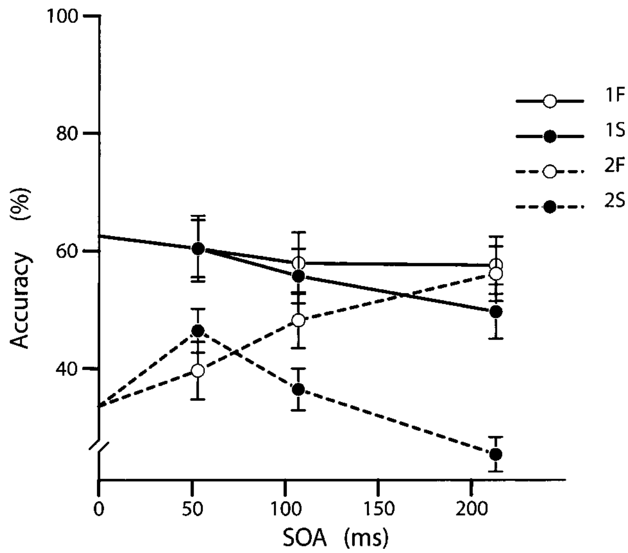

Figure 6. Experiment 5: Percentages of trials on which a given word was reported correctly at stimulus onset asynchronies (SOAs) of 0, 53, 107, and 213 ms, separately for the first word (F) and second word (S). The two top curves represent the one-word condition, in which the SOA and first (1F) versus second word (1S) designations were nominal, corresponding to the serial position of a given word in the stimulus stream. The two lower curves (2F and 2S) represent the two-word condition and can be compared with Figures 3 and 5. Error bars represent standard errors.

versus two words and first or second word, $F(1, 13) = 5.57$, $p < .05$, as well as an interaction between SOA and first or second word, $F(2, 26) = 15.71$, $p < .001$. These interactions were qualified by a three-way interaction among one versus two words, first or second word, and SOA, $F(2, 26) = 7.08$, $p < .01$ (see Figure 6).

Separate analyses of the one-word and two-word conditions were then carried out. For the two-word trials, there was a main effect of first versus second word, $F(1, 13) = 20.29$, $p = .001$, and an interaction with SOA, $F(2, 26) = 16.43$, $p < .001$. At an SOA of 53 ms the second word was more likely to be reported (although the difference was not significant), whereas at longer SOAs the first word was increasingly likely to be reported, at the expense of the second word (the first word was significantly more likely to be reported than the second word at SOAs of 107 ms, $p < .01$, and 213 ms, $p < .001$). The analysis of the one-word conditions showed only one significant effect, a main effect of nominal SOA, $F(2, 26) = 4.99$, $p < .05$. At an SOA of 53 ms, the mean probabilities of reporting a single word in the first and second positions were identical; that is, a serial position difference of 53 ms had no effect on reports. Only at the longest SOA of 213 ms was there a difference between nominally first and second words ($p < .05$), with the first word reported more accurately than the second. Presumably, this was because the second word appeared, on average, 213 ms later than the first, and much later than the average serial position on all trials.

The presentation of two to-be-reported words produced clear mutual interference at all SOAs between 0 and 213 ms, except that (as in Experiment 4) the first word was relatively immune from interference when the second word appeared 213 ms later (and the second word was often blinked). The interference we observed in Experiments 4 and 5 was found even though the viewer did not know in advance whether there would be one or two words presented on a given trial.[7] Moreover, the presence of two words had an impact not only on the second word but also on the first word (except when the second word did not arrive for 213 ms). Thus, the first of two words remains vulnerable to interference from another to-be-encoded word for at least 107 ms, and the second of two words is subject to increasing interference as SOA increases to 213 ms. The complementarity between performance on the two words is just what the two-stage competition model predicts.

Experiment 6: Attention to One Location

A question about the interference between two words in the present experiments is whether it can be modulated or overcome by selective attention to just one of the two streams (Egeth & Yantis, 1997; Eriksen & Schultz, 1979; Kahneman, Treisman, & Burkell, 1983; Yantis & Johnston, 1990) or whether (as in some but not all forms of metacontrast masking and backward masking) the distracting effect of the other word is largely impervious to attentional set. In relation to the competition model, the question is whether the lability of attention in the first stage is a result of a low-level, involuntary pull of attentional resources toward a second target word or a result of the intentional set to report both words. In the former case, one would expect the involuntary pull from the other word to be greater at short SOAs (in the metacontrast range, which is also the range in which a second-item advantage has been observed in the present experiments) than at longer SOAs. To evaluate these predictions, we instructed participants in Experiment 6 to attend to one or the other stream and to report only the word in that stream. The word in the to-be-reported stream was equally often the first and the second word, and the SOA was varied as in Experiment 2.

Method

The method was similar to that of Experiment 2, except as specified subsequently.

Participants. The 7 participants were drawn from the same pool used in the previous experiments; none had participated in the earlier experiments.

Design and procedure. SOAs were 0, 40, 107, and 213 ms. The materials were divided into two counterbalanced blocks of 70 trials each. Participants were instructed to attend to the upper stream in one block and the lower stream in the other. The stream to be attended in the first block was counterbalanced over participants to the extent possible. Feedback was given only on the word in the indicated stream.

Results and Discussion

The results were clear, as shown in Figure 7. Correct performance on the attended word averaged 91% in the simultaneous condition and 93% in the nonsimultaneous conditions, as compared with an average of 59% correct for each of the words in

[7] The pattern of results was the same in a further experiment using the procedure of Experiment 4, except that the one-word and two-word conditions were between subjects, so participants knew whether there would be one or two words.

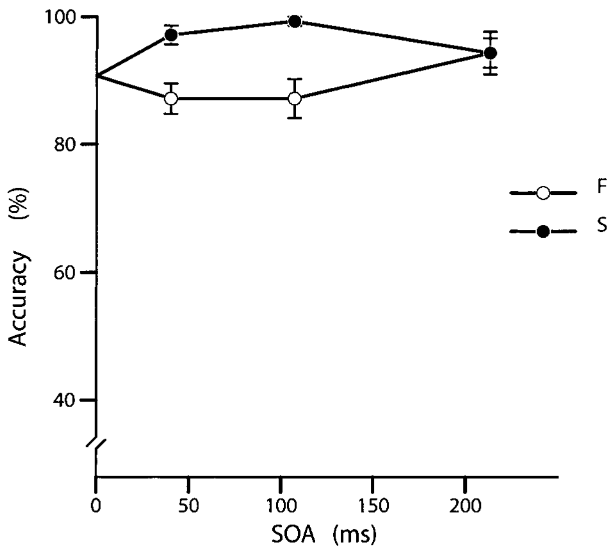

Figure 7. Experiment 6: Percentages of trials on which the word in the specified stream was reported correctly at stimulus onset asynchronies (SOAs) of 0, 40, 107, and 213 ms, when the attended word was the first word (F) versus the second word (S). Error bars represent standard errors.

Experiment 2. An analysis of the nonsimultaneous conditions showed two significant effects: The second word, when it was the one cued by location, was reported more accurately than the first (97% vs. 90%), $F(1, 6) = 24.40$, $p < .01$, and first or second word interacted with SOA, $F(2, 12) = 4.09$, $p < .05$. The interaction, as shown in Figure 7, consisted of a benefit for the second word at the two shorter SOAs ($p < .05$ and $p < .01$ for SOAs of 40 and 107 ms, respectively) but no first- or second-word difference at an SOA of 213 ms. Thus, when T1 was in the attended stream, T2 produced some interference at the shorter SOAs, indicating that the arrival of T2 did attract a certain degree of involuntary attention. Nonetheless, the results show that attention to one stream enabled successful processing of the word in that stream on most trials. The first word did not cause a blink of the second word at an SOA of 213 ms, when the second word was in the attended location. Thus, attention to the spatial location of a word almost guaranteed its successful report, regardless of the onset of another nearby word shortly before or shortly thereafter.

Because we did not measure eye fixations, we do not know whether participants fixated the stream they were instructed to attend to. However, because the centers of the two rows of stimuli were separated by only 0.95° vertically, it is unlikely that fixation of one stream would have substantially reduced perceptibility of stimuli in the other stream (e.g., LaBerge, 1983).

The finding that instructing participants to direct their attention to one stream greatly reduced interference from a word in the other stream suggests that the attentional competition between two words observed in the previous experiments occurs at a higher level than standard backward masking, which is produced by a following distractor that appears in the same location as the preceding stimulus and is not generally reduced by manipulations of attention. Perceptual masking was presumably present for each target, in the form of the following distractor, in all of the dual-stream experiments reported here. It is important, however, to make a distinction between perceptual masking, which occurs at SOAs of about 100 ms or less and depends critically on the physical properties of the mask in relation to the target, and conceptual masking, which occurs at SOAs up to at least 300 ms and is less dependent on physical properties (Briand & Klein, 1988; Intraub, 1984; Loftus & Ginn, 1984; Potter, 1976).[8] Conceptual masking, unlike perceptual masking, is reduced or eliminated if the viewer has no reason to attend to the masking stimulus (e.g., Intraub, 1984). We can infer, then, that interference from the presentation of another target word in a different location and stream of stimuli falls in the category of conceptual masking (or conceptual competition) rather than perceptual masking. Attending to just one of the two streams greatly reduced but did not eliminate conceptual masking at SOAs of 40 and 107 ms.

General Discussion

The goal of the present research was to examine SOAs between two targets that were shorter than those characteristic of previous attentional blink studies, which is the reason that in all but the first experiment the two targets were presented in separate streams of stimuli. This allowed us to hold stimulus duration constant at 53 ms (chosen to keep performance off ceiling) while varying the SOA between the two targets from 0 to 213 ms (the targets partially or completely overlapped in time when the SOA was less than 53 ms). In previous studies of the attentional blink, T1 was usually easy to report, and indeed it was that fact that made the difficulty of reporting T2 (at SOAs between 200 and 500 ms) so surprising. Thus, in the present study we did not explicitly study the attentional blink as it has been standardly defined, as a change over SOA in reporting T2 when T1 has been reported correctly. Instead, we looked at the unconditional report of each of the two targets.

The results showed a rapidly changing pattern of competitive attention between the two targets as SOA increased: In all of the two-word experiments except Experiment 3 (which involved SOAs of 40 ms or less), this interaction of SOA and first–second word was significant. When the SOA between the two target words was between 13 and 53 ms, the second word was more likely to be reported (a consistent direction of difference that was significant in some of the experiments and not significant in others); at an SOA of 107 ms, the two words were more or less equal; and, at an SOA of 213 ms, the first word was more likely to be reported (with an attentional blink for the second word). This pattern was found whether there was a single stream of stimuli (Experiment 1) or two streams (Experiments 2–6). The net effect of mutual competition between the two words was nearly constant over SOAs between 0 and 213 ms. An average of about 1–1.2 words was reported per two-stream, two-word trial in Experiments 2–4 at SOAs of 0, 13, 27, 40, 53, 107, and 213 ms. (Performance was somewhat lower in Experiment 5, with random digits and keyboard symbols as distractors.) In contrast, when participants were instructed to report the word in only one of the two streams (the upper or the lower), performance was near ceiling (Experiment 6), indicating that attention could be largely restricted to one of the two streams even though they were separated by less than a degree of visual angle.

[8] For related phenomena, see Breitmeyer (1984); Di Lollo, Lowe, and Scott (1974); Enns and Di Lollo (1997, 2000); and Merikle (1977).

An important question is whether the division of attention when viewers were attempting to report two words was brought about by the onset of the second word or whether attention was divided between the two streams in advance. In Experiment 6, it was shown that a viewer could confine attention to a specified location. Was it equally possible to predivide attentional resources between the two locations in the display? In Experiment 4, a random two thirds of the trials had only one word; on those trials, performance was much higher (74%) than on the two-word trials (54%), showing that it was the presence of a competing word that was largely responsible for the lower performance, not a previous division of attention or processing capacity between the two streams. In Experiment 5, with a more difficult set of distractors, 57% of words on one-word trials were reported, as compared with 42% of the words on two-word trials. In both Experiment 4 and Experiment 5, the first word showed a deficit if the second word appeared within 107 ms but escaped interference when the second word did not arrive for 213 ms. The second word was substantially worse at all SOAs than its one-word control. If attention had been preallocated to the two streams rather than being adjusted dynamically as targets appeared, performance on a given word would have been the same whether or not another word also appeared on that trial.

The Two-Stage Competition Model of Attention

The findings support the hypothesis that target detection involves two attentional stages with different time courses: an early stage in which attention is labile and a later stage in which attention is fixed. These stages correspond with Chun and Potter's two stages of target detection in RSVP sequences, in which the first stage begins with detection of a potential target and ends with the identification of the target, initiating the second stage (which takes 200–400 ms to complete) in which the target is consolidated in short-term memory (Chun & Potter, 1995; Jolicœur & Dell'Acqua, 1998; Potter, 1993, 1999). The other word may be identified during this interval but cannot be consolidated immediately and may be forgotten, creating an attentional blink. The new claim of the competition model is that attention in Stage 1 is labile, permitting a second relevant stimulus to attract processing resources in such a way as to reduce the resources already allocated to an earlier stimulus. Thus, depending on SOA as well as other factors, either the first or second word may be the word identified first. The second stage of processing that is required for report of the target begins only after one of the targets has been identified (not simply detected); until a target has been identified, there is no certainty that the stimulus in question is a target, and there is nothing to consolidate.

A new explanation of Lag 1 sparing. Lag 1 sparing in the standard attentional blink procedure is the reduction or elimination of an attentional blink for T2 when that target appears immediately after T1, at an SOA of about 100 ms. Frequently, both T1 and T2 are reported correctly, although the probability of reporting T1 is somewhat lower in the Lag 1 condition than at longer lags and the perceived order of the two targets is often reversed, suggesting that there is some competition between them (Chun & Potter, 1995). Chun and Potter followed several earlier investigators (Broadbent & Broadbent, 1987; Raymond et al., 1992; Weichselgartner & Sperling, 1987) in hypothesizing that the attentional gate that opens when T1 is detected closes inexactly, so it normally admits the stimulus following T1 for second-stage processing; when the following stimulus is a distractor, processing of T1 is slowed, but when it is T2, both will be successfully processed on many trials.

The two-stage competition model of attention offers a different explanation of Lag 1 sparing. In the initial, labile phase of attention—Stage 1—there is an ongoing competition between targets for a limited pool of processing resources. When the experimental setup makes each target difficult to process or to retain in Stage 1, as in the present two-stream procedure with an exposure duration of 53 ms per item, this competition means that on average only one target word is likely to be reported: the one that is first identified and that then monopolizes Stage 2 processing. Before T1 has been identified, the appearance of T2 attracts some of the processing resources initially accrued by T1, slowing T1's identification and increasing the probability that T2 will be the first to be identified and hence consolidated. Thus, T2 benefits from detection of T1, accounting for T2's superiority at short SOAs. However, the longer the SOA between the two targets and, hence, the longer T1's head start, the greater the likelihood that T1 will be the first one identified, monopolizing Stage 2.

In the present experiments, the two targets were competitively equal at an SOA of about 100 ms, exhibiting the phenomenon of Lag 1 sparing inasmuch as performance on T2 was much better at an SOA of 107 ms than at an SOA of 213 ms. We showed for the first time, however, that Lag 1 sparing at an SOA of about 100 ms is just one point on a competitive continuum in which relative attention to each target shifts as SOA changes. The evidence that T2 is more likely to be reported than T1 at still shorter SOAs requires a modification of the inexact gate model. First, the processing of T1 is affected by the onset of T2, showing that the competition is mutual, not solely an effect of T1 on T2. Second, the transient attentional episode initiated by T1 does not automatically sweep both T1 and any stimulus that follows it into Stage 2, or T1 and T2 should have been equally likely to be reported at each SOA of 100 ms or less.

Can the inexact gate account be salvaged by proposing (as did Weichselgartner & Sperling, 1987, and Shih, 2000) that the gate opens sluggishly in response to T1 detection, as well as closing sluggishly? This modified model would explain why, at short SOAs, T2 is more likely to be reported than T1, but it would predict that T1 would be just as badly off when T2 was omitted or delayed: The opening of the attentional gate by T1 would always be slow, leaving too little time to process T1. Put the other way, if the gate opens quickly enough to admit T1 when T2 does not show up, why is T1 not admitted as readily when T2 arrives shortly after? Any account of this effect must propose competition between T1 and T2 at some stage. As noted, Chun and Potter (1995) suggested that T1 and T2 compete to some extent when they are together in Stage 2, but that cannot account for the present pattern, in which very short SOAs show a T2 advantage that changes to a marked T1 advantage as the SOA increases to 213 ms. If, as we propose, the competition for processing resources occurs in Stage 1 rather than Stage 2, the SOA pattern is more readily explained.

The two-stage competition model places the competition between T1 and T2 in Stage 1, when both targets have been detected but neither has yet been identified. Once one is identified, it alone enters Stage 2, the bottleneck associated with short-term memory consolidation. Why, then, are both T1 and T2 reported successfully at Lag 1 in many attentional blink experiments (e.g., Chun &

Potter, 1995)? We propose that the longer exposure durations (e.g., 100 ms per item) used in most such experiments permit processing of T1 to reach a point at which it can be retained briefly without Stage 2 processing so that a shift of resources to T2 (followed by Stage 2 processing of T2) allows both targets to be reported on many trials. As noted earlier, at Lag 1 T2 is often reported more accurately than T1, and they are also frequently reported in reverse order (Chun & Potter, 1995). These results have been taken to indicate that T1 and T2 compete in Stage 2 (at Lag 1), but they are equally compatible with the present model, in which competition is restricted to Stage 1. Whether T1, T2, or both will be reported depends on the presentation conditions (duration, masking, one vs. two streams, and the like) and on the SOA between them.

Do two targets ever enter Stage 2 together? Neither the present study nor previous research provides a firm answer to this question, in part because we have no independent marker for presence of an item in Stage 2 other than the ability to report targets presented close in time under some conditions. However, as shown in the present experiments, when neither target is near ceiling even when presented alone, Lag 1 sparing no longer looks to be a free ride in Stage 2 for T2 (along with T1). Rather, attentional blink sparing of T2 at an SOA of 100 ms represents just one point in the shifting competitive success of the two targets. A second-target advantage begins at an SOA as short as 13 ms and extends to about 100 ms, reflecting a continual competition between the two targets in Stage 1 that ends only when one target is identified and monopolizes Stage 2. The fact that the T2 advantage appears so early in processing suggests that it occurs in Stage 1. We suggest that the triggering of a transient attentional episode by detection of a potential target in Stage 1 (leading to target identification) is a possible alternative to the idea that the attentional episode occurs after identification, resulting in the transfer of a target (and the following item) to Stage 2 for further processing and consolidation in short-term memory.

Relation to models of the attentional blink and VSTM. As noted earlier, the present experiments were designed to investigate short SOAs between targets, shorter than those in previous attentional blink studies, using methods that departed from those used in most previous studies: a short exposure duration and two streams of stimuli. Thus, one would not necessarily expect that previous models of the attentional blink could be readily extended to account for the present results. Indeed, we concluded that the Chun–Potter two-stage model (1995) needed to be modified significantly to account for the present results. We noted some similarities between the present model and two other models, the interference model of the attentional blink (Raymond et al., 1995; Shapiro et al., 1994) and Bundesen's TVA model of target search in a simultaneous display (Bundesen, 1990, 2002); there are also significant differences, however, and neither of the latter models makes direct predictions for the range of SOAs and the stimulus conditions in the present study. Whether either of those models could be adapted to account for the present results is a question to be answered by further research and theory development.

Conclusion

The present studies provide a detailed picture of attentional engagement over the first 200 ms or so of processing two targets. We observed marked interference between two words at all SOAs between 0 and 213 ms, but which of the two words was more likely to be reported varied dramatically with SOA. The crossover from a second-word advantage to a first-word advantage occurred at an SOA of about 100 ms. We propose that two processing stages are required to account for the findings: a competitive stage that begins with detection of the first potential target and ends when one of the two targets has been identified and a second stage in which only this target is consolidated in short-term memory. A potential target attracts attentive processing resources quickly, but in the first stage attention is labile, so detection of a second potential target attracts resources away from T1. Identification of one of the targets initiates the second stage of consolidation for that target alone; the other target, which cannot receive Stage 2 processing until the initial target has been consolidated, is vulnerable to interference or forgetting during the wait. When the SOA between targets is short, T2 is often the first to be identified, but as the SOA increases, T1 is increasingly likely to be the first to be identified. The two-stage competition model of attention thus proposes that until one of the words has been identified, attention remains labile, but once a word has been identified, attention becomes fixed as that word alone enters a consolidation stage.

References

Barriopedro, M. I., & Botella, J. (1998). New evidence for the zoom lens model using the RSVP technique. *Perception & Psychophysics, 60,* 1406–1414.

Breitmeyer, B. G. (1984). *Visual masking: An integrative approach.* Oxford, England: Clarendon Press.

Breitmeyer, B. G., Ehrenstein, A., Pritchard, K., Hiscock, M., & Crisan, J. (1999). The roles of location specificity and masking mechanisms in the attentional blink. *Perception & Psychophysics, 61,* 798–809.

Briand, K. A., & Klein, R. M. (1988). Conceptual masking in brief visual displays. *Canadian Journal of Psychology, 42,* 496–502.

Broadbent, D. E., & Broadbent, M. H. (1987). From detection to identification: Response to multiple targets in rapid serial visual presentation. *Perception & Psychophysics, 42,* 105–113.

Bundesen, C. (1990). A theory of visual attention. *Psychological Review, 97,* 523–547.

Bundesen, C. (2002). A general theory of visual attention. In L. Backman & C. von Hofsten (Eds.), *Psychology at the turn of the millennium.* (Vol. 1, pp. 179–200). Hove, England: Psychology Press.

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 109–127.

Chun, M. M., & Potter, M. C. (2001). The attentional blink and task switching within and across modalities. In K. Shapiro (Ed.), *The limits of attention: Temporal constraints in human information processing* (pp. 20–35). Oxford, England: Oxford University Press.

Di Lollo, V., Lowe, D. G., & Scott, J. P., Jr. (1974). Backward masking and interference with the processing of brief visual displays. *Journal of Experimental Psychology, 103,* 934–940.

Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological Review, 87,* 272–300.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96,* 433–458.

Duncan, J., Ward, R., & Shapiro, K. (1994, May 26). Direct measurement of attentional dwell time in human vision. *Nature, 369,* 313–315.

Egeth, H. E., & Yantis, S. (1997). Visual attention: Control, representation, and time course. *Annual Review of Psychology, 48,* 269–297.

Enns, J. T., & Di Lollo, V. (1997). Object substitution: A new form of masking in unattended visual locations. *Psychological Science, 8,* 135–139.

Enns, J. T., & Di Lollo, V. (2000). What's new in visual masking? *Trends in Cognitive Sciences, 4,* 345–352.

Eriksen, C. W., & Schultz, D. W. (1979). Information processing in visual search: A continuous flow conception and experimental results. *Perception & Psychophysics, 25,* 249–263.

Francis, W. N., & Kucera, H. (1982). *Frequency analysis of English usage: Lexicon and grammar.* Boston: Houghton Mifflin.

Hunt, S. M. J. (1994). MacProbe: A Macintosh-based experimenter's workstation for the cognitive sciences. *Behavior Research Methods, Instruments & Computers, 26,* 345–351.

Intraub, H. (1984). Conceptual masking: The effects of subsequent visual events on memory for pictures. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 10,* 115–125.

Jolicœur, P., & Dell'Acqua, R. (1998). The demonstration of short-term consolidation. *Cognitive Psychology, 36,* 138–202.

Joseph, J. S., Chun, M. M., & Nakayama, K. (1997, June 19). Attentional requirements in a "preattentive" feature search task. *Nature, 387,* 805–807.

Juola, J. F., Duvuru, P., & Peterson, M. S. (2000). Priming effects in attentional gating. *Memory & Cognition, 28,* 224–235.

Kahneman, D. (1968). Method, findings, and theory in studies of visual masking. *Psychological Bulletin, 70,* 404–425.

Kahneman, D., & Treisman, A. (1984). Changing views of attention and automaticity. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention* (pp. 29–62). New York: Academic Press.

Kahneman, D., Treisman, A., & Burkell, J. (1983). The cost of visual filtering. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 510–522.

LaBerge, D. (1983). Spatial extent of attention to letters and words. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 371–379.

Loftus, G. R., & Ginn, M. (1984). Perceptual and conceptual masking of pictures. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 10,* 435–441.

Luck, S. J., & Vogel, E. K. (1997, November 20). The capacity of visual working memory for features and conjunctions. *Nature, 390,* 279–281.

Luck, S. J., Vogel, E. K., & Shapiro, K. L. (1996, October 17). Word meanings can be accessed but not reported during the attentional blink. *Nature, 383,* 616–618.

Maki, W. S., Frigen, K., & Paulson, K. (1997). Associative priming by targets and distractors during rapid serial visual presentation: Does word meaning survive the attentional blink? *Journal of Experimental Psychology: Human Perception and Performance, 23,* 1014–1034.

McLaughlin, E. N., Shore, D. I., & Klein, R. M. (2001). The attentional blink is immune to masking-induced data limits. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 54*(A), 169–196.

Merikle, P. M. (1977). On the nature of metacontrast with complex targets and masks. *Journal of Experimental Psychology: Human Perception and Performance, 3,* 607–621.

Pashler, H. (1998). *The psychology of attention.* Cambridge, MA: MIT Press.

Phillips, W. A. (1983). Short-term visual memory. *Philosophical Transactions of the Royal Society of London, Series B, 302,* 295–309.

Potter, M. C. (1976). Short-term conceptual memory for pictures. *Journal of Experimental Psychology: Human Learning and Memory, 2,* 509–522.

Potter, M. C. (1993). Very short-term conceptual memory. *Memory & Cognition, 21,* 156–161.

Potter, M. C. (1999). Understanding sentences and scenes: The role of conceptual short term memory. In V. Coltheart (Ed.), *Fleeting memories* (pp. 13–46). Cambridge, MA: MIT Press.

Potter, M. C., Chun, M. M., Banks, B. S., & Muckenhoupt, M. (1998). Two attentional deficits in serial target search: The visual attentional blink and an amodal task-switch deficit. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24,* 979–992.

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance, 18,* 849–860.

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1995). Similarity determines the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 653–662.

Shapiro, K., Driver, J., Ward, R., & Sorensen, R. E. (1997). Priming from the attentional blink: A failure to extract visual tokens but not visual types. *Psychological Science, 8,* 95–100.

Shapiro, K. L., Raymond, J. E., & Arnell, K. M. (1994). Attention to visual pattern information produces the attentional blink in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 357–371.

Shih, S. (2000). Recall of two visual targets embedded in RSVP streams of distractors depends on their temporal and spatial relationship. *Perception & Psychophysics, 62,* 1348–1355.

Visser, T. A. W., Bischof, W. F., & Di Lollo, V. (1999). Attention switching in spatial and nonspatial domains: Evidence from the attentional blink. *Psychological Bulletin, 125,* 458–469.

Visser, T. A. W., Zuvic, S. M., Bischof, W. F., & Di Lollo, V. (1999). The attentional blink with targets in different spatial locations. *Psychonomic Bulletin & Review, 6,* 432–436.

Weichselgartner, E., & Sperling, G. (1987, November 6). Dynamics of automatic and controlled visual attention. *Science, 238,* 778–780.

Yantis, S. (1993). Stimulus-driven attentional capture. *Current Directions in Psychological Science, 2,* 156–161.

Yantis, S., & Egeth, H. E. (1999). On the distinction between visual salience and stimulus-driven attentional capture. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 661–676.

Yantis, S., & Johnston, J. C. (1990). On the locus of visual selection: Evidence from focused attention tasks. *Journal of Experimental Psychology: Human Perception and Performance, 16,* 135–149.

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