Processing deficits in RSVP:
The Attentional Blink and Repetition Blindness

by

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B.A., Psychology
Yonsei University, 1989

Submitted to the Department of Brain and Cognitive Sciences
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
at the
Massachusetts Institute of Technology
September, 1994

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Abstract

When two targets are presented among distractors in rapid serial visual presentation, correct identification of the first target (T1) results in a deficit for a second target (T2) appearing 200-500 ms after the onset of T1. This attentional blink (AB; Raymond, Shapiro, & Arnell (1992)) deficit was examined for categorically defined targets (letters among non-letters) in 7 experiments. AB was obtained for two letter targets among digit distractors (Experiment 1) and also for a third target (Experiment 2). In Experiments 3-4, we confirmed that AB is triggered by local interference from immediate post-target stimulation (Raymond et al., 1992) and additionally show that AB is modulated by the discriminability between T1 and its immediately following distractor. Increasing the discriminability of all distractors markedly reduces AB (Experiment 5). Experiments 6-7 further examine the effects of both local interference and global discriminability. A two-stage model is described to account for the AB results and its relation to other phenomena in visual attention.

In the second chapter, the attentional blink and repetition blindness are directly compared. While AB is obtained for two different targets in RSVP target search tasks, the repetition blindness (RB) deficit refers to an additional deficit for two targets that are identical. AB reflects a general difficulty for generating object token representations of correctly perceived types. RB has been interpreted as an additional failure in token individuation for a repeated type (Kanwisher, 1987). What is the relationship between these two deficits? Support for a distinction was obtained from a double dissociation between AB and RB shown across a series of 4 experiments. AB and RB follow different time courses (Experiments 1 and 4a), RB persists without AB when target recognition is easy (Experiment 2 and 4a), and AB can occur without RB (Experiment 3 and 4b) when token individuation is aided by a color cue. The implications of the double dissociation between AB and RB for theories of visual processing are discussed.

In the final chapter, illusory conjunction errors in RSVP tasks are examined. The AB lag effect was used as a manipulation of attentional load and pattern shifts in the distribution of temporal illusory conjunctions in an RSVP task were obtained. These pattern shifts can be used to infer how the visual system integrates separately processed information codes such as color and form. The results are consistent with predictions of the AB model described in the first chapter and further extend previous studies by showing dynamical effects of attentional load on illusory conjunctions.

Thesis Supervisor : Dr. Mary C. Potter

Title : Professor of Psychology

Acknowledgements

While I have benefitted from many wonderful teachers and mentors throughout my life, I am extremely grateful to have met my thesis advisor, Prof. Molly Potter, at this most critical stage of my academic training. Molly was a great advisor: her research expertise, enthusiasm, dedication, and the intellectual challenges she always posed to me was a source of inspiration for me during times when the amount of work could have been overwhelming. She was always generous with her time and help, whether it was for editing a poorly written draft, going over data, or just to chat about life in science. For the academic assistance she has shown me over the past 3 years alone, I would have considered myself most fortunate to work with her. Her impact on my starting career was much more profound, however. Molly was my mentor : she helped me find my priorities, and she helped me realize that I'm doing what I want to do.

I am also highly indebted to Prof. Jeremy Wolfe for the tremendous academic and moral support he has shown me over the past 4 years. Jeremy was a role model in showing how you could both do good science and have a bunch of fun. His enthusiasm for various issues is contagious, he played a role in the improvement of my writing and oral skills, and he deserves a ton of credit for helping me to get integrated into the visual community (especially ARVO).

One final person who has been a strong influence is Prof. Chan-Sup Chung, from my undergraduate institution, Yonsei University. His course in experimental psychology is what got me hooked into this whole business. He has guided my long journey from a freshman in college to coming here to MIT. Most of all, he is the type of researcher and *person* I strive to become.

I am most grateful to my other committee members for reading through my thesis and providing many helpful comments: Prof. Susan Carey, Prof. Nancy Kanwisher, Prof. Michael Jordan.

My graduate life here in E10 was memorable. I thank John Houde and David Poeppel for sharing their intellectual and recreational interests with me. I thank Suzie Johnson and Sergey Avrutin for their moral support and comradarie in the final few weeks. I thank my other Muddy friends, including Jennifer Ganger, Claudia Uller, Adee Matan, and Tony Harris. Through ARVO, I have been able to interact with several wonderful people from other areas of our department including Corrie Lathan, Janine Mendola, Karl Zipser, George Chou, Marc Sommer, Alex Bilsky, I-Han Chou, Emanuela Bricolo, and Pietro Mazzoni. I would also like to thank other members of the E10 community who have been so kind to me and were fun to hang out with: Daphne Bavelier, Kevin Brohier, Wey Fun, Zoubin Ghahramani, Steve Gilbert, Gavin Huntley-Fenner, Tommi Jaakola, John Kim, Eric Loeb, Raquel

Olgin, Sandeep Prasada, Philip Sabes, Annie Senghas, William Snyder, Greg Solomon, Cristina Sorrentino, James Thomas, Michael Ullman and Fei Xu.

I couldn't have been able to run all of my experiments without the help of Molly's excellent technical assistants, Diana Stiefbold and Elliott Moreton, as well as her hard-working and always cheerful UROPS : Conan Hom, Hilary Bromberg, Kyra Raphaelidis, Sabrina Kwon, Millie Wang, Evelyn Smith, Chris Lim, Yaoda Xu, and Brad Banks.

I am most grateful to Jan Ellertsen for all of her help throughout the years, admitting now that I am still in awe of how competent she is at her job. I thank Greta Buck and Robin Nahmias for their assistance in many other practical matters, and also Pat Claffey for maintaining such a wonderful library. I thank Steve Wadlow for ordering two-page monitors and fast macs in the computer room.

My life in Boston was also greatly enriched by the wonderful friends I have beyond E10. I am most grateful to my two housemates, Seong-Joon Park and Sang-Hoon Ahn. I thank Kyoo-Chan Cho, Woo-Jae Hahn, Sun-Wook Kim, Tai-Jong Kim, Kyung-Sun Joo, Young-Chang Joo, Boong-Kyu Lee, Chun-Hyuk Lee, Tai-Gyu Lee, Yu-Cheol Rhim, Sung-Hwan Shin for their friendship and frequent invitations to enjoy a home-cooked meal. I would also like to thank Kwang-Hee Han, Min-Shik Kim and Jae-Hoon Cheong for their comradarie as well as Sang-Joon Kim and Dae-Yeol Lee with whom I exchanged e-mail diversions to discuss computer hacking, neuroscience, and life in general. I thank Woo-Kyoung Ahn and Seong-Hee Hong for being such nice friends also.

I dedicate this thesis to my father and mother. Unfortunately, this token is only like a speck of dust compared to all of the love and support they have shown me throughout my life.

Chapter I

A Two-Stage Model for Multiple Target Detection in RSVP

Work on visual attention has focused on capacity limitations arising when multiple stimuli must be processed in a single spatial array. Different issues arise when stimuli are presented sequentially. In this study, we examine attentional limitations for processing a temporal sequence of visual stimuli. When subjects search for targets among stimuli presented in a sequence at high rates, correct identification of one target produces a marked deficit for detecting a subsequent target appearing in a 200-500 ms interval after the onset of the first one (Broadbent & Broadbent, 1987; Raymond, Shapiro, & Arnell, 1992). These tasks used rapid serial visual presentation (RSVP) in which each item replaces the previous one at the same spatial location. The RSVP paradigm has been a useful tool for exploring the temporal characteristics of information processing because it provides the experimenter with precise control not only over the time a given item is in view, but also over the preceding and subsequent processing demands on the subject. In RSVP each item not only eliminates the previous item from sensory storage (Kahneman, 1968), but also presents a new item to be processed, thus constraining the time available for higher-level cognitive as well as perceptual processing (Potter, 1976).

One of the earliest of these studies using RSVP to study target detection was that of Lawrence (1971), who measured recognition accuracy for a single capitalized target word appearing at various serial positions within an RSVP stream of lowercase distractor words, at rates between 6 to 20 items/sec. Recognition accuracy decreased with higher rates of presentation. Target identification errors mainly consisted of distractor word intrusions (78%); 88% of these intrusions were of the word directly following the target. The prevalence of posttarget intrusion errors is suggestive of a two-step filtering process in which the subject noted the target-defining capitalization and then encoded a word (Lawrence, 1971; McLean, Broadbent, & Broadbent, 1983; Gathercole & Broadbent, 1984).

The Attentional Blink

The focus of the present paper is on interference with subsequent target detection, when a first target has been identified. Broadbent and Broadbent (1987) extended Lawrence's study by requiring the subject to report two uppercase words embedded among lowercase words, varying the lag between the two targets. Using presentation times of 80 to 120 ms per item, which allowed a single target to be identified on a high proportion of the trials, they showed that correct identification of the first target (T1) interfered with identification of a second target (T2) appearing within 500 ms. They demonstrated a similar pattern of deficits in a condition where the targets could be a word appearing in uppercase (defined by a physical feature) or an animal word (categorically defined target). They concluded that detecting the features that signal the presence of a target is possible at the rates they used, but once a target is detected it triggers more demanding processes of identification that interfere with subsequent target detection and identification. They cite the work of Duncan (1980), who pointed out that targets in simultaneous arrays interfere with each other.

In a different task, Weichselgartner and Sperling (1987) presented a stream of digits in RSVP and subjects were asked to report the four digits starting with a target digit that was cued by luminance or an outline square.

The data were collapsed across trials to produce a distribution of recall probability as a function of lag from the target. A bimodal distribution was obtained, with digits most likely to be reported if they appeared either 0-200 ms or 400-500 ms after the onset of the target cue. Thus, there was an interval between 200 and 400 ms after the initial target in which subjects seemed unable to encode further targets. The authors interpreted this bimodal distribution as indicative of two different modes of attention : a quick, effortless, automatic process triggered by target detection; and a slower, effortful, controlled process whose latency depends on practice and task difficulty.

Raymond, Shapiro, and Arnell (1992) replicated and extended these results using a different procedure in which all of the items were single letters. T1 was marked by being white, whereas the other letters were black, against a grey background. T2 (presented on 50% of the trials) was always the letter X; the task was to identify T1 and to decide whether the X probe had occurred or not. When the X appeared with a stimulus onset asynchrony (SOA) between 200-500ms, it was often missed. Raymond et al. (1992) hypothesized that the processing time needed for identification of a target item exceeded the onset to onset time of 90 ms in their experiments. They proposed that the onset of a new stimulus before processing of T1 is complete causes interference and invokes an attentional suppression mechanism. Attentional suppression, characterized as a "shut-and-locked" attentional gate, lasts for several hundred milliseconds, increasing the probability that targets appearing within that interval will be missed. They termed this deficit an attentional blink (AB), in analogy to the suppression of visual processing made during rapid saccadic eye movements (Volkman, Riggs, & Moore, 1980). Raymond et al. (1992) tested an implication of their hypothesis, that adding processing time immediately after the first target would eliminate AB. As they predicted, when a blank interval of 90 - 270 ms was substituted for the items that immediately followed T1, no AB deficit was found.

Like Weichselgartner and Sperling (1987), Raymond et al. (1992) found that when the next item after T1 was T2 (at lag 1), then T2 was relatively easy to detect. Thus the AB curve was again a U-shaped function of lag. Raymond et al. (1992) proposed that the deficit in the 200-500ms SOA range is the result of shutting an attentional gate, when the item following T1 interferes with its identification. Accordingly, the gate is closed to prevent further confusion. Thus T1 and an immediately following item are processed together, so a second target at lag 1 is not suppressed.

Thus, the two previous explanations of the AB deficit are that it results from an attentional suppression mechanism, or that it reflects two distinct types of attentional processes. We propose a new two-stage model that incorporates aspects of both of the previous models. In this two-stage model, the AB deficit is the result of a limited-capacity second stage in which targets detected in the first stage are processed and consolidated serially. This second processing stage does not begin until the first stage signals the probable presence of a target, so that the second stage typically overlaps with the presentation of the following items in an RSVP sequence. This stage of processing operates on whatever internal representations of items are available at the time processing begins, and thus not only the first target but also the immediately following item (target or distractor) is likely to be included in processing. When the duration of this limited-capacity processing of T1 and the following item exceeds the SOA between T1 and T2, there will be interference with the processing of T2. When the lag 1 item is a distractor, the difficulty of discriminating it from T1 determines the time course of the second-stage bottleneck. When the lag 1 item (the item that immediately follows T1) is also a target (T2), then it is processed together with T1 and is likely to be reported.

In the present study, we looked more closely at AB and the conditions necessary for its appearance, focusing on the nature of the nontarget items and in particular the item (if any) that immediately follows T1. In all experiments the task was to detect and identify unspecified letters among digits or symbols; the lag between the letter targets was varied. To anticipate, the results show that while interference from the immediate posttarget item is a major factor in producing a deficit for detecting a second target, search performance is subject to other factors, especially the overall discriminability between the target set and non-target distractors. In the general discussion, we consider how the AB deficit in RSVP can be understood in terms of the two-stage model just outlined, with a first stage of target detection and a second capacity-limited stage in which candidate targets are fully identified and registered in memory. We also discuss how the AB deficit relates to previous research on dual-target and dual-task interference, and what important differences arise from the characteristics of the RSVP paradigm.

Experiment 1

In the first experiment we replicated and extended previous studies of the AB deficit (Broadbent & Broadbent, 1987; Raymond et al., 1992; Weichselgartner & Sperling, 1987) using a somewhat different task. In most earlier studies, targets in an RSVP stream were specified by a separate target-defining feature such as color, lettercase, or luminance[1]. The target-defining features of the first critical item (T1) were independent of the target features to be reported, requiring a conjoining of the two sets of features. Such conjoining of arbitrary features is believed to require focal attention (Treisman & Gelade, 1980), and it is possible that AB results from such focal attention to T1. Alternatively, AB may be the result of attentional processing inherent to identification and consolidation of T1 appearing in RSVP.

To evaluate these alternative hypotheses, in the present experiment the targets to be detected were defined by their categorical identity as letters. Duncan proposed that the categorical identities of letters and digits are available preattentively (prior to analysis through a limited capacity system bottleneck) and may serve as a basis for selection into a more limited capacity system of analysis (Duncan, 1980, 1983). Others have suggested that digits and letters may be separated on the basis of some key stimulus features (Treisman & Gelade, 1980; Krueger, 1984). Still others (Sperling, Budiansky, Spivak, & Johnson, 1971) have suggested that the specific identity of digits (and presumably also letters) is available at least as quickly as their categorical identity. Whether the full identity of an item is available preattentively or not, the features used to signal targethood in the present experiments were the same features that needed to be analyzed for subsequent report.

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[1]In one of their experiments, Broadbent and Broadbent (1987) used targets that were defined by their categorical identity (animals among non-animals). However, these categorically defined targets were intermixed with targets defined by a separate physical feature (uppercase words among lowercase distractors), making it difficult to draw conclusions about pairs of categorically defined targets.

Another characteristic of many of the previous dual-target experiments was that the target specification for T1 was different (or might have been different) from that for T2. It is possible, therefore, that the needed switch in set from T1 to T2 would cause AB. In Experiment 1, however, subjects were simply instructed to report the two letters appearing in the stream of digits. Thus, unlike in the Raymond et al. (1992) probe detection task, subjects did not need to change selection set from T1 to T2 (e.g., search through black non-targets for a white letter, T1, then a black X, T2). The first question, then, was whether an AB deficit for T2 would appear in a categorically defined target task which would not require conjunction of arbitrary features and would not require the subject to switch set from T1 to T2.

Method

Subjects. Six subjects participated in Experiment 1. In this and the later experiments, the subjects were from the Massachusetts Institute of Technology volunteer subject pool. All observers reported normal or corrected-to-normal visual acuity. Informed consent was obtained prior to participation and subjects were paid for their participation. None of the subjects was aware of the purpose of this experiment.

Design and procedure. The stimuli were eight single digits and 24 capital letters (0, 1, O, and I were omitted to avoid confusion). Each trial consisted of 16 items : 14 digits and 2 letters. The digits on a given trial were randomly generated by the computer under the constraint that the same digit did not appear in the previous four positions. Two randomly sampled (but not identical) uppercase letters, designated T1 and T2, were selected as targets. The position of T1 was randomly permuted so that it appeared an equal number of times in serial positions 3 to 7. Eight lags between T1 and T2, lag 1 (no intervening items, SOA=100ms) to lag 8 (SOA=800ms), were crossed with the five serial positions of T1, and the design was replicated six times for a total of 240 trials, with 30 trials at each lag. One practice block of 20 trials was followed by three experimental blocks of 80 trials each.

The experiment was self-paced. The subject began each trial by pressing the space bar on the computer keyboard. A plus sign lasting 400 ms appeared at the center of the monitor screen for fixation. 100 ms after the fixation cross went off, the stream of stimuli appeared successively without interstimulus blanks at the same location for 100ms each (presentation rate : 10 items per second). The sequence was followed by a "&" mask for 100 ms, signalling the end of the trial. Subjects were instructed to report the two letters aloud, in any order, immediately after the trial. They were encouraged to avoid making wild guesses. The experimenter wrote down the response; no feedback was given. The experiment was carried out in normal room illumination held constant for all subjects.

Apparatus. The same experimental apparatus was used for all the experiments presented in this paper. The letter and digit stimuli were generated by an IBM-AT computer on a CRT screen with a rapid fade phosphor. The stimuli measured about 0.3 cm in width and 0.4 cm in height. The display was viewed from 30 cm; thus each stimulus subtended about 0.57 × 0.76 degrees visual angle. An example of the stimulus sets is shown in Chun and Potter (in press, Figure 1).

Results and Discussion

In brief, a marked AB deficit, comparable to that reported by Raymond et al. (1992), was obtained in report of the second of two letter targets among digits. Thus, neither an arbitrary T1 specifier that must be conjoined with other target features, nor a switch in target set from T1 to T2, is required to produce AB.

Table 1

Full summary of target report percentages for Experiment 1

Lag	SOA	Neither T1 nor T2	Only T1	Only T2	Miss T1	Both T1 and T2	T2 I ~T1	T2 I T1
1	100	3	16	31	33	51	94	76
2	200	7	53	12	19	28	63	34
3	300	6	60	5	11	30	45	32
4	400	7	40	16	22	38	73	47
5	500	7	23	12	19	58	63	70
6	600	6	18	6	12	70	50	79
7	700	2	20	10	12	69	83	77
8	800	3	16	7	10	74	70	81

Table 1 shows, for each lag, the percentage of trials on which neither T1 nor T2, only T1, only T2, not T1, and both T1 and T2 were correctly reported. Letters were counted as correct regardless of the order of report. The next column shows the conditional percentage of T2 report given that T1 was not reported (T2 I ~T1). The final column shows the conditional percentage of recall of T2 at each lag, that is, the percentage of trials on which T2 was reported, given that T1 was reported (T2 I T1). This conditional percentage was computed for each subject at each lag and averaged across subjects. It is this conditional percentage that is used to measure the AB deficit, shown graphically in Figure 1. These graphed functions are used to present the main results of all experiments in this paper.

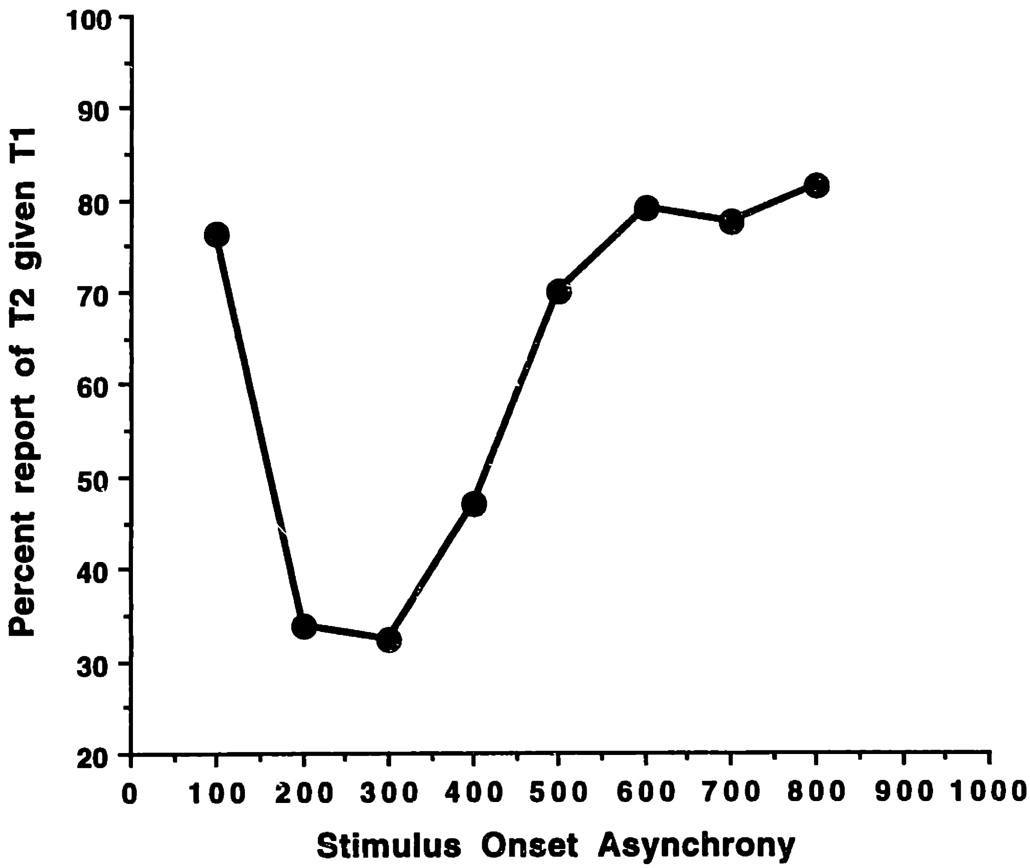


Figure 1. The AB effect : Percent report of T2 (given report of T1), as a function of SOA, in Experiment 1.

Correct identification of T1 produced a lag-dependent deficit for reporting T2. A one-way analysis of variance on the conditional report of T2 | T1 showed a significant effect of lag, $\underline{F}(7,35)=13.5$, $\underline{p}<.001$. Report of T2 | T1 was lowest at lags 2 and 3, improving with increasing lag. The blink function reached an asymptote at lag 6. We will refer to this U-shaped curve, especially the monotonic portion showing increasing performance with increasing SOA, as the lag effect.

As noted earlier, an important characteristic of the dual-target pardigm is that the AB post-target deficit does not occur for a target immediately following T1. As Figure 1 shows, when T1 and T2 were temporally adjacent (lag 1) T2 was reported on a high proportion (76%) of the trials on which T1 was correctly identified. The conditional probability of T2 | T1 at lag 1 was significantly higher than at lag 2 ($t(5)=6.6$, $p<.01$), lag 3 ($t(5)=4.1$, $p<.01$), and lag 4 ($t(5)=2.1$, $p<.05$, one-tailed). (All t-test p values are two-tailed unless otherwise specified.)

However, Table 1 shows that T1 was missed on a higher proportion of trials (33%) when it was immediately followed by a second target, than when T2 appeared at any other lag (all t-test comparisons, $p<.05$, one-tailed). That is, T1 was less likely to be missed when it was followed by a distractor digit than when followed by another target letter. Thus target identification in RSVP tasks appears to be affected by the kind of item which follows the target. We explore the role of the item directly following the target in more detail throughout this paper.

The results of Experiment 1 mirror closely those of earlier studies (Broadbent & Broadbent, 1987; Raymond et al., 1992; Weichselgartner & Sperling, 1987), showing a deficit for reporting a second target appearing in the interval 200 to 500 ms from onset of the first target when T1 has been identified and recalled correctly, while showing no deficit for an item appearing at lag 1. The results demonstrate that the AB deficit occurs for targets which are categorically defined. Thus, AB is not merely a consequence of having to conjoin an arbitrary, separate target-defining feature (such as color or lettercase) with target-identifying features (the particular target letter or word that is to be reported). Processing the features intrinsic to the identity of an item (here, a letter) and encoding the target for subsequent report were sufficient to produce interference in detecting a subsequent target.

The presence of a characteristic AB deficit in our task also supports the conclusion that it is not a switch in set from T1 to T2 that is causing the deficit. Horlitz, Johnston, and Remington (1992) report results that support this conclusion. They independently varied T1 and T2 to be either a color-specified letter identification task or a visual discrimination task (determine the orientation of a Landolt C). They showed that the AB deficit is not due to filter switching costs (AB occurred whether the target-specifying color was the same or different for T1 and T2), nor task switching costs (AB occurred whether task 1 and task 2 were the same or different). Raymond et al. (1992) also suggested that the absence of AB for lag 1 in their task indicates that a switch in set is not likely to be a factor.

The results of Experiment 1 suggest that the categorical identity of each item appearing in RSVP is rapidly available (within 100 ms, the presentation rate used here). Apparently, detection of a target in the designated category triggers further processing of the item, and this subsequent stage of processing results in a temporary deficit for subsequent targets.

Experiment 2

In Experiment 2, we ask whether an AB deficit is produced not only after the first target (T1), but also after the second target (T2), if the second target is processed successfully. If AB is the result of a limited-capacity second stage for processing targets, as we propose, then it should occur with each detected target. Previous studies do not address this question directly. Weichselgartner and Sperling (1987) hypothesize that the onset of their second stage, a sustained, controlled mode of attention, allows for multiple subsequent items to be processed. They asked subjects to report the four items beginning with detection of a target. Unfortunately, their presentation of the data does not reveal the contingent pattern of item report within a single trial. It is that pattern which needs to be examined to determine whether registration of each successive item was accompanied by an attentional blink, or whether their hypothesized sustained component, once initiated, allowed for interference-free processing of several to-be-reported items. Regardless of the pattern of results in Weichselgartner and Sperling's procedure, report of an intermittent series of targets might be expected to generate repeated AB.

In Experiment 2, we instructed the subjects to detect and report three letters embedded in an RSVP stream of digits. We systematically varied the lag between T1 and T2, and between T2 and T3.

Method

The method was like that of the previous experiments except as specified.

Subjects. Sixteen subjects from the MIT subject pool were tested in this experiment.

Design and procedure. Three target letters were embedded in an RSVP stream of 17 digits. The position of T1 was randomized to appear in either serial position 2, 3, or 4. There were 6 possible lags (SOA=100 to 600) between T1 and T2, and between T2 and T3, making a total of 36 lag configurations. There were 8 trials in each of these 36 configurations for a total of 288 trials. The experimental trials were preceded by a practice block of 20 trials. The entire experiment took about an hour and was self-paced, with breaks initiated by the computer after every 40 trials. The subjects wrote their responses on a separate answer sheet.

Results and Discussion

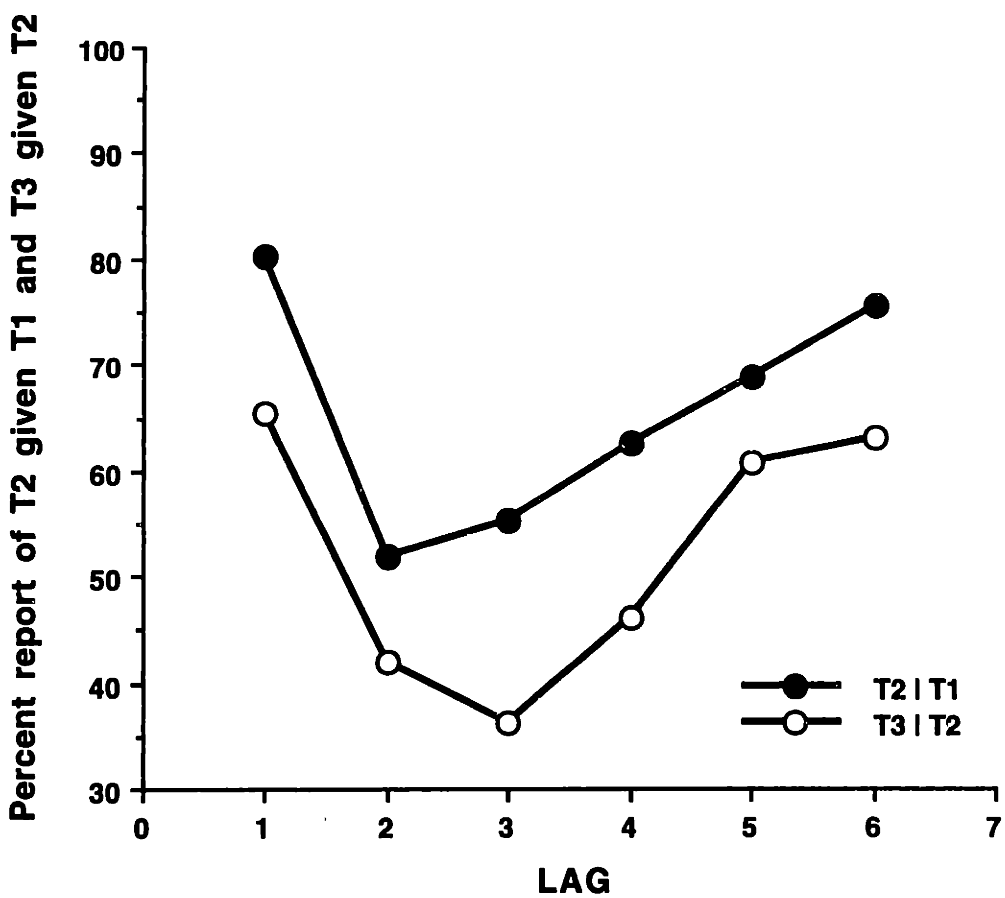


Figure 2. AB for three targets in Experiment 2 : Percent correct for T2|T1 and T3|T2 shown as a function of lag between T1 and T2 and between T2 and T3 respectively.

For this and subsequent experiments we omit the full table of results given for Experiment 1 and report mainly the conditional report of T2 and T3. Other results are reported where relevant. (Full tables are available from the first author.) The main results are presented in Figure 2, where lag indicates the lag between T1 and T2, and between T2 and T3, for report of T2 | T1, and T3 | T2, respectively. The conditional probability of reporting T2 given that T1 was reported showed the standard AB deficit as a function of lag. The conditional probability of reporting T3 given that T2 was reported (regardless of T1-T2 lag) also showed a strong AB pattern. There was a main effect of lag for T2 | T1, $F(5,75)=21.4$, $p<.001$, and T3 | T2, $F(5,75)=18.4$, $p<.001$. Performance for reporting T2 | T1 was better than for reporting T3 | T2, $F(1,15)=83.3$, $p<.001$, but this difference did not interact with lag, $p>.22$. Because of the small number of trials on which T1 was missed (15.5%), it was not possible to test the effect of T1 report on T3 across individual subjects, but inspection of the two grouped curves for T3 | T2 and T3 | (T1&T2) indicated that they overlapped almost exactly, suggesting that T1's effect on T3 was minimal. The family of separate T3 | (T1&T2) curves for each T1-->T2 lag all reveal a U-shaped AB pattern, arguing further against a sustained component of attention in our task. The group data analysis also show that the probability of reporting T3 was lower when T2 was reported than when T2 was missed. All these results support the main conclusion that each target occurrence creates an AB deficit for a subsequent target.

This demonstration of a second characteristic AB effect after a correctly identified T2 makes it clear that AB occurs after each selected target, not only after the first one. The decrement in performance for T3 | T2 compared to T2 | T1 may be due to memory load or other factors, but the characteristic U-shape of the deficit for T3 | T2 and the lack of an interaction with T2 | T1 suggests that both curves represent a common AB effect. This finding of a second AB effect does not directly disconfirm Weichselgartner and Sperling's (1987) proposal for a sustained mode of attention in their task, which required report of a continuous sequence of items once T1 was detected. Whereas our task could be described as involving partial report, the Weichselgartner and Sperling task used whole report for subsequent items. There may be differences between the two strategies for reporting items in RSVP. The results of Experiment 2 suggest that at least in RSVP search tasks with targets embedded among hard-to-discriminate distractors, the detection and processing of each target creates a transient deficit for a subsequent one. This result supports the proposed two-stage model, inasmuch as each successive target would be expected to create a temporary second-stage bottleneck.

Experiment 3

In Experiments 1 and 2, the presence of AB in our categorically-defined target task suggests that AB is not due to conjoining of a target-defining feature with a target's identity, nor is it due to task switching between T1 and T2. In the next two experiments, we examine Raymond et al.'s (1992) proposal that the post-target processing deficit is triggered by local events that interfere with target identification. They demonstrated that the AB deficit was reduced or eliminated when the first target (including its normal ISI) was immediately followed by a blank interval of 90 ms or longer, replacing one or several subsequent items (Raymond et al., 1992, Experiments 3 and 4). In contrast, a blank interval appearing after a single immediate posttarget event did not prevent AB. Thus, an immediate posttarget event is what seemed to trigger the deficit for T2. Although Raymond et al. (1992) showed a main effect of blank duration, inspection of their results suggests that a blank of 90ms (duration of 1 item) was sufficient to significantly reduce the deficit for T2. In Experiment 3 we examine the effect of a single blank interval on report of letter targets among digits. A reduction of the AB deficit for T2 when T1 is followed by a blank in our task would support the idea that the item immediately following T1 interferes with its identification and consolidation, thus increasing the duration of second-stage processing.

Method

Subjects. Eight subjects from the MIT subject pool were tested in this experiment. One subject was replaced because of an error rate that exceeded a preset criterion (no more than 10% trials on which neither target was reported correctly).

Design and procedure. Except as noted, the method was identical to that of Experiment 1. Each trial consisted of 15 items. T1 appeared randomly in serial positions 3 to 7, and T2 at lags of 1-7 (lag 8 was eliminated). There were two blank conditions and a baseline condition. In the baseline condition (equivalent to Experiment 1) no blanks were presented. The lag-1-blank condition had a blank at lag 1, with T2 appearing equally often at each of the other lags. The lag-2-blank condition had a blank at lag 2; T2 appeared equally often at all lags except lag 2. Thus, there were 7 T2 lags in the baseline condition and 6 lags in each of the two blank conditions. There were 15 trials at each lag in each condition for a total of 285 trials. The experiment was preceded by a block of 20 practice trials. Trials from all three conditions were intermixed within blocks and within subjects.

Results and Discussion

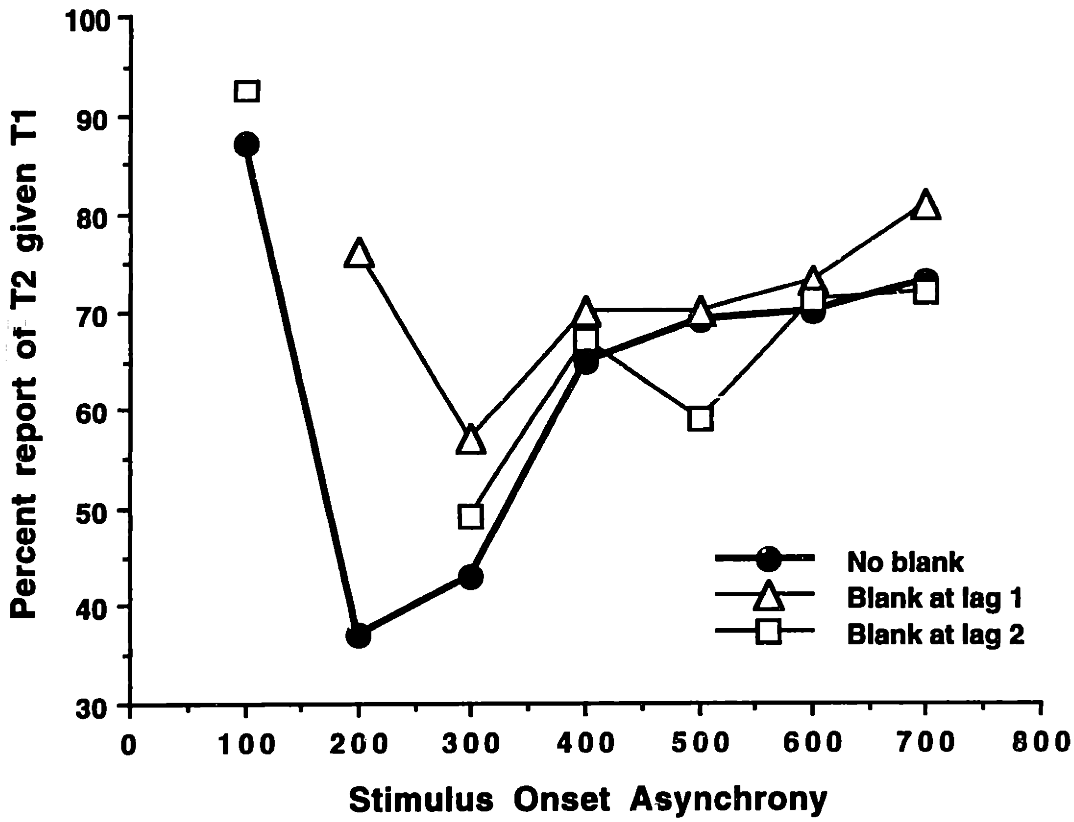


Figure 3. Effect of a blank among digits: Experiment 3

Figure 3 shows the percent report of T2, given correct report of T1. The baseline condition without a blank resulted in an AB pattern very similar to that in Experiment 1. AB was reduced when a blank was presented immediately after T1, but not when the blank appeared at lag 2. The two blank conditions were compared with the baseline condition in separate ANOVA tests. The lags included in comparison with the baseline condition were those lags used in the respective blank conditions. For the lag-1-blank and the baseline, there were significant main effects of condition, $\underline{F}(1,7) = 29.341$, $\underline{p} < .001$, and lag, $\underline{F}(5,35) = 7.785$, $\underline{p} < .001$. The interaction between condition and lag was also significant, $\underline{F}(5,35) = 3.864$, $\underline{p} < .01$. Individual t-tests at each lag shown that the lag-1 blank condition led to better T2 performance than the no-blank baseline at lag 2, $t(7)=5.8$, $p<.001$, and at lag 3, $t(7)=3.4$, $p<.01$, but not at lags 4 to 7. For the lag-2 blank condition versus the baseline, the ANOVA showed no difference between the two conditions ($p>.60$). There was a significant main effect of lag, $F(5,35) = 10.2$, $p < .001$, reflecting the usual AB pattern, but the interaction between lag and condition was not significant ($p>.30$).

The first target (T1) was correctly reported on 87% of trials in the baseline condition, excluding the lag-1 condition. Report of T1 was significantly better (98%) in the lag-1-blank condition, $F(1,7) = 20.0$, $p<.01$, but significantly worse (82%) in the lag-2-blank condition, $F(1,7) = 9.8$, $p<.05$. When T1 was followed by T2 at lag 1, T1 was reported on 76% of the trials in the baseline condition, and 68% of the trials in the lag-2-blank condition (where T2 was followed by a blank). Thus performance on T1 was higher when followed by a digit than when followed by another target (as in Experiment 1), and was best when followed by a blank.

The results are generally consistent with the findings reported by Raymond et. al. (1992). A blank equivalent to the duration of an item (100ms) was sufficient to reduce the deficit for T2 when the blank immediately followed T1, but not when it followed the first distractor after T1. Thus, the deficit for identifying T2 occurs only or most strongly when immediate post-target stimulation interferes with T1 processing.

However, the release from AB in the present experiment does not appear to be complete. There is still a suggestion of a deficit for targets presented after the blank interval immediately following T1 (the triangles in Figure 3). There is also a significant dip from SOA 200, right after the blank, to SOA 300, after one intervening digit, $t(7)=3.6$, $p<.01$, as though the intervening digit produced a small-scale AB effect. That is, there was a relative benefit for a target at lag 2, right after the lag-1 blank interval, compared with a target at lag 3. Raymond et. al.'s results seem to show the opposite pattern, with an apparent deficit for items appearing immediately after the blank interval (the significance of this slight deficit is not reported). These minor discrepancies in results may be due to several differences in the methods of the two experiments. In Raymond et al's (1992) experiments the RSVP stimuli were presented in flicker fashion, with blank intervals appearing between every item; in the present experiment each new item replaced the previous one, with no ISI. The basic tasks in the two experiments were different. Also, we used only one blank duration (100ms) in Experiment 2, whereas their experimental blocks consisted of blank durations of variable length (from 90 ms to 270 ms). Although our blank of 100 ms was sufficient to produce a significant benefit in report of T2, perhaps the duration wasn't long enough to allow stage-two processing of T1 to be fully completed before post-stimulation resumed at lag 2, resulting in the minor AB pattern just noted.

Any proposal for explaining the AB deficit will have to account for the fact that performance in detecting T2 is modulated by the sequence of visual events following the correctly identified first target. Among the posttarget events, the presence of an item directly following T1 appears to be most critical. A question not answered by the present experiment and that of Raymond et al. (1992) is what characteristics of the visual event following T1 determine the presence and extent of the AB deficit. While the use of a blank interval following T1 may be the strongest test for investigating the role of immediate post-target stimulation, it is not useful in understanding the nature of local interference that post-target stimulation is imposing on target identification processes. In Raymond et al's (1992) study, the interfering item was a letter potentially confusable with letter T1, even though T1 appeared in a different color (white rather than black). This was also the case for most previous studies : the item appearing immediately after T1 was always a member of the set of possible targets, and thus was confusable with T1. However, in our experiments the interfering item was a digit rather than a letter, and even though it was not a potential target it still produced a large deficit for reporting T2.

This raises the question of whether the source of interference could be any visual event, or only a visual event that shares confusing visual features or categorical similarity with T1. Raymond et al. (1992) suggested in their general discussion that the amount of attentional suppression should be a function of the degree of visual similarity between T1 and its following item. In Experiment 4, we directly examine the effect of local interference by manipulating the ease of discriminating between T1 and its following distractor, and between T2 and its following distractor.

Experiment 4

In Experiment 4, to examine the effect of local interference, we used distractor sets of digits and keyboard symbols. The keyboard symbols were chosen to be more discriminable from the letter targets than the digit distractors. The letter targets were presented among a distractor set consisting of a mixture of digits and symbols, and we varied the type of distractor that immediately followed T1 and also the distractor that immediately followed T2. Thus, the global discriminability of targets from distractors was constant across trials, but the items immediately following each target were varied.

Method

The method was like that of Experiment 1 except as noted.

Subjects. Sixteen subjects from the MIT subject pool were tested in this experiment.

Design and Procedure. Only uppercase letters were used as targets; the letters I, O, U, V and L were excluded. Digit characters 2 through 9 (8 items) were used for the digit distractor set, and 8 different keyboard symbols (<, >, =, #, %, ?, /, *) were used as distractors for the symbol distractor set. The stimuli are shown in Chun and Potter (in press, Figure 1). Trials included 13 items : T1, T2 and 11 distractors. T1 was randomly selected to appear in serial position 3, 4, or 5. T2 appeared at one of six SOA's, 100-600ms. The final item before the ampersand mask was always a distractor. The type of distractor (digit or symbol) immediately following T1 (which we denote as D1), and the distractor type immediately following T2 (denoted as D2) were systematically varied. All other distractors were chosen randomly with equal probability of being either a symbol or a digit. There were 12 trials for each of the four possible D1 and D2 distractor combinations at each lag, for a total of 288 trials. D1 was not varied for lag 1 (SOA=100) since T1 was directly followed by T2. The results for lag 1 were analyzed separately. The experiment was preceded by a practice block of 20 trials.

Results and Discussion

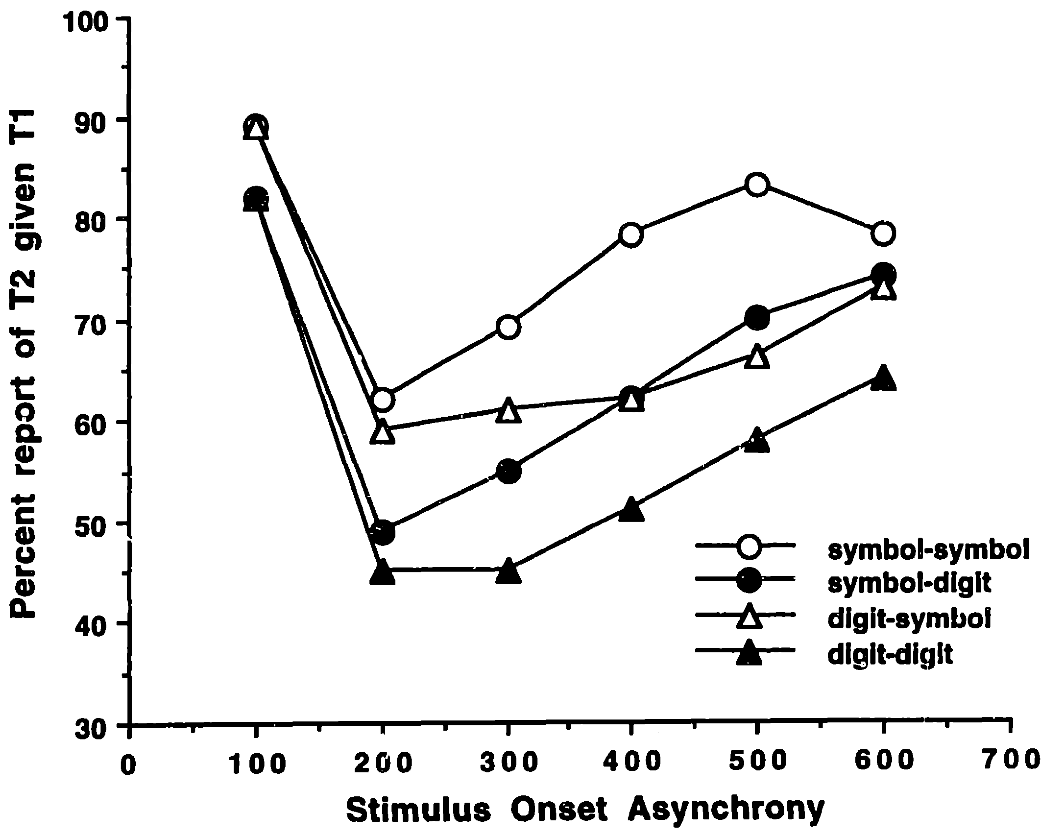
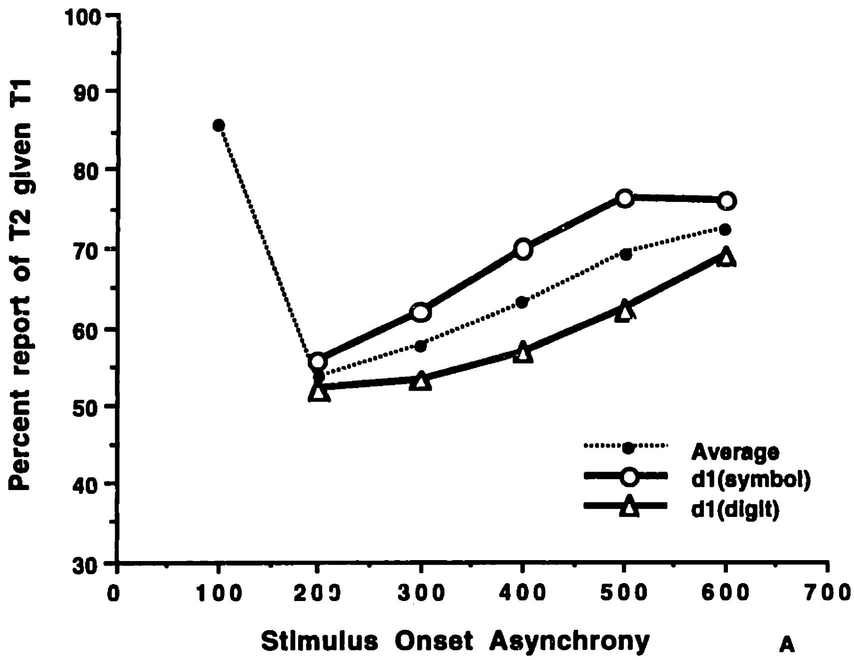


Figure 4. The effects of the type of distractor following T1 and T2 in Experiment 4.



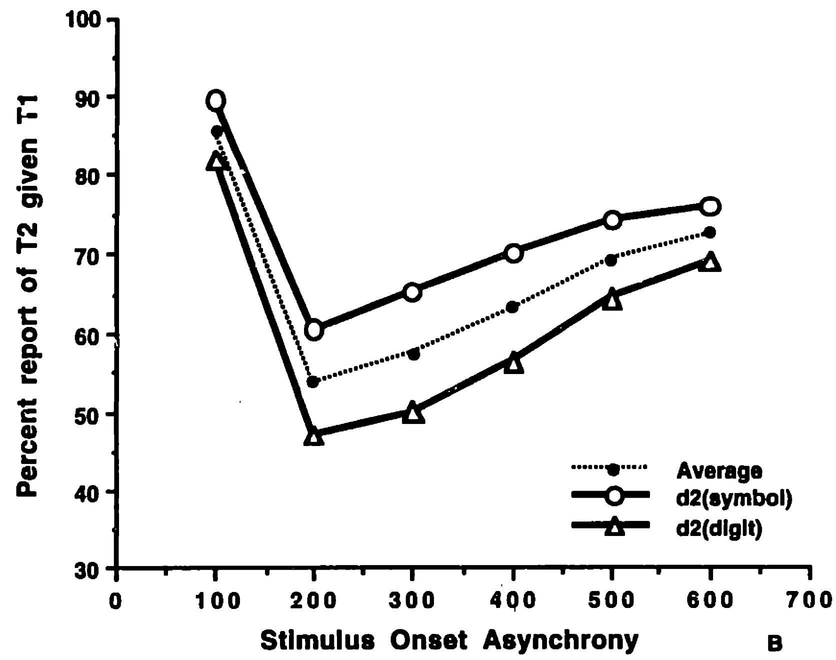


Figure 5. Effects of (a) the distractor following T1, and (b) the distractor following T2, in Experiment 4.

The results for Experiment 4 by condition are shown in Figure 4. The effects of D1 and D2 are shown separately in panels A and B of Figure 5, respectively. Note that at lag 1 there was no D1, so only D2 is a variable. Excluding lag 1, there was a main effect of lag, $F(4,60)=15.5$, $p<.001$, type of D1, $F(1,15)=30.5$, $p<.001$, and type of D2, $F(1,15)=43.8$, $p<.001$. Neither interaction of D1 with lag nor D2 with lag was significant (both $p>.21$). Thus, the results indicate that T2|T1 performance is sensitive to both the type of distractor (D1) immediately following T1 and the type of distractor (D2) following T2, with higher performance occurring when either target is followed by a symbol rather than a digit. The effects of D1 and D2 appear to be independent of each other, as suggested by the lack of interactions, either between D1 and D2 ($p>.82$), or among D1, D2 and lag ($p>.83$). For lag 1, T2|T1 was reported on 89.4% of the trials when T2 was followed by a symbol, and on 82.0% of the trials when T2 was followed by a digit, $F(1,15)=4.9$, $p<.05$.

The type of D1 had an effect on the proportion of trials that T1 was correctly identified (excluding lag 1). When T1 was followed by a symbol, it was reported on 89.7% of the trials; by a digit, on 79.2% of the trials, $F(1,15)=30.1$, $p<.001$. At lag 1, when T2 immediately followed T1, T1 was correctly reported on 65.4% of the trials when D2 was a symbol, and on 69.8% of the trials when D2 was a digit ($p>.13$).

This increase in performance for T1 when it was followed by a symbol compared to when it was followed by a digit supports our a priori expectation that letters would be easier to discriminate from these symbols than from digits. Of particular interest, however, is the effect that the type of D1 had on T2 identification. The main effect of D1 suggests that the AB deficit is modulated by the difficulty of T1 identification processing, as the two-stage model predicts.

However, while Experiment 4 highlights the local effects of the type of distractor immediately following T1 (as well as that following T2), it is clear from Figures 4 and 5 that an AB lag effect is still present, even when both T1 and T2 are followed by more readily discriminable symbol distractors. In Experiment 4, both letter targets still appeared among a set of mixed distractors, where roughly half of the distractors were less discriminable digits. This raises the question of how T2|T1 performance would be affected by the discriminability between the letter targets and the distractor set as a whole. In the following experiment, we varied the overall discriminability of the target and distractor sets. We predicted that an overall increase in discriminability would shorten the first stage of detection because viewers could lower their criterion for initiating stage-two target processing. As a consequence, stage-two processing would be completed more rapidly, reducing the size and duration of AB.

Experiment 5

In the previous experiment we examined the effect of local discriminability using a mixture of digit and symbol distractors on each trial. Though main effects of local interference were found, an overall AB deficit persisted for all conditions tested. Experiment 5 explored how overall discriminability between targets and distractors affects the magnitude and shape of the AB function. A separate question we also investigated was whether holding constant the serial position of T1 would reduce AB by allowing more rapid target detection. Subjects were divided into two groups. Each group of subjects was run in two blocked conditions. In the digit block, the task was identical to that of Experiment 1 : two letter targets appeared among digit distractors. In the symbol block, keyboard symbols were substituted for the eight digit distractors. One group of subjects was run in a session where the serial position of T1 could vary from trial to trial, as in Experiment 1; each trial included 13 items. For the other group of subjects, the procedure was simplified by having T1 in serial position 2 on all lists; the lag of T2 was varied as before; and trials were 9 items long. To anticipate, this simplification did not affect the size of the AB deficit in the digit condition and had only a minor effect in the symbol condition.

Method

The method was like that of the previous experiment except as specified.

Subjects. Sixteen subjects from the MIT subject pool were tested in this experiment, eight in each of the two groups (T1-fixed versus T1-variable in serial position).

Design and procedure. There were two within-subject conditions. In the low-discriminability (digit) condition the two target letters were embedded in an RSVP stream of digits. In the high-discriminability (symbol) condition the letters were embedded in a stream of keyboard symbols. The two conditions were run in separate blocks : the order of the blocks was counterbalanced across subjects in each group.

The letter targets and symbol and digit distractors were from the same sets used in Experiment 4. For one group of subjects, the T1-variable group, each trial consisted of 13 items. The position of T1 was randomly permutated to appear an equal number of times in serial positions 2 to 6. For the second group of subjects, the T1-fixed group, each trial was shorter, consisting of 9 items. T1 always appeared in serial position 2 on the list. For both groups, T2 lag was varied from lag 1 to lag 6. Thus, T2 never appeared as the last item in the list in either group. Each trial was preceded by a 300 ms "+" fixation point and followed by a mask item "&". Subjects were run in 20 trials at each of the six lag conditions, yielding a total of 120 trials for each block. Lag was randomized within each block.

The entire experiment was self-paced by the subject, who initiated each trial with a press of the spacebar on the keyboard. Subjects were informed of the procedure and then run in a practice block of 20 trials using low discriminability distractors (the digit set). No practice trials were given with the symbol distractors. Subjects wrote their responses on a separate answer sheet.

Results and Discussion

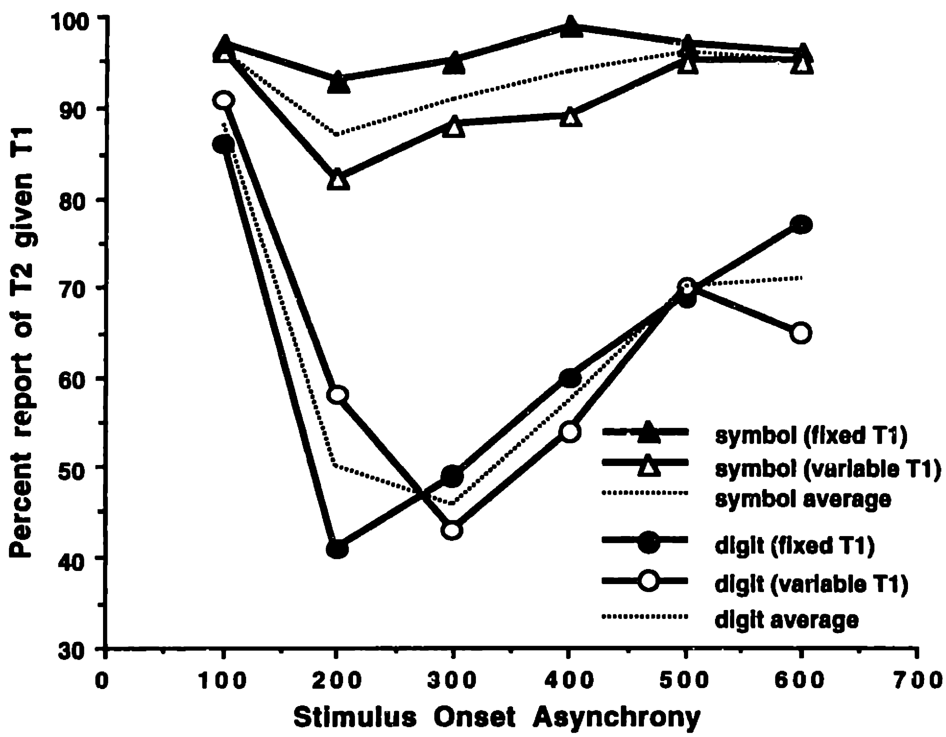


Figure 6. Effect of distractor set (symbol vs. digit) for fixed or varied serial position of T1, in Experiment 5

Figure 6 shows the average percentage of trials that T2 was correctly identified when T1 was correctly reported. The results clearly indicate a difference between the two distractor conditions with digits producing lower T2 performance, $F(1,14)=80.4$, $p<.001$. There was a main effect of lag, $F(5,70)=18.2$, $p<.001$, and an interaction between distractor condition and lag, $F(5,70)=11.5$, $p<.001$. The main effect of T1-position variability, tested between groups, was not significant ($p>.55$). However, there was a three-way interaction between T1-position variability, distractor condition, and lag, $F(5,70)=2.7$, $p<.05$.

Separate analyses were also carried out for each group of subjects (variable T1 and fixed T1 position). In the variable-T1 group there was a main effect of distractor condition, $F(1,7)=79.5$, $p<.001$, a main effect of lag, $F(5,35)=10.9$, $p<.001$, and a significant interaction between condition and lag, $F(5,35)=6.0$, $p<.001$. A similar pattern of results was obtained for the fixed-T1; there were main effects of distractor condition, $F(1,7)=30.3$, $p<.001$, and lag, $F(5,35)=8.7$, $p<.001$, and an interaction between distractor condition and lag, $F(5,35)=8.2$, $p<.001$.

Separate analyses of the two distractor conditions showed main effects of lag in the digit distractor condition, $F(5,70)=16.7$, $p<.001$, but no difference between the fixed and variable-T1 groups, $F(1,14)=0.0$, $p>.99$, and no interaction, $F(5,70)=1.8$, $p>.11$. In the symbol distractor condition there were main effects of lag, $F(5,70)=5.4$, $p<.001$, and of T1-variability, $F(1,14)=4.6$, $p<.05$, and an interaction, $F(5,70)=2.4$, $p<.05$. Inspection of the upper curves in Figure 6 indicates that there was little or no lag effect with symbol distractors when T1 was in a fixed serial position, but there was a small AB deficit when T1 was variable.

Thus, the overall effect of fixing the position of T1 and shortening the sequence to nine items was to improve performance, but only when the distractors were symbols. There was no consistent effect of fixing T1, when the distractors were digits. The AB effect was at least as large when T1 was fixed, as when it varied.

Excluding lag 1, T1 was correctly identified on 98.1% of the trials in the symbol distractor condition, and on 85.9% of the trials in the digit distractor condition, $\underline{F}(1,14)=42.2$, $\underline{p}<.001$. Thus a letter target was easier to report when it appeared among discriminable symbols than among digits. Surprisingly, there was no main effect of T1 predictability (fixed, 93.1%; variable, 91.0%) on T1 identification (as before), $\underline{p}>.41$, and no effect of T2 lag (excluding lag 1), $p>.65$. When T1 was immediately followed by T2, T1 was detected 79.1% of the trials in the digit condition and on 85.9% of the trials in the symbol condition, $\underline{F}(1,14)=4.2$, $\underline{p}<.07$, and at this lag there was a main effect of T1-predictability, $\underline{F}(1,14)=7.5$, $\underline{p}<.05$, with predictable T1 reported on 87.8% of trials, variable T1 on 77.2%.

The main finding of the present experiment is that the deficit for detecting T2 is markedly attenuated when the targets are readily discriminable from the distractor set. Raymond et al. (1992, Experiment 3) have shown that when T1 is followed by a blank, the deficit is eliminated. This suggests that local interference by an immediately following item is a necessary condition for triggering the AB deficit. However, the near elimination of AB in the symbol condition here, together with the smaller reduction of AB in the D1-symbol condition of Experiment 4, suggests that the AB deficit is graded rather than triggered in an all-or-nothing fashion by any post-target event. Though there was an effect of lag in the symbol condition, the AB effect was much weaker, and the significant interaction of lag and distractor condition indicates that the time course of AB was affected by the distractor condition. Moreover, the much greater reduction in AB when all the distractors are symbols, compared to the mixed-distractor conditions of Experiment 4, show that it is not just D1 and D2 that determine the presence and time course of AB : the global distractor set also has a substantial effect. This is consistent with our assumption that the global set influences the threshold criterion for detecting a target and initiating second stage processing.

Inversion Errors

In the experiments reported in this paper, subjects were encouraged but not required to report the target items in the order that they appeared. The order of each subject's response (when two items were reported) was not recorded in Experiment 1. However, subjects were observed to have made some order inversion errors. In Experiment 2 and all later experiments, the order in which subjects reported the targets was recorded (for written responses, the lefthand item was assumed to be the first item reported). Trials in which both targets were reported were scored as correct, regardless of the order of report. In a separate analyses, all trials on which both both T1 and T2 were reported were scored for the percentage of inversion errors, separately for each condition and SOA. The means from Experiment 5 are shown in Figure 7[2].

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[2]Though not reported for the other experiments, the same pattern of inversion errors was observed in all of the AB experiments in this paper (inversion data were not available for Experiment 1).

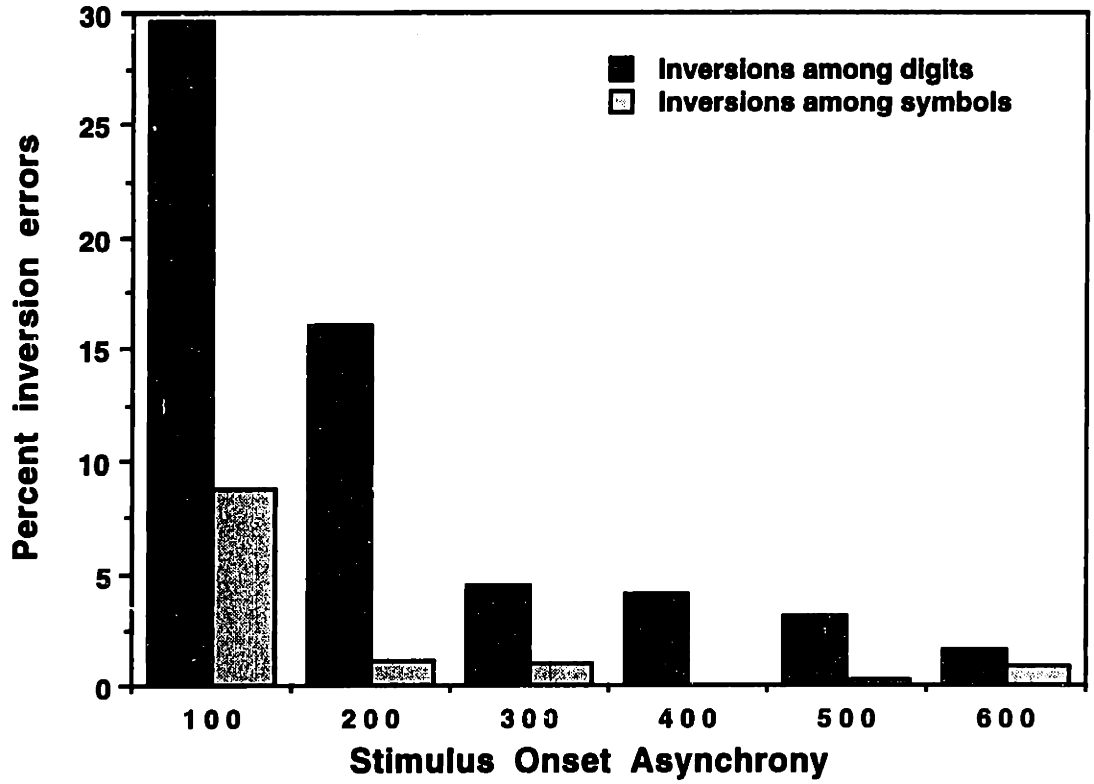

Figure 7. Percent inversion errors in each condition, given report of both T1 and T2, in Experiment 5

ANOVAs were carried out on the percentage of inversion errors at each SOA for the two distractor conditions (combining the two T1- position groups, for which the results were similar). There was a main effect of lag, $F(5,70) = 13.2$, $p<.001$, with the majority of inversion errors occuring at lag 1 (SOA=100ms), when T1 and T2 were adjacent in the RSVP list sequence. Figure 7 indicates that the proportion of inversion errors decreased rapidly with increasing lag between T1 and T2. A significantly higher proportion of inversion errors were made in the more difficult high-similarity condition, $F(1,14)=12.7$, $p<.01$, suggesting that temporal uncertainty increases when the temporally adjacent letter targets are flanked by similar digit distractors. The interaction between condition and lag was also significant, $F(5,70)=5.7$, $p<.001$, and seems to be due to a floor effect in the symbol condition. The rarity of inversion errors at longer lags suggest that subjects were following our instruction to try to report the two targets in the order that they perceived them.

The occurrence of order errors at short target separations has been reported in many previous studies (e.g., Scarborough & Sternberg, 1967; Reeves & Sperling, 1986), and has been taken to indicate a failure of temporal resolution. The high proportion of inversion errors when the targets are adjacent is consistent with the hypothesis that second-stage processing of T1 overlaps with that of the following item. When the following item is a distractor, then the degree of visual similarity determines the amount of interference in correctly identifying T1. T1 is identified correctly on a higher percentage of trials when it is followed by a symbol than when it is followed by a digit. When the following item is another target, that saves T2 from the AB effect, at the cost of uncertainty in target order.

The prevalence of lag 1 inversion errors in our task is analogous to the pattern of T1 misidentification errors reported in previous studies. When T1 is a colored letter among black letter distractors, the majority of identification errors involve intrusions, rather than total misses (Raymond et al., 1992). A high proportion of these errors are +1 intrusions in which the letter distractor immediately following T1 is misreported as being the colored target (see also Lawrence, 1971; McLean et al., 1983; Gathercole & Broadbent, 1984; Broadbent & Broadbent, 1987).

In the two-stage model we propose the second, capacity-limited stage is initiated by detection of T1, but it frequently includes both T1 and the following item. The evidence for frequency inversion errors when T1 and T2 are adjacent is consistent with this hypothesis. That the inversion errors are markedly reduced (even at lag 1) when the distractors are symbols supports the additional hypothesis that stage-two processing of T1 begins earlier and thus will have less overlap with T2 at lag 1, when targets are globally distinct from distractors.

Experiment 6

We examined the role of local discriminability in Experiments 3 and 4, and the effect of global discriminability in Experiment 5. The results indicate an effect of both local and global discriminability. In the next two experiments we looked at the effects of local interference within a global set of digit distractors (Experiment 6) and symbol distractors (Experiment 7).

In Experiment 4 either a digit or a symbol immediately following T1 was sufficient to produce AB when the targets appeared among a mixed distractor set of symbols and digits. In Experiment 6 we use a digit distractor set as our baseline and examined the effects of a single symbol distractor placed at either lag 1 or lag 2 in the RSVP stream. Experiment 6 was identical to Experiment 3, except that the blank intervals were replaced with an equals sign ("="). In a pilot experiment in which one of 8 different symbols randomly replaced the blank, there was variation in the effect of different symbols. To reduce variability we used only the equals sign in Experiment 6; it was the item that produced the smallest AB effect in the pilot study.

Method

The method was the same as that of Experiment 3 except as specified.

Subjects. Eight subjects from the MIT subject pool participated in this experiment.

Design and procedure. The design and procedure were identical to those in Experiment 3 except that blanks were replaced with an equals sign. Thus, there were three conditions : no equals sign (only digit distractors), an equals sign at lag 1, or an equals sign at lag 2. All trials were intermixed randomly. The task was to report the two letters.

Results and Discussion

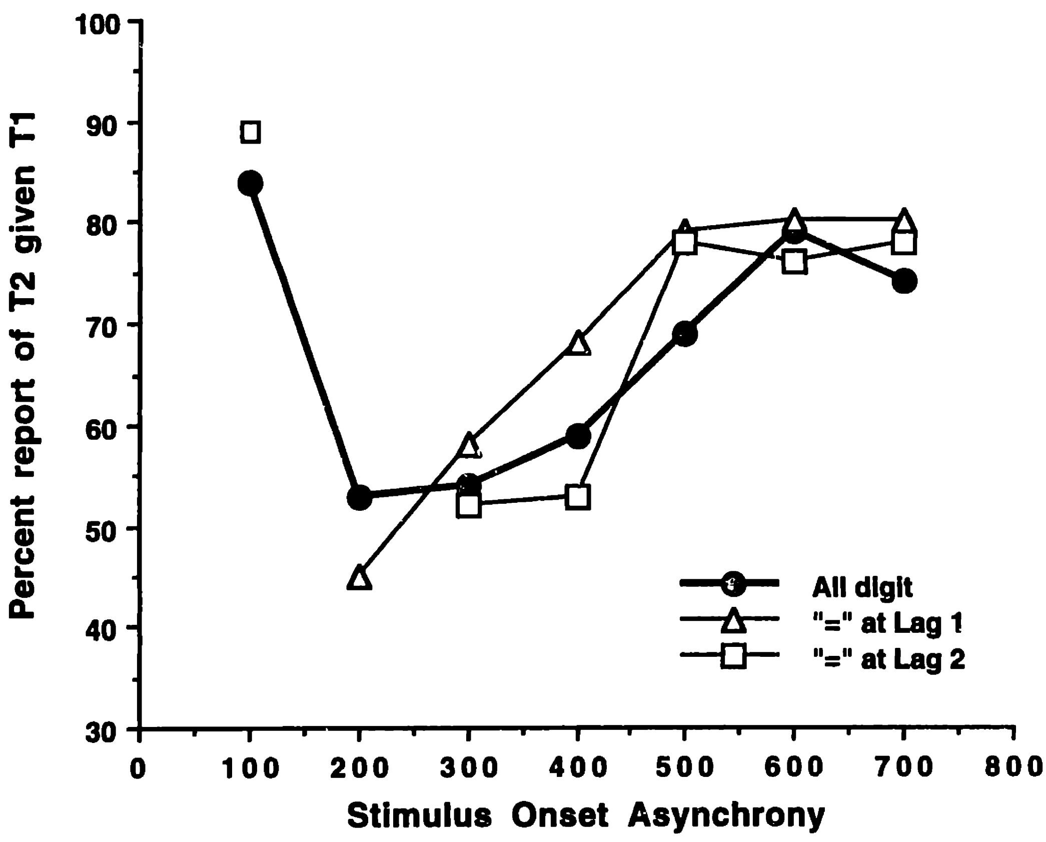

Figure 8. Effect of an equals sign among digits : Experiment 6

Figure 8 shows the mean percent report of T2 given report of T1 for each condition. The results of the baseline condition are similar to the corresponding conditions in Experiments 1, 3, and 5, although the AB effect appears to be less marked in Experiment 6. Whether the equals sign appeared at lag 1 or lag 2, it had a similar interfering effect to that of a digit in the baseline condition. Comparing the lag-1-symbol condition with baseline, there was a main effect of lag, $F(5,35)=10.7$, $p<.001$, but no effect of condition ($p>.26$) and no interaction between SOA and condition ($p>.14$). The apparent divergence of the two conditions was significant for lag 5 (SOA 500), $t(7)=2.2$, $p<.05$, one-tailed, suggesting quicker recovery in the lag-1-symbol condition. The main result, however, is that the equals sign appearing immediately after T1 was sufficient to produce an AB deficit for T2. As expected, presenting the equals sign at lag 2 also had no differential effect relative to the baseline. There was again a main effect of lag, $F(5,35)=11.7$, $p<.001$, but no interaction between condition and lag ($p>.23$).

The equals sign did affect T1 report, however. T1 was correctly reported on 87% of the trials in the baseline condition, when it was immediately followed by a digit, while it was correctly reported on 96% of the trials when it was immediately followed by an equals sign, $F(1,7)=37.3, p<.001$. Thus T1 was easier to identify and report when it was followed by a simple visual event than when it was followed by a digit. When T1 was followed by an equals sign at lag 2, it was detected on 88% of the trials, compared with 87% in the baseline condition (n.s.). When T2 appeared at lag 1, T1 was detected on 80% of the trials in the baseline condition, and on 76% of the trials when T2 was followed by an equals sign.

The results are consistent with the results of Experiment 4 in showing that an easily discriminable, to-be-ignored visual event, a symbol that was unlike both the letter targets and the digit distractors, is not equivalent to a blank interval. Raymond and her colleagues obtained a similar finding using a simple dot pattern mask in their task in place of a distractor letter (personal communication, May, 1992). Even though the equals sign had less of an interference effect on T1, it was sufficient to produce a salient AB effect, especially at the shorter lags.

Experiment 7

In the previous experiments we saw that target report is dependent on the visual event directly following it. In Experiment 6, except for a single equals sign, T2 was still embedded in a stream of digits, making it hard to identify. In Experiment 7, we switched the roles of symbols and digits, thus manipulating T1 identification difficulty while making T2 relatively easy to detect, since it appeared in a global environment of highly discriminable symbols, as in Experiment 5's symbol condition.

Method

The method was like that of Experiment 6 except as noted.

Subjects. Eight subjects from the MIT subject pool were tested in this experiment.

Design and procedure. The basic design of Experiment 7 was like that of Experiment 6, except where noted. Keyboard symbols replaced digit distractors and one (random) digit replaced the equals sign used in Experiment 6. Each trial in Experiment 7 consisted of 9 items, with T1 always appearing as the second item in the list. The letter targets and digit and symbol distractors were from the same sets used in Experiment 4. The two target letters were randomly chosen from the target set for each trial, without replacement. Distractor items were also randomly chosen from their respective set with the constraint that the same distractor item did not appear within the previous five serial positions in the RSVP list. In the all-symbol condition, all distractors were symbols. In the lag-1-digit condition, a digit appeared immediately after T1. In the lag-2-digit condition, a digit appeared at lag 2; either a target letter or a symbol appeared at lag 1. Fifteen trials at each lag in each condition were run. All conditions were randomly intermixed for a total of 240 trials, preceded by a block of 20 practice trials.

Results and Discussion

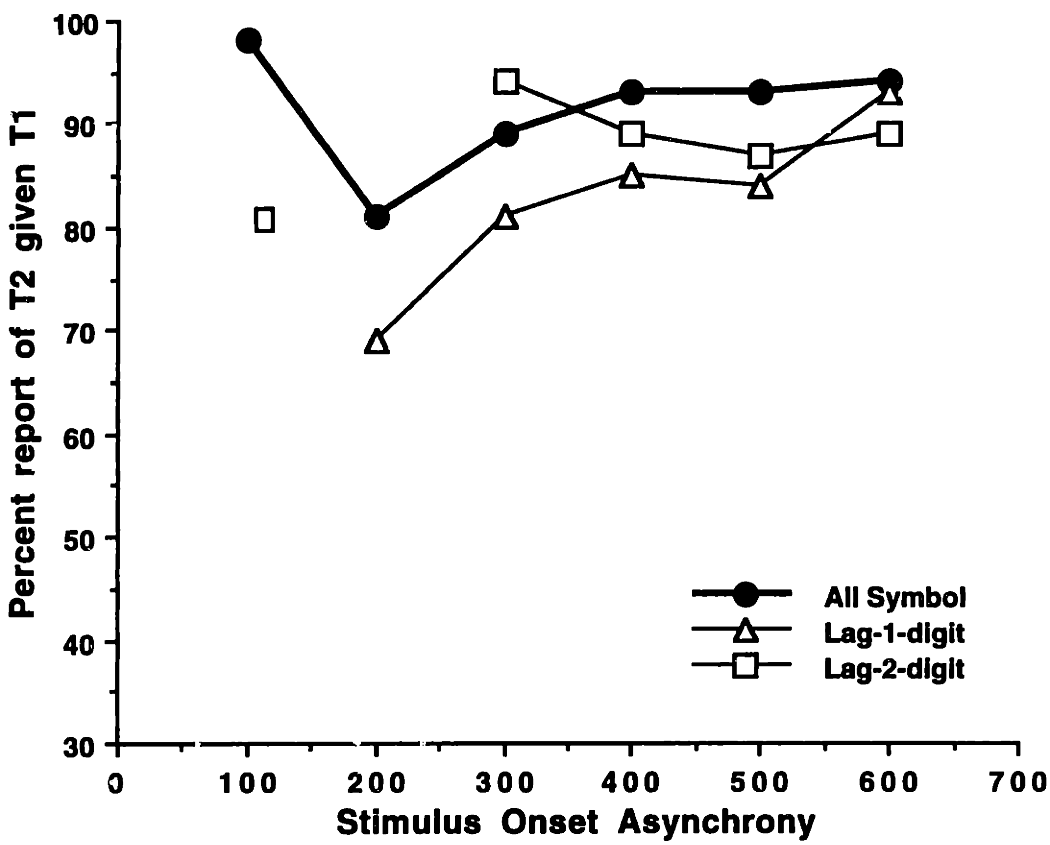

Figure 9. Effect of a digit among symbols : Experiment 7

The results of the experiment are shown in Figure 9. In the all-symbol condition, there was an effect of lag, $F(5,25)=4.5$, $p<.01$. Inspection of Figure 9 shows an AB effect that is much smaller than when the distractors were digits, although larger than the null effect in Experiment 5 with blocked all-symbol distractors. Comparing the baseline condition with the condition in which a digit distractor appeared immediately after T1, there was a main effect of condition, $F(1,5)=18.0$, $p<.01$, and of lag, $F(4,28)=5.9$, $p<.01$, but the interaction was not significant ($p>.74$). Thus, the presence of a single digit immediately after T1 increased the AB deficit. When the single digit appeared at lag 2, the pattern was quite different. There was no indication of an increased AB effect (compared with the all-symbols condition) after the digit (at SOA's of 300-600), $p>.24$, although there was an interaction between condition and lag, $F(3, 21)=3.8$, $p<.05$. More interesting is the highly significant difference between the baseline and lag-2-digit condition at lag 1, $t(7)=5.5$, $p<.001$. It was more difficult to report the second of two adjacent letters when the second letter was immediately followed by a digit than when it was followed by a symbol distractor, indicating that the item following T2 has an effect on its encoding, just as the item following T1 affects T1 encoding. This result is consistent with the results of Experiment 4. Excluding lag 1, T1 was identified on 99% and 93% of the trials in the all-symbol and lag-1-digit conditions respectively, $F(1,7)=8.5$, $p<.05$. In the lag-2-digit condition T1 was identified on 98% of the trials.

In Experiment 7, both T1 and T2 were discriminable from all distractors except the occasional digit. Even when T1 identification was made difficult by an immediately following digit, AB was much reduced, compared with Experiment 4. The results from Experiment 6 and 7 suggest that the deficit is modulated by the amount of local interference with T1, but they also confirm a strong global effect of discriminability of the targets from the main distractor set. We discuss the implications of these results in the general discussion.

General Discussion

The experiments in the present study extend previous findings of a deficit for detecting the second of two targets appearing among distractors in RSVP (Raymond et al., 1992; Broadbent and Broadbent, 1987; Weichselgartner and Sperling, 1987). The previous studies had shown that it is processing of T1 that is producing the deficit for T2. However, it was not clear whether the processing necessary for AB involved conjoining a target-defining feature with the correct features of the target (e.g., a white letter with that letter's identity), or whether registering any sort of target would be sufficient to produce AB, under RSVP conditions. In the present experiments, targets were defined by their category: subjects were asked to detect and report letter targets among distractors, presented for 100 ms/item. In Experiment 1, two letters were presented among digit distractors. When the first letter (T1) was correctly reported there was a strong deficit for reporting a second letter (T2) appearing within an SOA of 200 to 400 ms, demonstrating that an AB deficit occurs even for categorically defined targets appearing among distractors that were not members of the target set. This suggests that the source of interference in AB is the attentional requirement of having to process a target that must be discriminated from a sequence of items.

In Experiment 2, we presented three targets and showed that the AB effect is produced anew by each target reported. We then examined the effect of discriminability in target search by manipulating both the overall discriminability between targets and distractors, and the local discriminability between a target and the immediately following distractor. In Experiment 3 we replicated Raymond et al.'s (1992) results showing that the AB deficit for

T2 is highly reduced when the effective duration of T1 is extended by a blank frame. This indicates that post-target interference from an immediately following item is a necessary condition for AB. To evaluate the effect of distractor discriminability, in Experiment 4 we varied the type of distractor (digit vs. symbol) immediately following T1 and T2, in mixed sets of distractors. As predicted, T2 | T1 performance was modulated not only by the type of distractor following T2, but also the type of distractor following T1, suggesting that the AB deficit is a graded function of T1 processing difficulty.

To examine the effects of global target-distractor discriminability, we tested subjects in separate blocks of all-digit distractors and all-symbol distractors in Experiment 5. Supporting the idea that target discriminability is a major factor, letter targets that appeared among discriminable symbols were much easier to detect than when they appeared among digit distractors. The effect of global discriminability was strong, in that the AB effect was virtually abolished when target letters appeared among symbol distractors. In the last two experiments, we manipulated local discriminability between T1 and the following distractor in a search task for letter targets among digit or symbol distractors (Experiments 6 and 7, respectively), with a single distractor from the other set on some trials. A difficult (but not an easy) local distractor following T1 again modulated the dominant effect of the global set of distractors.

In summary, the results indicate that target search performance in RSVP is a function of both global and local target-distractor discriminability, and that the degree of post-target interference on T2 | T1 is modulated by the difficulty of T1 processing. What is not clear from our experiments or previous studies is exactly what features determine the discriminability between targets and distractors. Empirically, letters and symbols were more readily discriminated in the present experiments than letters and digits, as measured by the systematic relation between T1 performance and distractor type. Not only is there apparently less visual overlap between the letters and symbols we used than between the letters and digits, it is also likely that the symbol set was less conceptually similar to letters than digits are. Among other things, both digits and letters have names that are highly familiar, unlike most of the symbols. Thus, letters appearing among symbol distractors are presumably not only easier to process because of weaker visual masking effects in our RSVP task, but are also probably more discriminable as conceptual entities. Further research is needed to clarify and separate the effects of visual similarity and categorical similarity.

A Two-stage Model for the Attentional Blink

As discussed in the introduction, Raymond et al. (1992) proposed that confusion between T1 and the immediately following item (specifically, confusion about how to conjoin the features of each item) triggers temporary attentional suppression for subsequent items. We propose instead that identification and consolidation of T1 is slowed down when there is an immediately following item, leading to a delay in allocating second-stage processing to T2 when it appears 200-400 ms after the onset of T1, which results in loss of T2 on some trials. While our experiments do not rule out an attentional suppression model, the pattern of results is more consistent with the proposed two-stage model. In the following sections, we discuss the explanatory power and generality of the model with respect to our own and other AB results, as well as to other paradigms in the selective attention literature.

The two-stage model we propose extends Broadbent and Broadbent's (1987) observations that early stages of detection are succeeded by more demanding and capacity-limited processes. This type of two-stage conceptualization dates back at least to Neisser's (1967) proposal that preattentive processes guide the operation of a focal attention stage. It has been incorporated into various theories of spatial selective attention (e.g., Duncan, 1980, 1985; Hoffman, 1978; Treisman & Gelade, 1980; Wolfe, Cave, & Franzel, 1989), and also temporal selective attention (e.g., Shiffrin & Gardner, 1972; Gardner, 1973). The present two-stage model proposes that the AB deficit arises from a limited-capacity stage of processing and consolidation of the target, after it has been initially detected in the first stage.

First stage : Rapid detection : When items are presented for 100 ms each, virtually every item will be processed through stage one, which analyzes features relevant for target detection. Consistent with Broadbent and Broadbent (1987), we assume that processing at this stage of analysis allows for selection of candidate targets on the basis of independent feature cues, such as color or lettercase, or detection of targethood on the basis of their categorical identity. Based on evidence from RSVP experiments using word and picture stimuli, it has been proposed that short-lived conceptual representations are constructed for stimuli presented at rates as high as those used in AB studies (about 10/sec) (Potter, 1976, 1983, 1993). The results of our experiments are consistent with this claim, suggesting that at presentation rates of 10/sec the categorical identity of most of the items and probably their specific identity (see Sperling et al., 1971) is briefly available and may serve as the basis of selection into subsequent stages. We assume that these initial representations are subject to rapid forgetting when there is interference from subsequent

RSVP stimuli, unless they are selected for further processing and consolidation (Potter, 1976, 1993).

Second stage : Capacity-limited processing : In accord with Duncan (1980), we assume that the representations resulting from early levels of processing (first stage) cannot serve as the basis for subsequent report or response, but require additional processing. A representation of a candidate target stimulus which is momentarily active must be transferred into a more durable representation (such as verbal STM) to be available for subsequent report, or, as Duncan suggests, even to serve as a basis for a manual response. This requires second-stage processing, which results in full identification and consolidation of the target for subsequent report. We consider this stage to be capacity-limited and to exceed the item's stimulus duration at the high presentation rates used in RSVP tasks. This stage of processing does not commence with the onset of a stimulus, but only after first-stage target detection. We hypothesize that the second stage is initiated by a transient attentional response that occurs upon first-stage detection of a (probable) target. This attentional response actively selects and enhances processing of the target (Weichselgartner & Sperling, 1987; Nakayama & Mackeban, 1989). We also assume that the timing and resolution of this processing enhancement is such that T1 and the lag 1 item (T2 or distractor) are likely to be processed together. Second-stage processing then identifies and consolidates the one or two targets present in the input, discarding distractor "noise". Until this second processing stage is completed, no subsequent items are processed beyond stage one. When T2 appears before the second stage is free, it will be detected by stage-one processing but stage-two processing will be delayed. The longer the delay, the greater the probability that T2 will have been lost, according to our previous assumption that stage-one representations are short-lived.

T1 performance : Local discriminability between T1 and the following item affects T1 report accuracy. Effects of local interference on T1 detection were observed in all of the present experiments : a following letter led to the least accurate T1 report, with improving T1 report when the following event was a digit, symbol, or blank, in that order. According to the model, the duration or efficiency of stage-two processing reflects T1 processing difficulty. In the following sections, we discuss how this correlates with report of T2.

T2 Lag Effect (Lag 1) : If the item appearing at lag 1 is processed together with T1, then when it is a target it should benefit from stage-two processing. This prediction is supported by the lack of a deficit for T2 when it appeared at lag 1 (Experiments 1-7). The high proportion of inversion errors at lag 1 but not at other lags (Experiment 5) is consistent with the assumption that the two targets are being processed together at lag 1.

A further prediction is that T1 and T2 should produce some mutual interference when both are processed together at lag 1, and indeed T1 is least often reported when T2 immediately follows (see Table 1). Conversely, although T2 is more likely to be recalled at lag 1 than at lags 2-4 when T1 is reported, it is even more likely to be recalled if T1 is missed : for T2 | ~T1 (T2 given that T1 was missed), the probability of recall was 94% whereas for T2 | T1 it was 76%, in Experiment 1. Similarly, the likelihood of reporting both T1 and T2 was lower at lag 1 (51%) than at lags 6-8 (71%), when the AB deficit was no longer in evidence (see Table 1). At lag 1 only, T1 performance also appears to be affected by the type of distractor that follows T2 (Experiments 3 and 6). When T2 was followed by a blank or symbol (presumably making T2 easier to process), there was more interference with T1 than when T2 was followed by another digit. Thus, T1 and T2 seem to be in competition when they are temporally adjacent, which is what the two-stage model predicts.

T2 Lag Effect (Lags 2 -4) : Resources from the capacity-limited second stage are unavailable for allocation to T2 while T1 is being processed. Thus, a second target appearing during this time will have to wait. Within this interval, targets appearing at shorter SOA's must wait longer, on average, and are thus more susceptible to erasure by subsequent items. When the lag of T2 exceeds the duration of stage two processing of T1, performance is no longer impaired.

Effects of T1 processing difficulty : If the duration of second-stage processing of a target is determined by the amount of interference (either visual feature overlap or conceptual similarity) from the following distractor, then this should show up in T2 performance. Experiments 3, 4, 6 and 7 all show evidence for quicker recovery from the AB deficit as a function of the difficulty of discriminating between T1 and the following item. Differences in T1 processing difficulty do not always show up at lag 2, but often only at later lags (3-5) (see Experiments 4 and 6: Figures 4, 5A, and 8). This would be expected if we assume that the second stage of processing overlaps with lag 2 even when the distractors are easy to discriminate : the difference between easy and difficult distractors only begins to show up at lag 3.

Global distractors and target criterion : Even when the items following T1 and T2 were held constant, the global distractor set had an influence on performance (Experiments 4-7). We hypothesize that subjects establish a target detection criterion in accordance with the set of distractors, lowering the criterion when discrimination between the target and distractors is easy (as with symbol distractors) and raising it when distractors are more difficult to discriminate from targets (as with digit distractors). This effect would be predicted to be largely independent of the effect of the specific distractor following a target.

A lower criterion means fewer target-relevant features must be detected before stage-two processing is triggered. The earlier that second-stage processing is begun, the sooner it will be completed, the smaller the likelihood that the lag-1 item will be included with the target, and the less overlap in processing there will be with subsequent items. When targets and distractors are highly discriminable in a given block (Experiment 5 : symbol condition) the criterion can be set very low. The minimal AB deficit and the lower proportion of lag 1 inversion errors in the symbol condition support this suggestion. Evidently stage-two processing was initiated before the following item was available to be included in processing and was usually completed before T2 was lost through interference. A comparison across experiments showed that a small deficit occurred on all-symbol trials when they were intermixed with trials that included a single digit distractor (Experiment 7) or when all-symbol trials were blocked but the position of T1 was randomized (Experiment 5). The criterion for target detection can presumably be set lower when the all-symbol trials are blocked and when T1 position is fixed.

Comparing the two-stage model with previous AB models

The current model ties together several ideas brought up by previous models of AB. As discussed before, Broadbent and Broadbent (1987) were the first to suggest that the AB deficit might be indicative of a two-stage process of initial detection of target features followed by more demanding processes of identification. However, their initial proposal did not extend much beyond this general observation and is not specific enough to account for the lack of

AB at lag 1, nor for the effect of local and global distractor interference. Weichselgartner and Sperling (1987) proposed a two-component attentional mechanism to account for post-T1 deficits, and according to this model, T2 appearing at lag 1 will be picked up along with T1 by virtue of a transient attentional response. However, in their model report of later targets is processed by a qualitatively different second, sustained component of attention. In a task using three targets (Experiment 2), we showed that the AB pattern (lag-1 benefit, lags 2-4 deficit) iterates for each occurrence of a correctly reported target, a result that would not be expected if T2 is detected by a sustained component. Weichselgartner and Sperling's model also makes no prediction about variation in the type of distractor following T1.

Raymond et al. (1992) reported several results important to understanding the cause of AB. Of particular importance is the finding that the item appearing immediately after T1 plays a critical role in producing AB. Thus it is not target identification alone, but interference from immediately following visual stimuli, that is required to produce the deficit for T2. The role of this critical item immediately following T1 (D1) has been a major focus of this paper.

Our experiments and two-stage model extend the results reported by Raymond et al. (1992) and share several assumptions about the AB effect, especially in regard to the role of D1 in the AB effect. Both models also assume that T1 and D1 are usually processed together. Furthermore, Raymond et al. (1992) suggest that the amount of interference is proportional to the degree of similarity between D1 and T1 (Duncan & Humphreys, 1989). The lack of AB at lag 1 and the high proportion of inversion errors for T1 and T2 at lag 1 shown in our results are consistent with the assumption that T1 and D1 are processed together. The effect of local discriminability between targets and immediately following distractors, as well as the effect of the global distractor set, support the predicted effect of greater interference as a function of increasing similarity.

However, there are major differences between our two-stage model and the attentional suppression model proposed by Raymond et al. (1992). First, they proposed that the main source of interference with T1 identification is a feature-conjunction confusion arising when the target-defining feature (a white letter) has to be conjoined with letter features, and both T1 and and the lag-1 letter are present in a sensory store that does not represent serial order. They proposed that when the system detects the potential for confusion a suppressive mechanism is initiated to eliminate further confusion. Our set of results showing AB with categorically defined targets suggest that the deficit is not the result of having to conjoin a target-signalling feature with target identity.

As discussed earlier, Raymond et al. (1992) explain the AB deficit as the result of an inhibitory attentional suppression mechanism which is invoked by the visual system to prevent further interference from items following T1. In particular, this inhibitory process is described in terms of an attentional gate which becomes both "shut and locked" in the presence of confusion, thus producing an attentional blink. Because their T2 task (detecting the presence or absence of an 'X' probe) was assumed to require only a minimal level of processing, Raymond et al. (1992) concluded that the suppression mechanism blocks off further visual processing at a relatively early stage. However, detection of an X appearing among a rapid sequence of other distractor letters may be a more demanding process than it seems. "Yes-no" detection of even a prespecified letter appearing among other letters may require identification of the features of each distractor letter (see Sperling et al., 1971). The main point is that if their T2 probe task was actually more complex than Raymond et al. assumed, there is no reason to conclude that in AB visual processing is suppressed at an early level: stage-one processing may be occurring, as we propose.

While the suppression model takes into account the effect of local similarity in modulating the size of the AB deficit, it is not clear how this fits with a shut-and-locked attentional mechanism. In order to explain the effects of local interference on the size of the AB deficit, as found in the present study, the suppression model must postulate that increased local interference results in either 1) increased probability of a shut-and-locked mechanism being activated or 2) stronger inhibition of subsequent stimuli. The latter account would require an added mechanism; as it was described, the locking mechanism is ballistic in that once initiated, it is insensitive to post-target events. The main effects of D2 immediately following T2 in Experiment 4 suggest that the detectability of T2, not just that of T1, must be taken into consideration.

In short, while the AB effect can be explained by the operation of the hypothesized attentional gate, some further specification of the operational characteristics of the attentional gate is needed. Our model provides such an account. Rather than hypothesizing that AB is due to some inhibitory mechanism, we propose that the AB deficit reflects a fundamental characteristic of visual processing : that there is a limited-capacity stage for identifying and consolidating targets in RSVP, with characteristics that we have outlined here.

The two-stage model and other target-interference paradigms

It has been well established in a variety of other target search paradigms that simultaneous targets in a single array produce mutual interference. Duncan (1980) reviewed the evidence and presented several experiments to support his proposal for two levels of perceptual representation. At the first, preattentive level, targets and non-targets may be distinguished in parallel (Duncan used categorically defined alphanumeric targets and distractors). However, targets must pass through a Limited-Capacity System (LCS) to a second level before forming a reportable perception. Multiple targets compete for access through the limited-capacity system, resulting in impaired detection performance for any given target when multiple targets are presented simultaneously. Our two-stage model for target detection in RSVP is consistent with Duncan's work, if one assumes that the onset of LCS processing is affected by the subject's global detection criterion and its duration and accuracy are affected by the following distractor. When targets are presented in RSVP, the AB deficit shows how this mutual target interference extends over time.

Duncan and Humphreys (1989) have proposed a comprehensive theory based on the effects of similarity to explain a wide range of experimental results from the spatial visual search literature. The three main components of Duncan and Humphreys' model are 1) a parallel stage of perceptual description that produces a structured representation of items in the visual field at a number of spatial scales. 2) matching of these representations against an internal template of the target 3) selection of template-matching items for entry into VSTM (visual short term memory), which is limited in capacity. According to the model, access to VSTM is strictly limited and items are competitively assigned weightings according to their degree of match to current target templates. Thus target search difficulty in spatial displays increases as a function of increased similarity of targets to non-targets and decreased similarity between nontargets. Though the similarity-based model for visual search is specific to simultaneous arrays, not RSVP target search, our experimental results and the two-stage search model we propose are consistent with certain aspects of the Duncan and Humphreys model, especially in regard to the predicted effects of target-distractor similarity. On the other hand, the Duncan and Humphreys model has nothing to say about lag effects or about multiple targets and the AB effect[3].

A related paradigm for studying processing limitations is the overlapping tasks paradigm (otherwise known as the psychological refractory period (PRP) paradigm) (Welford, 1952; Pashler, 1984, 1992). Here, two stimuli (S1 and S2) are presented in a sequence and subjects are asked to make a separate response (R1 and R2) to each stimulus in the order of presentation. As the SOA is decreased between S1 and S2, such that S2 is presented before R1 is made, interference occurs between the two tasks which results in increased reaction time (RT) for R2. One class of models to explain the slowing of R2 proposes that there is a bottleneck such that certain stages of processing cannot be performed simultaneously on more than one input (Welford, 1952; Pashler, 1984; Pashler & Johnston, 1989; McCann & Johnston, 1992). Thus, S2 processing that involves this stage must be postponed until response selection for S1 is completed. Another class of models to explain the PRP effect does not posit a bottleneck, but instead proposes that many

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[3]Recently, Shapiro and Raymond (in press) have proposed a reformulation of their attentional suppression model to a "similarity model" based on Duncan and Humphreys (1989). This model, also, is substantially different from the present two-stage model.

cognitive operations draw on a common pool of resources (Kahneman, 1973). When multiple stimuli compete for the limited resources in this pool, the processing of some or all of the stimuli is slowed or degraded. It is difficult to distinguish empirically between these two models. However, there is one pattern in our results that is more readily explained by a serial bottleneck than by parallel competition for resources : the delay of onset of differential effects of the distractor following T1 on T2 report (see Figures 4 and 5). (This pattern has also been seen in experiments not reported here.) Such a pattern is consistent with a bottleneck that persists until at least lag 3, even in the easier of two conditions; the pattern is not easily explained by a competing-resources model.

An important issue in understanding the PRP effect is the identity of the cognitive process that is causing the delay of R2. The stages of processing of S1 and S2 can be roughly divided into three components : perception, response selection, and response execution. The evidence suggests that it is response selection that constitutes a bottleneck in PRP dual tasks (see Pashler, 1984, 1989; Pashler & Johnston, 1989).

It is not yet clear whether the response selection bottleneck for performing speeded vocal or manual responses in the PRP paradigm is the same bottleneck we propose as the source of AB. For an auditory first task (S1) and a visual second task (S2 : report the highest digit among an array of digits), Pashler (1989) has shown that perceptual processing of a masked visual display (S2) can proceed while response selection for S1 is underway. It is only the corresponding response selection stage for S2 that is being delayed, which results in R2 slowing (but no increase in errors) when a speeded response is required. However, when S1 is also a visual task (orientation feature search), then there is a dramatic increase in R2 errors when the SOA is short. Together, these results suggest that the source of interference producing RT slowing in PRP tasks may be different from the error-producing interference which occurs between two visual tasks. The limited-capacity process producing AB probably falls under the latter category; in that case the bottleneck in the present model is different from the bottleneck causing PRP slowing. However, more directly comparable experiments will be required to make clear the relation between the two paradigms and their models.

Another deficit that appears in RSVP tasks and shares similarities with the AB deficit is repetition blindness (RB) (Bavelier, 1992; Bavelier & Potter, 1992; Kanwisher, 1987; Kanwisher & Potter, 1989, 1990; Kanwisher, 1991). Whereas AB is a deficit in reporting a second RSVP target when T1 and T2 are different, RB is the additional difficulty of reporting T2 when it happens to be the same stimulus as T1 (e.g., both are the letter A). Unlike the AB paradigm, however, in most RB studies subjects are required to report all the items presented, not just the two critical items. The presentation rates used are comparable to those in AB studies, and the lags at which RB is found are similar. RB has typically been studied with RSVP sentences where AB does not generally occur, though both AB and RB occur for unrelated stimuli such as random letters (for RB : Kanwisher, 1991; Bavelier & Potter, 1992; for RB and AB, Chun & Potter, 1992). Also, under certain conditions AB occurs without RB (Chun & Potter, 1993; Ward, Duncan, & Shapiro, 1992), suggesting that the two deficits, though closely related, are doubly dissociable and reflect independent limitations in visual processing. Nonetheless, the effect of a repetition is additive with AB : if T2 survives AB, it is at risk for RB when T1 and T2 are identical. RB apparently results because T2 is perceived as the same event as T1 and so fails to be registered independently.

A question not addressed by the present experiments is whether selecting a subset of targets from an RSVP stream involves additional processes that would not be present in whole report of every item in the sequence. AB studies employ a partial report task, where targets need to be selected from the RSVP stream for subsequent report; there may be an additional cost for such monitoring and selection. Unpublished pilot experiments from this lab that compare whole and selective report using letter and digit stimuli in short RSVP sequences suggest that a whole report strategy does not increase the absolute probability of report of an item in T2 position. However, the number of items to be reported was confounded with whole report versus selection, making it difficult to reach a firm conclusion about a possible selection cost in partial report.

The issue of selection versus whole report may be relevant to understanding the lack of intermittency on individual trials, in perceiving and recalling RSVP sentences (e.g., Potter, 1983; Potter, Kroll, Yachzel, Carpenter, & Sherman, 1986). Studies using words that constitute contextually meaningful and grammatical sentences are typically whole report tasks, and these tasks can be performed with high accuracy at the same presentation rates used in AB studies. Thus, it is not clear from existing research whether the apparent absence of AB-like intermittency in whole report of sentences indicates that there is an additional selection cost in the AB paradigm, or whether the speed of encoding successive words in meaningful sentences avoids the AB deficit.

The lack of AB for RSVP sentences presented at the same rate that produces AB in target search does, however, lend support to the idea that the AB deficit is not simply an effect of low-level masking, but rather reflects a bottleneck in higher-level processing. According to our two-stage model, since AB occurs in RSVP target-search tasks because of a rate-limiting stage between initial perception and subsequent report. Thus, it can easily account for the lack of AB for sentences by assuming that contextual cues and syntactic parsing mechanisms allow for rapid and efficient encoding and retention of the incoming word stream. Support for this can be found in a study by Forster (1970), who presented lists of 6 words at 62.5 ms /word. Performance for a string of words was highest when the words formed a simple sentence, lower for complex sentences, and significantly worse for scrambled strings. Pfafflin (1974) and Potter, Kroll, Yachzel, Carpenter, and Sherman (1986) also report that recall performance for scrambled sentences is much poorer than for the same sentence presented in normal order.

In sum, the present results support a two-stage model in which a first stage of perceptual detection is followed by a capacity-limited second stage that is required for conscious retention of a target's identity for subsequent report. This stage constitutes a bottleneck that produces a transient deficit for second-stage processing of subsequent targets. This deficit extends over a period of up to 500 ms after T1's onset, during which performance on T2 improves with increasing lag (between lags 2 and 5). The amount of interference from T1 is modulated by the difficulty of discriminability between T1 and the following item, as well as the global discriminability between targets and distractors, and is largely eliminated by a blank interval immediately after T1 (see also Raymond et al., 1992). The lack of a deficit for a second target appearing at lag 1 and the high proportion of order inversion errors made in that condition are consistent with the model's assumption that T1 and an immediately following item (whether another target or a distractor) are likely to be processed together in stage two.

Although the present study has focused on temporal limitations of search for multiple targets in an RSVP display, the model we propose is consistent with an array of models proposed for spatial visual search, and further research may allow generalization to the wide range of tasks in which attention must be deployed among multiple objects across space and over time.

Chapter 2

A type-token framework for visual processing : A double dissociation between the Attentional Blink and Repetition Blindness

The focus of this study is to examine the relationship between two separate target report deficits: the attentional blink and repetition blindness. The attentional blink (AB) refers to the difficulty in reporting a second target (T2) appearing within 200-500 ms after a correctly identified T1. Repetition blindness (RB) is an additional deficit for when T1 and T2 are identical. A systematic comparison between AB and RB is absent from the literature. Yet, both AB and RB occur in a variety of RSVP tasks and the two deficits share enough similarities to merit a direct comparison[1]. First, both deficits seem to reflect capacity limitations in attentional processing of the relevant items. RB only occurs when T1 is attended (Kanwisher, 1991), and the same is true for AB (Raymond, Shapiro, & Arnell, 1992). Second, both AB and RB reflect temporal lag-dependent effects of a correctly processed T1 on T2. Finally, both effects occur for items presented at high rates (8-12 items/sec). Thus, the main empirical question of this study is whether the two RSVP deficits reflect some general, common capacity limitation for processing rapidly presented visual objects, or whether AB and RB are functionally dissociable deficits in visual processing.

[1] A difference between the standard AB and RB paradigms is that in most RB studies subjects report all of the stimuli presented on a trial — there is no distinction made between targets and distractors.

The theoretical issues underlying the comparison between AB and RB are fundamental to an understanding of vision. The goal of vision has been described as "the process of discovering from images what is present in the world, and where it is" (Marr, 1982). The visual system needs to determine "what" objects are in a visual scene (type recognition), and also "where and when" these objects occur (a process referred to as token individuation). Much of the research in visual processing has been concerned with type recognition, the matching of a sampled image or image region to some previously stored representation that classifies the present object or scene as a chair or a restaurant, for example. However, it has been proposed that a functionally independent process, token individuation, is required to note how objects are occurring episodically in the environment over space and time (Kahneman & Treisman, 1984; Kahneman, Treisman, & Gibbs, 1992; Kanwisher, 1987). As Kanwisher (1991) has pointed out, "After all, when we look at the world we perceive not an unstructured soup of visual categories, but rather a spatiotemporally organized array in which those categories are associated with particular objects and events. (p404)".

The activation of the long-term representation of a type is devoid of any episodic information regarding how the activated type is occurring in the environment over space and time. Thus, our perception of events may be mediated not by the activation of type nodes, but by temporary "episodic" representations which link activated type information with spatiotemporal tokens (Kahneman & Treisman, 1984). These episodic representations linking type information with spatiotemporal information have been termed "object files" (Kahneman & Treisman, 1984; Kahneman et al., 1992), or "tokens" (Kanwisher, 1987), or "object tokens" (Kanwisher & Driver, 1992).

Our central theoretical claim is that AB may reflect a general limitation in the binding of correctly identified types to object tokens, whereas RB reflects an additional limitation for individuating two separate tokens for repeated types. In either case, the failure to instantiate an object token for a perceptual event will result in that item being unavailable for subsequent report. If the deficit for unrepeated targets (AB) can be dissociated from the deficit for repeated targets (RB), then this would suggest that the deficits represent separate attentional limitations in different mechanisms of visual processing. We employ double dissociation logic to support such a functional distinction. To preview, we show that RB can occur under conditions where there is no AB, and that AB can occur without additional RB.

Selective attentional deficits in RSVP

The experiments described in this paper examine and directly compare two selective deficits that occur when multiple target items are reported from a sequentially presented stream of distractors, using rapid serial visual presentation (RSVP). In RSVP a stream of items is presented at rapid rates (8-12 items/second) at the same spatial locus. In the present experiments, subjects are asked to report the identity of the targets ("A", "B", ...) at the end of each trial sequence. Targets to be reported can be defined categorically (e.g., letters among digits) or by independent feature cues (e.g., colored letters among black letters). When only one target is presented on a given trial, performance is remarkably good at relatively high presentation rates (e.g., Lawrence, 1971).

The Attentional Blink (AB). The first of the two deficits we are focusing on occurs when two different targets are presented among distractors in RSVP. Correct identification of the first target (T1) produces a robust deficit for the second target (T2) when T2 appears 200-500 ms after the onset of T1. This deficit was termed the "Attentional Blink" (AB) by Raymond, Shapiro, and Arnell (1992) and has been examined by other investigators (Broadbent & Broadbent, 1987; Chun, 1994; Chun & Potter, 1992, 1993a, in press; Duncan, Ward, & Shapiro, 1994; Horlitz, Johnston, & Remington, 1992; Ward, Duncan, & Shapiro, 1992; Weichselgartner & Sperling, 1987). The AB deficit is typically demonstrated in simple tasks where only two targets are to be reported (e.g. two letters embedded within an RSVP stream of digits). The temporal lag or stimulus onset asynchrony (SOA) between the two targets is varied systematically and report performance is measured as a function of lag[2]. Performance on T1 is generally accurate and is little affected by T2 lag or T2 accuracy. However, the proportion of trials on which T2 is reported (given that T1 was reported) shows a strong lag dependency. Performance is lowest at lags 2 and 3 (SOA=200-300 ms), and improves with increasing lag, asymptoting at around lag 5 to 6 (SOA=500-600 ms). An interesting aspect of the AB deficit is that performance for T2 is generally high when it appears immediately after T1. Thus, AB shows a U-shaped function of temporal lag. Throughout this paper, we shall refer to this U-shaped function as the "AB lag effect".

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[2]It should be noted that lag is defined differently in the current paper than in previous RB studies. Previously, lag was defined as the number of items intervening between the two critical events. Here, we define lag as the temporal separation between two events: lag 0 would correspond to simultaneously occurring events, while lag 1 refers to temporally adjacent events (SOA=100 or 105ms depending on the presentation rate used). Therefore lag 1 in previous RB studies corresponds to lag 2 in the current study, and so forth.

The AB deficit occurs in a variety of tasks, independent of how targets are differentiated from distractors, and the effect is robust across various types of stimuli (e.g., words, letters, Landolt C's). The AB deficit was initially shown by Broadbent and Broadbent (1987) for uppercase target words presented among lowercase distractor words. When there were two targets, subjects often failed to report the second target when it appeared within 200-500ms after the first one. Others showed an AB effect in a task where subjects monitored a stream of digits and were asked to try to report the four digits starting with a target digit that was cued by luminance or an outline square (Weichselgartner & Sperling, 1987). The deficit also occurs when the selection set is different for T1 and T2 : In Raymond et al.'s experiments (1992), the task was to report the letter that had appeared in white (T1) among black letter distractors, and then try to detect whether a black letter 'X' probe (T2) had appeared or not. Detection performance for probe presence/absence was poor at lags 2 and 3, gradually recovering with increasing lag. More recently, Duncan, Ward, and Shapiro (1994) have demonstrated that an AB effect also occurs with only two masked targets appearing a different spatial loci. In all of these studies, the qualitative shape of the deficit was the same : initially good performance at lag 1, worst at lags 2 and 3, and gradual improvement as a function of increasing lag.

Chun and Potter (in press) examined the AB effect in a simplified task in which subjects were instructed to report two letter targets appearing among digit distractors. Of particular relevance to the current study is their finding showing that the discriminability of targets from distractors is a major factor in the magnitude of the AB deficit. While a robust AB effect was found in a search for letters among digits, little or no AB was found for letters presented among more discriminable keyboard symbols.

The AB deficit represents a capacity limitation for processing a second target appearing close in time. The AB deficit for T2 was explained by Chun and Potter (in press) in terms of a bottleneck model. They suggested that internal processing time for a target may exceed its actual presentation duration in RSVP search tasks, tying up a limited capacity process. If T2 appears before this process is complete, it is likely to be missed. Duncan et al. (1994) have recently proposed a similar idea that AB reflects "attentional dwell time" during which identification processing of T1 occupies limited attentional capacity.

Repetition Blindness (RB). The second RSVP deficit we study here was initially reported by Kanwisher (1987). Repetition blindness (RB) refers to the difficulty that subjects have in detecting repetitions of words, letters, or pictures presented in RSVP. For example, when presented with the RSVP sentence, "It was work time so work had to get done", many subjects would report, "It was work time so had to get done", omitting the second occurrence of the word "work" in their immediate verbal recall. Anecdotal evidence for RB is found in proofreading a manuscript : it is difficult to detect repetitions of words, as seems to be indicated by the the "repeated word" feature included in many computer word processor spelling checking programs (Did the reader notice the repeated "the" in the previous sentence?). While RB has been obtained for repeated items in simultaneous spatial arrays (Kanwisher, 1991; Kanwisher, Driver, & Machado, 1993; Luo & Caramazza, 1994; Mozer, 1989), it is most marked in sequential presentations of the kind we used in the present study. In typical RB studies, performance on repeated items (denoted in the RB literature as critical items C1 and C2, corresponding to the T1 and T2 convention used here) is measured in comparison to baseline performance for unrepeated items. For the previous example, report of the second instance of the T2 word "work", would be compared with report of the same word appearing in a baseline sentence, "It was day time so work had to get done". RB has been interpreted as a failure in token individuation for the second occurrence of the repeated item (Bavelier, 1994; Bavelier & Potter, 1992; Kanwisher, 1987, 1991; Kanwisher et al., 1993; Kanwisher & Potter, 1989, 1990; Mozer, 1989; Park & Kanwisher, 1994). According to this token individuation hypothesis, it is assumed that the second occurrence of a repeated item is recognized as a visual type (activating its corresponding long-term representation), but that it is not individuated as a distinct event: instead it becomes assimilated into T1.

The token individuation hypothesis posits the type-token distinction described earlier. In short, object tokens provide an episodic anchor mediating conscious processing of items. When a token is not available for an object, the item is not available for report.

Overview

In Experiment 1, we compare performance for unrepeated and repeated targets as a function of lag, systematically varied between the two targets. This direct comparison between the attentional blink and repetition blindness confirms previous findings of an additional deficit for repeated targets. We also show the AB lag effect and RB lag effect, and demonstrate that the time courses of the two are different, suggesting independent capacity limitations. In Experiment 2, we show that repetition blindness occurs under conditions where there is no AB. In Experiment 3, we show the converse : the attentional blink without repetition blindness. In Experiment 4, we further generalize our conclusions by providing some controls to replicate the previous results with some slight experimental variations. Finally, in the general discussion we discuss the implications of our series of experiments for the type-token distinction in visual processing and related theories of perception.

Experiment 1

In Experiment 1, we directly compare performance for detecting unrepeated and repeated targets. Lag is systematically varied between the two targets (T1 and T2). The task is simply to report two letter targets appearing among digit distractors. As noted in the introduction, a robust attentional blink is produced in this task for unrepeated targets. Report performance on T2, given that T1 was correctly reported, shows a strong dependency on SOA (AB lag effect). The main purpose of this experiment was to examine repeated target performance (RB) in direct comparison to this AB lag effect for unrepeated targets. Unrepeated (AB) and repeated (RB) target performance has not been examined systematically across a wide range of temporal lags in previous RSVP studies for tasks in which an AB lag effect is produced. Here, we examine performance for targets separated by lags 1-6 (100-600 ms).

Method

Subjects. Nine subjects participated in Experiment 1. The data from one subject was removed and replaced with that of another due to an abnormally high error rate which exceeded our preset criterion (over 10% of trials in which no target was reported). In this and all subsequent experiments, the subjects were recruited from the Massachusetts Institute of Technology volunteer subject pool. All observers reported normal or corrected-to-normal visual acuity and normal color vision. Informed consent was obtained prior to participation and subjects were paid for their participation.

Materials and Design. The stimuli were 8 single digits (0 and 1 were omitted to avoid confusion) and 42 letters (uppercase and lowercase versions of 21 letters excluding I, L, O, U, and V). Each experimental trial consisted of 9 items : 7 digits and 2 letters. In addition, there were 20 filler trials consisting of 8 digit distractors and 1 letter target. The digit distractors on a given trial were randomly generated by the computer under the constraint that the same digit did not appear in the previous four positions. Three target factors were crossed in a factorial design : target repetition, target lettercase, and temporal lag between the two targets. On half of the trials, T1 and T2 were randomly sampled non-identical letters (unrepeated target condition). On the other half, T2 was a repeated type of a randomly sampled T1 (repeated target condition). The two letter targets (T1 and T2) always differed in letter case. Within each target condition (unrepeated vs. repeated), T1 appeared in uppercase and T2 in lowercase on half of the trials, and vice versa. Six lags between T1 and T2, lag 1 (no intervening items, SOA=100ms) to lag 6 (SOA=600 ms), were counterbalanced over repetition and lettercase. The position of T1 was fixed at serial position 2.

There were 10 trials in each of 24 conditions, for a total of 240 experimental trials. These were interspersed with 20 filler trials in which only one letter target was presented. The order of this total of 260 trials was randomized independently for each subject.

Procedure. The experiment was self-paced. The subject began each trial by pressing the space bar on the computer keyboard. A plus sign lasting 300 ms appeared at the center of the monitor screen for fixation. One hundred ms after the fixation cross went off, the stream of stimuli appeared successively without interstimulus blanks at the same location for 100 ms each (presentation rate : 10 items per second). The sequence was followed by a "&" mask for 100 ms, signaling the end of the trial. Subjects were instructed to try to detect the one or two letter targets that had appeared and write them down on a separate answer sheet. They were required to write down their responses in the order and lettercase that the letter targets had appeared, circling the letter that had appeared in uppercase. In particular, they were explicitly told that many trials would have repeated targets (e.g. A and a), and that they should write the same letters twice on these trials. The experiment was preceded by a practice block of twenty trials. The experiment was carried out in normal room illumination held constant for all subjects.

Apparatus. The letter and digit stimuli were generated by an IBM-AT computer on a CRT screen with rapid fade phosphor. The stimuli measured about 0.3 cm in width and 0.4 cm in height. The display was viewed from approximately 30 cm, thus each stimulus subtended about 0.57 × 0.76 degrees visual angle. A sample of the stimulus sets is available in Figure 1 of Chun and Potter (in press).

Scoring. As in our previous AB study, in the main analyses responses were counted as correct regardless of their order of report and regardless of the lettercase given in report.

Results and Discussion

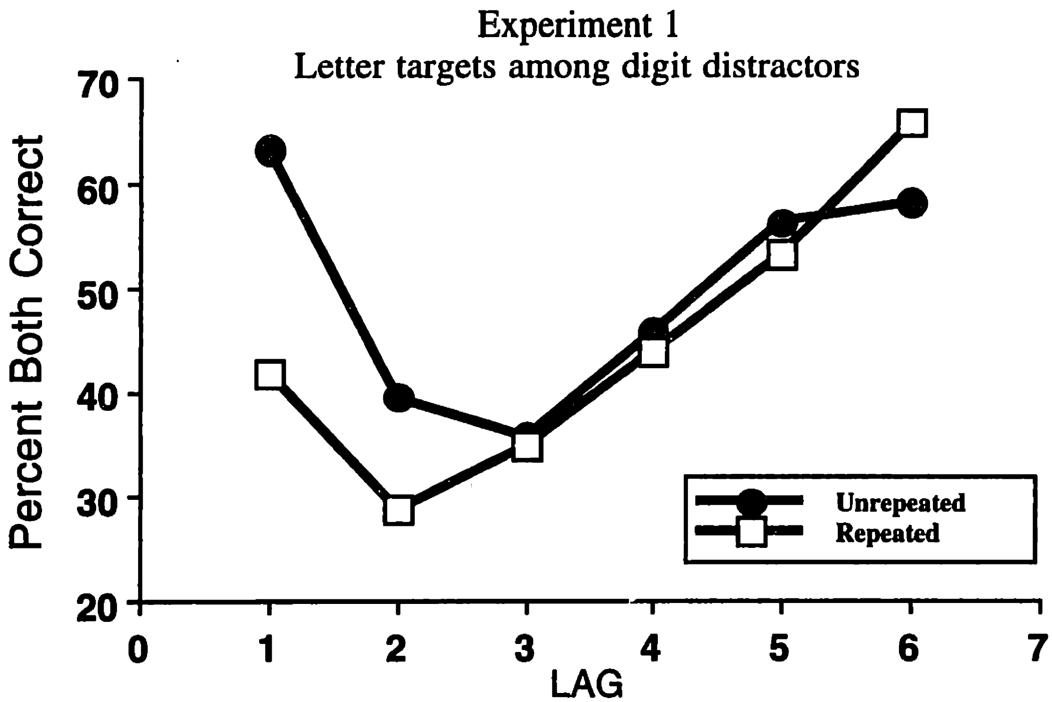


Figure 1. Percentage of trials on which both targets were correctly reported as a function of lag in Experiment 1, for repeated and unrepeated targets. Letter targets were presented among digit distractors.

Figure 1 shows, for each lag, the proportion of trials on which both T1 and T2 were correctly reported. There was a main effect of lag, $\underline{F}(5,35)=7.63$, $\underline{p}<.001$. The difference between unrepeated and repeated targets, compiled across all lags, was not significant, $\underline{p}>.29$, but the interaction between Target Repetition and Lag was significant, $\underline{F}(5,35)=2.65$, $\underline{p}<.05$. As Figure 1 shows, RB was maximum at lag 1, paired $\underline{t}(7)=2.62$, $\underline{p}<.05$ (one-tailed), present at lag 2, paired $\underline{t}(7)=1.92$, $\underline{p}<.05$ (one-tailed), but absent at all longer lags, indicating that unrepeated and repeated targets were differentially affected by lag. The effect of Lettercase was also significant, $\underline{F}(1,7)=15.81$, $\underline{p}<.01$. Though not shown in Figure 1, the probability of reporting both targets was higher for uppercase T1-lowercase T2 target combinations (m=50.7%) than for lowercase T1 -

uppercase T2 trials (43.6%). Lettercase did not interact with any other variables.

In sum, both an attentional blink for unrepeated targets and repetition blindness for repeated targets was obtained in our simple dual target search task. Performance for unrepeated targets showed a standard AB lag effect : the performance on reporting both T1 and T2 was lowest at lags 2 and 3, gradually recovering as a function of increasing lag. As shown in previous AB studies, performance for targets appearing temporally adjacent to each other (lag 1) was relatively high. Performance for reporting two repeated targets was lower than that for unrepeated targets at lags 1-2. This difference represents the standard RB lag effect, where the magnitude of the repeated target deficit decreases with increasing lag (Kanwisher, 1987; Park & Kanwisher, 1994). However, repeated items have not been previously tested at lag 1. RB typically extended to lags 4 or 5 in previous studies (Kanwisher, 1987; Park & Kanwisher, 1994). RB seems to have disappeared by lag 3 in the current experiment; this may be because the target letters always differed in lettercase, and subjects were required to attend to lettercase. Bavelier (1994) has shown that RB is reduced when subjects must encode a feature that differentiates the nominally identical items. Nevertheless, the results replicate previous findings that RB can occur at a processing level abstracted beyond the actual physical orthography (Bavelier & Potter, 1992; Kanwisher & Potter, 1990).

Of main interest here are the apparent differences in the time course of AB and RB, as shown in Figure 1, and also indicated in the significant interaction between Repetition and Lag. Two unrepeated targets are most difficult to report when separated by one or two intervening items (SOA=200-300ms) and performance gradually improves but does not seem to asymptote until lag 5. In contrast, RB is maximal for temporally adjacent items, but seems to recover within 300ms. Therefore, while the AB effect shows a U-shaped function of lag, RB (as measured by the difference between unrepeated and repeated target performance) follows a more linear trend. Note that the maximal RB effect at lag 1 cannot be due to temporal summation of the two target stimuli which would affect nominally different letters as well as the same letter appearing in different lettercases.

This difference in time course suggests that the two deficits are caused by different limited-capacity mechanisms. In the current experiment RB diminished by lag 3, while AB lasted up to lag 5. Such a dissociation in time courses would be inconsistent with a model describing both deficits in terms a single general attentional limitation for processing targets in RSVP. However, the results do not uniquely support a token individuation account for RB, nor do they provide unequivocal evidence for a dissociation between AB and RB. The following three experiments examine whether the two deficits are dissociable from each other in other conditions.

Experiment 2

The previous experiment directly compared the attentional blink and repetition blindness as a function of lag. The significant differences in time course already provides some evidence that the two deficits may be caused by different mechanisms. In the next two experiments, we provide a stronger case for a functional dissociation between AB and RB. If AB and RB are caused by different mechanisms, then one should be able to demonstrate the occurrence of one deficit without the other. Chun and Potter (in press) have previously shown that the AB lag effect is essentially eliminated when the letter targets are presented among highly discriminable distractors such as keyboard symbols. Target-distractor discriminability is a strong factor in target object recognition (Duncan & Humphreys, 1989), and thus it is not surprising that target report is facilitated when both targets are presented among highly discriminable distractors. However, if the deficit for repeated targets is caused by an independent process, RB might still be present under these conditions.

In Experiment 2, we explore the effect of target-distractor discriminability, comparing performance for unrepeated and repeated targets over temporal lags 1-6 (100ms - 600ms).

Method

The method was like that of Experiment 1, except as specified.

Subjects. Eight subjects from the MIT subject pool were tested in this experiment.

Design and Procedure. The stimulus files used in Experiment 1 were used in this experiment, except that the digit distractors were replaced with 8 different keyboard symbol distractors (<, >, =, #, %, ?, /, *).

Results and Discussion

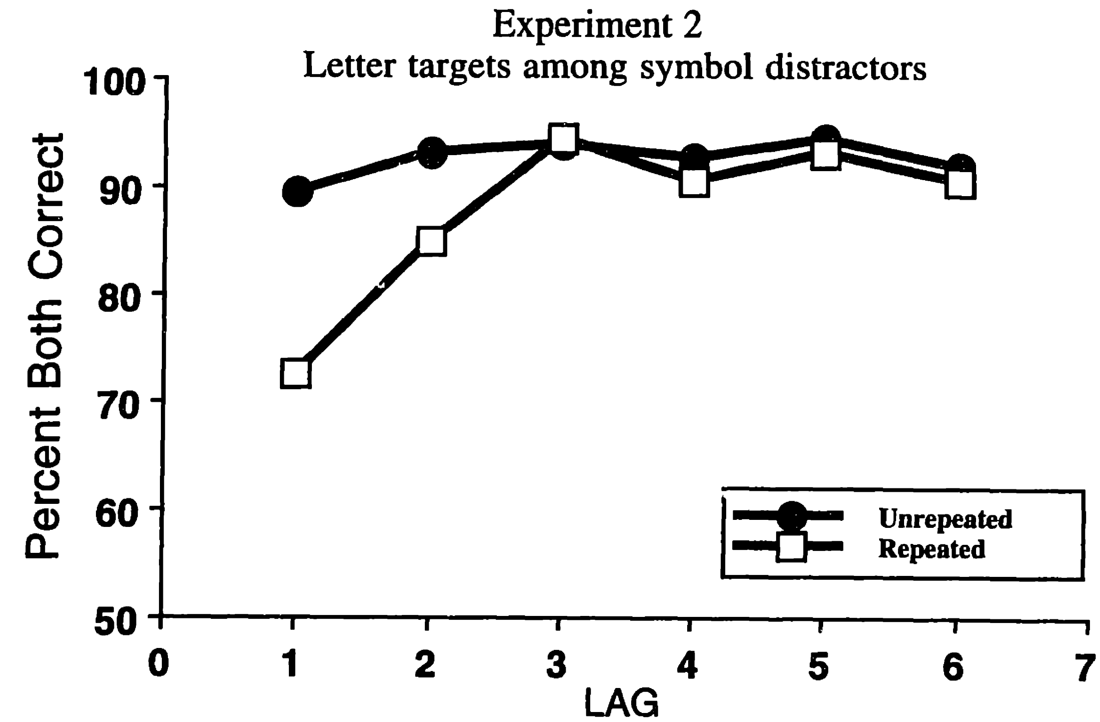


Figure 2. Percent both correct as a function of lag for unrepeated and repeated letter targets presented among highly discriminable letter distractors in Experiment 2.

Figure 2 shows, for each lag, the proportion of trials on which both T1 and T2 were correctly reported. The difference between unrepeated and repeated targets was significant, $F(1,7)=25.90$, $p<.01$, and there was a main effect of lag, $F(5,35)=4.74$, $p<.01$. As in the previous experiment with digit distractors, the interaction between Target Repetition and Lag was significant, $F(5,35)=4.50$, $p<.01$. Separate paired t-test analyses show that the RB effect was significant for lag 1, $t(7)=3.26$, $p<.01$ (one-tailed), and lag 2, $t(7)=3.27$, $p<.01$ (one-tailed). Unlike the previous experiment, there was no main effect of Lettercase ($p>.45$). A separate analysis of variance for unrepeated target trials alone indicate no main effect of lag, ($p>.76$), confirming the absence of an AB effect in the current experiment.

As predicted, increasing target-distractor discriminability eliminated the deficit for unrepeated targets while an RB effect remained. The magnitude and time course of RB was similar in Experiments 1 and 2. A separate analysis comparing the RB effect (difference between unrepeated and repeated target performance at each lag) obtained in Experiments 1 and 2 revealed no main effect of distractor type ($p>.96$), as is evident in a comparison between Figures 1 and 2. This strong dissociation between AB and RB strongly indicates that RB is caused by a different mechanism. By demonstrating RB in a dual-target AB paradigm and additionally showing RB for lag 1, the results complement and extend what has been shown in previous repetition blindness studies, in which subjects have typically reported all the stimuli, or have been given lists of at least three relevant items intermixed with highly discriminable distractors.

Experiment 3

In Experiment 2, repetition blindness was demonstrated under conditions where the attentional blink does not occur. While target-distractor discriminability allowed for unrepeated targets to be detected equally well at all temporal lags, the deficit for repeated targets persisted. The obtained dissociation between repetition blindness and the attentional blink provides further evidence for the idea that the two deficits are independent.

A stronger case can be made if the converse dissociation could be obtained. In the current experiment, we investigate whether the attentional blink could be shown *without* additional repetition blindness. According to the token individuation hypothesis, repetition blindness represents an additional difficulty in constructing a separate token for a repeated type. In other words, the conscious percept of T2 becomes assimilated into that of T1. We hypothesized that making the episodic distinction between T1 and T2 more salient would facilitate token individuation for T2, thus reducing or eliminating repetition blindness.

In the current experiment, we presented T1 and T2 in different colors (red and green) among black letter distractors. Subjects were simply required to report the two colored letters. These color cues were perceptually distinct from each other and from the distractor items, allowing the subject to easily determine that two target events had occurred. However, the color cue itself provides no information about the *identity* of the two targets to be reported. Thus while token individuation is facilitated by the two perceptually distinct visual events (colored letters), color would not enhance letter identification of the targets to be reported. In sum, we predicted that an attentional blink would be obtained, but repetition blindness would be reduced or eliminated.

Method

Subjects. 18 subjects from the MIT subject pool participated in Experiment 3. Because we were testing the null hypothesis (that there would be little or no RB), a larger number of subjects was tested in this experiment.

Materials and Design. The stimuli were uppercase and lowercase versions of 21 letters excluding I, L, O, U, and V, as in the previous two experiments. Each experimental trial consisted of 14 letters each of which could appear in either uppercase or lowercase with equal probability. As in the previous two experiments, three factors were tested in a factorial design : target repetition, target lettercase, and temporal lag. Two of the letters were designated as targets. T1 and T2 were unrepeated (different types) on half of the trials and repeated on the other half. The two letter targets always differed in lettercase (Uppercase T1 -Lowercase T2, Lowercase T1-Uppercase T2). 7 lags (lag 1 to lag 7) between T1 and T2 were varied. The position of T1 was varied randomly over serial positions 3, 4, and 5. The color of the two targets (red-green or green-red) was set randomly in each trial.

Ten trials per experimental condition were tested for a total of 280 trials. No filler trials were included. The order of the experimental trials was randomized independently for each subject.

Procedure. Each trial began with a plus sign appearing for 450ms at the center of the monitor screen for fixation. 105ms after the fixation cross went off, the stream of stimuli appeared successively without interstimulus blanks at the same location for 105ms each. The sequence was followed by a "&" mask for 105ms, signaling the end of the trial. Subjects typed their responses into the keyboard, pressing the space bar for any targets that they had missed. Unlike the previous experiments, subjects were not required to type their responses in the lettercase that they had seen the target appear. As before, they were explicitly informed that many trials would have repeated targets, and that they should make two keypresses for a repeated letter. Each keypress was flashed on the screen, but trial feedback was otherwise not given. After the subject made two keypresses, the computer initiated the next trial after a pause of 5 seconds. Breaks were given every 25 trials and the entire procedure lasted about 1 hour. The experiment was preceded with a practice block of twenty trials. The experiment was carried out in normal room illumination held constant for all subjects.

Apparatus. Experiment 3 was run on a Mac II computer with an AppleColor High Resolution RGB monitor. The software used for running the experiments was MacProbe version 1.5.0 developed by Aristometric Computers. The experiment was carried out in normal room illumination. The letter stimuli were presented in point 14 bold Monaco font.

Results and Discussion

A note on scoring. Observers made a small number of repetition intrusions in the current experiment. A repetition intrusion trial occurs when a repeated target response was made on an unrepeated target trial (e.g. reporting "M", "M" for targets "M" "C". Such guessing strategies would reduce RB since these repetition intrusions would be correct for repeated target trials. Although the proportion of this type of response was small, (1.98% of all trials, 5.41% of all guessing errors), any such biases would favor the null hypothesis. To counter this, we applied a conservative guessing correction.

Guessing corrections for each subject were made separately for each lag and each lettercase combination. We computed guessing biases as follows. For unrepeated trials on which one of the two targets was misreported and the other was correct, the proportion that were repetitions (e.g., "M", "M" reported when "M", "C" had been presented) is an estimate of the propensity to guess repetitions. For repeated trials, the number of intrusions of an unrepeated letter (e.g., "M", "C" when "M", "M" had been presented) was multiplied by the number of unrepeated trial repetition guess divided by the number of unrepeated trial non-repetition guesses, to obtain an estimate of repetition guesses. this number was subtracted from the "correct" repetition reports in that condition, to obtain the corrected estimate.

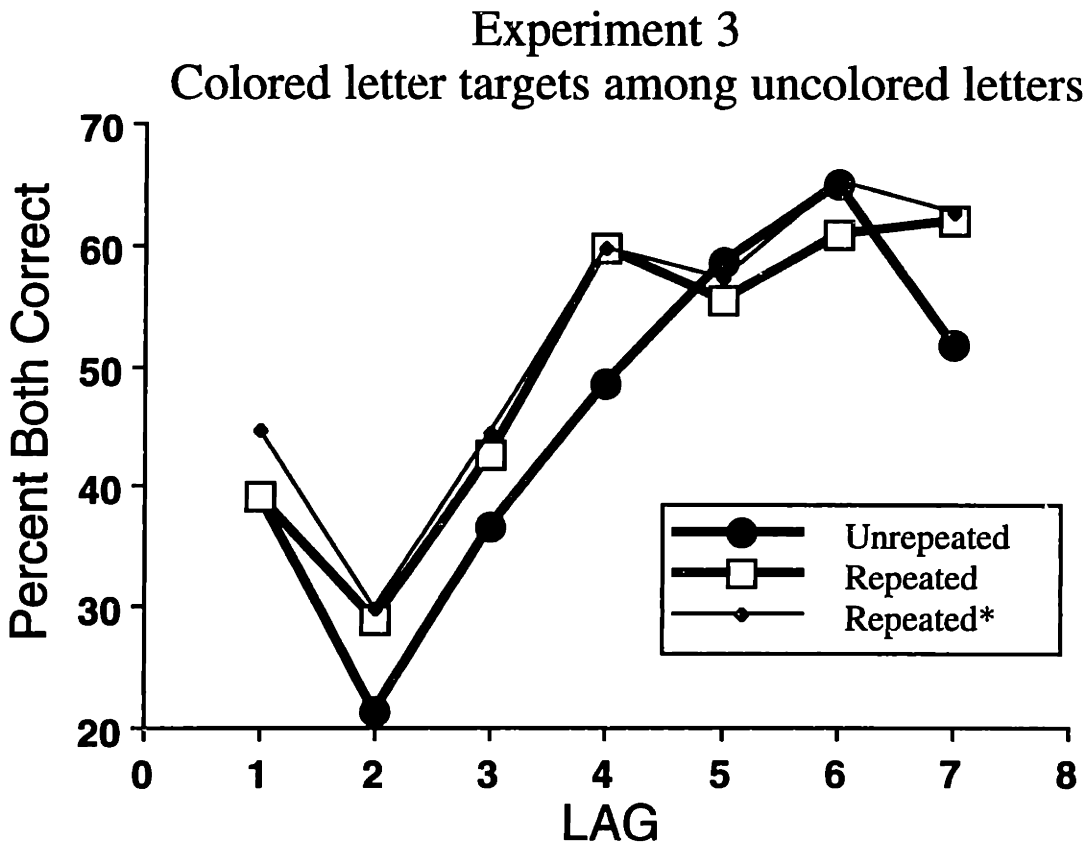


Figure 3. Percent both correct as a function of lag for unrepeated and repeated letter targets presented among letter distractors : Experiment 3. The target letters were colored red and green or vice versa, and the distractor letters were appeared in black. The dotted line (Repeated*) corresponds to the uncorrected raw data for unrepeated trials.

The results of this experiment for unrepeated and repeated target trials with and without guessing corrections is shown in Figure 3. All ANOVA tests were performed on the corrected data. There was a main effect of Lag, $\underline{F}(6,102)=33.59$, $\underline{p}<.001$, confirming the strong lag dependency in performance present in the data. However, even after conservative guessing corrections, no hint of RB was found: instead, there was a suggestion of positive repetition priming that approached significance, $\underline{F}(1,17)=3.15$, $\underline{p}<.10$, suggesting that repetition priming occurred. The interaction between target repetition and lag was significant, $F(6,102)=2.57$, $p<.05$.

The results clearly indicate a dissociation between AB and RB, that is the reverse of that obtained in Experiment 2. We confirmed the prediction that adding episodic information that distinguishes the two target events may eliminate RB even under conditions where AB occurs. Because the episodic cue (color) employed here provided no information about the actual identity of the target, a strong AB effect was obtained. Extracting the type information (the shape of the colored letter) remained difficult because the distractors were also letters, whereas token information — the fact that two targets had been presented — was enhanced by the independent color cues.

Ward, Duncan and Shapiro (1992) also presented results which indicated that when only two targets, each followed by a mask, were presented, RB was eliminated. Each trial consisted of only two discrete events (as opposed to a continuous stream of stimuli in RSVP tasks), and presumably the salient episodic division between the two items allowed for token individuation in their task also. A previous attempt by Park and Kanwisher (1994, Experiment 3), to test the hypothesis that enhancing the episodic division between T1 and T2 would reduce RB was unsuccessful. Significant RB was found even when a perceptible blank interval was introduced between T1 and T2. A possible explanation for the lack of an effect of the blank intervals on RB is that, unlike the color cue in the present task, blank intervals within the RSVP stream were irrelevant in episodically defining the critical target events per se.

Although the absence of RB in the current experiment is consistent with the token individuation hypothesis for RB, the results are at odds with a similar experiment reported earlier by Kanwisher (1991, Experiment 6). In her experiment, subjects were asked to report three colored letters appearing among white letter distractors. Either two of the colored targets could be repeated, or T2 was a repetition of a previous (uncolored) distractor. RB was found when the colored targets were repeated, but not if repetition occurred between a target and a distractor. These results confirmed that targets needed to be attended to in order to produce RB but are inconsistent with the current experiment. A number of differences between the two experiments might have accounted for the difference in results. We explored most of the factors in a series of unpublished experiments (Chun & Potter, 1993b). Neither the use of white rather than black distractors, nor an increase from two to three targets changed the present no-RB result. We finally explored the possibility that it may take some practice before the color cues begin to help in individuating target events. Kanwisher had 30 subjects who each saw 36 lists after 4 practice trials. We had 18 subjects who each saw 280 trials after 20 practice trials. In a posthoc analysis, RB was indeed found in the first block of trials, but diminished with further practice. The analysis was suggestive but not definitive because the trials had not been counterbalanced within blocks.

Even so, during an hour long session subjects apparently learned to use the color cue to distinguish the two events episodically. This practice effect is compatible with our hypothesis. Critically, no such practice effect was found in Experiments 1 and 2: *RB does not routinely diminish with practice.* Nevertheless, because of various procedural differences between Experiments 1, 2 and 3, and because we did not systematically block trials (all trials were fully shuffled, randomly intermixed), we decided it would be useful to replicate all of the previous results more systematically in a new experiment.

Experiment 4

The main purpose of Experiment 4 was to further replicate and generalize the findings obtained in the previous three experiments. First, to confirm the post hoc analysis of block effects described in the previous experiment, we ran two groups of subjects. Experiment 4a replicated Experiments 1 and 2: in one half, subjects had digit distractors and in the other half, symbol distractors. Colored targets were presented in Experiment 4b replicating Experiment 3: in one half, the distractors were letters, and in the other digits. In both 4a and 4b, the proportion of unrepeated and repeated targets was fixed within each block, and the procedure, apparatus, and design of the experiments were the the same except for the types of distractors and the presence or absence of color cues. Only uppercase targets were used, and lag 1 was not tested for repeated targets.

The overall level of performance for detecting targets in Experiment 3 was lower than in Experiments 1 and 2, raising the question whether RB was reduced by a floor effect. In Experiment 4b (with colored targets), we used digit distractors as well as letter distractors, on the assumption that digit distractors would make the task easier.

Experiment 4a

Method

Subjects. Twelve subjects from the MIT subject pool were tested.

Materials and Design. Each subject was run in two distractor-type conditions, digits and keyboard symbols. Five consecutive blocks of trials were run in each distractor condition for a total of 10 blocks per session. The order of distractor type was counterbalanced between subjects. Thus, Experiment 4a was a combination of Experiments 1 and 2 tested within subjects across halves. Subjects searched for letter targets appearing among distractors and all stimuli were colored white. Only uppercase letter targets were used: I, O, W, and Q were excluded from the stimulus set. The symbol distractor set included items <, >, Δ, /, +, ? =, and ≈. The digit distractor set included all digits excluding 0 and 1. Each experimental trial consisted of 12 items. As in the previous experiments, repetition and lag were the main variables tested within each distractor-type condition. The serial position of T1 was varied between 3-5. In each block of 36 trials there were 3 trials each (one for each T1 serial position) of unrepeated and repeated targets at each of five lags 2-6, 3 trials of unrepeated targets at lag 1 (a repetition of an identical uppercase letter at lag 1 would be equivalent to one letter presented for double the time), and 3 trials where only one target was presented.

Procedure. Each trial began with a '•' sign appearing for 300ms at the center of the monitor screen for fixation. 300ms after the fixation cross went off, the stream of stimuli appeared successively without interstimulus blanks at the same location for 105ms each. The sequence was followed by a "&" mask for 105ms, signaling the end of the trial. Subjects then reported the targets by typing them into the keyboard, as in Experiment 3, pressing the space bar for any targets missed. Breaks were given every 36 trials, at the end of each block. At the beginning of each distractor condition of 5 blocks, instructions were flashed on the screen instructing subjects which distractor set would appear. A single practice block of 5 trials (with digit distractors) preceded the entire experiment to familiarize subjects with the procedure. In all other respects, the procedure was identical to that of Experiment 3.

Apparatus.. The same experimental setup was identical to that used in Experiment 3.

Results of Experiment 4a

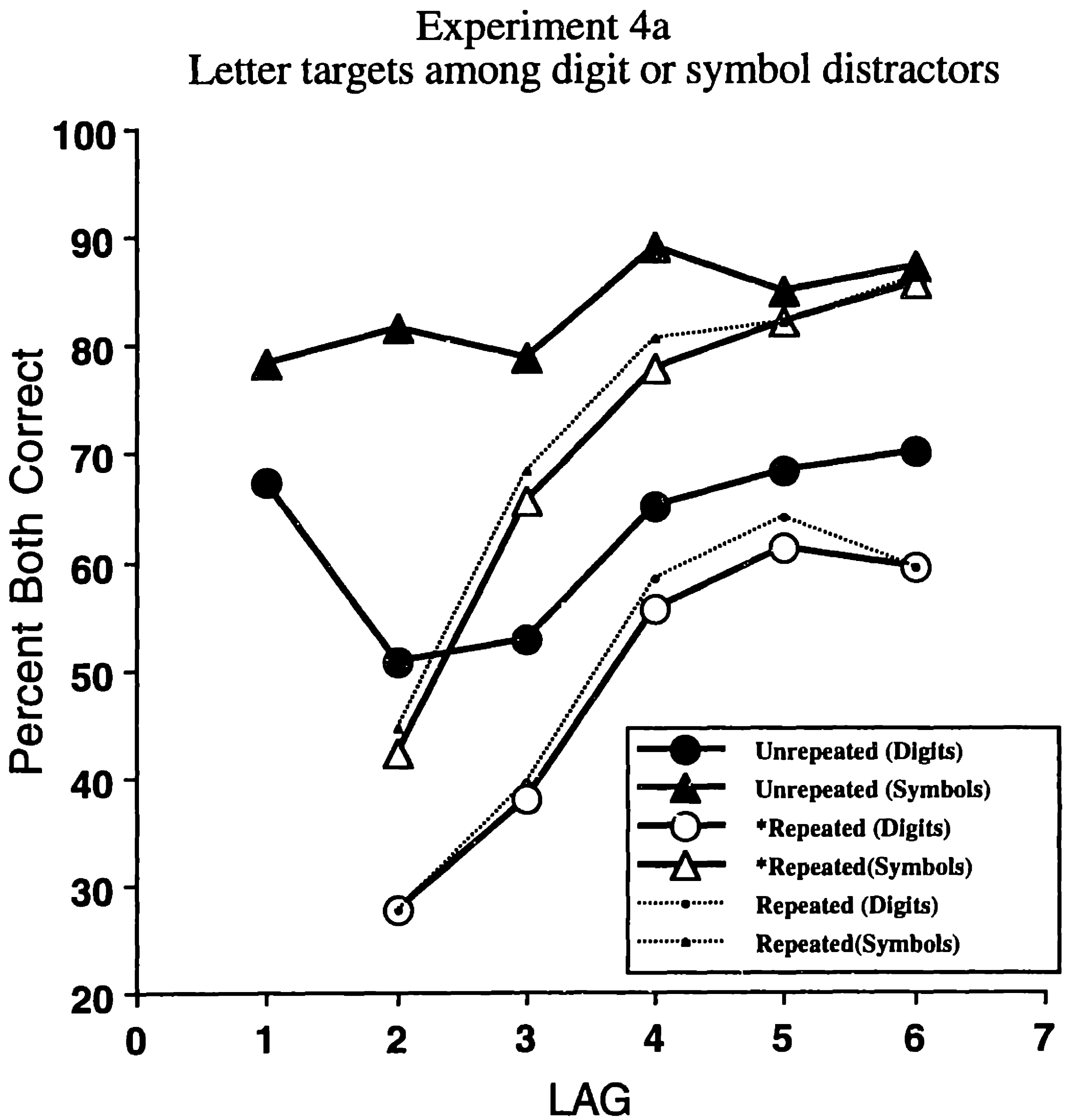


Figure 4. Percent both correct as a function of lag for unrepeated and repeated letter targets presented among either symbol distractors or digit distractors across blocks : Experiment 4a. Dashed lines (Repeated) correspond to the uncorrected data for the repeated target conditions.

The average data compiled across all blocks for each condition as a function of lag is shown in Figure 4. For the ANOVA, we compared performance for just lags 2-6. There were main effects of target repetition,

$\underline{F}(1,11)=37.19$, $\underline{p}<.001$, distractor type, $\underline{F}(1,11)=58.21$, $\underline{p}<.001$, and lag, $\underline{F}(4,44)=20.28$, $\underline{p}<.001$, as well as a significant two-way interaction between repetition and lag, $\underline{F}(4,44)=10.14$, $\underline{p}<.001$. The results replicate those from Experiments 1 and 2. There was a significant RB effect for repeated targets appearing among either discriminable (symbols) or less discriminable (digit) distractors.

The unrepeated target trials were analyzed separately including lag 1. There was a main effect of lag for unrepeated targets in the Symbol distractor condition, $\underline{F}(5,55)=3.39$, $\underline{p}<.01$. Inspection of Figure 4 shows that there was slightly depressed performance at lags 1-3. Note, however, the lack of benefit at lag 1, unlike the standard AB pattern seen in the unrepeated digits condition. There was a significant interaction between distractor-type and lag, $\underline{F}(5,55)=2.54$, $\underline{p}<.05$.

To examine the effects of practice (block) on target report for unrepeated and repeated targets, we averaged performance across lags 2-6 and plotted these as a function of block. This is shown in Figure 5. There was a main effect of block, $\underline{F}(4,44)=5.15$, $\underline{p}<.01$, suggesting that performance improved with practice. Block interacted with target repetition, $\underline{F}(4,44)=3.96$, $\underline{p}<.01$, but there seemed to be no systematic pattern. In particular, the RB effect was still strongly present in the last block, $\underline{F}(1,11)=87.84$, $\underline{p}<.001$, as is apparent in Figure 5.

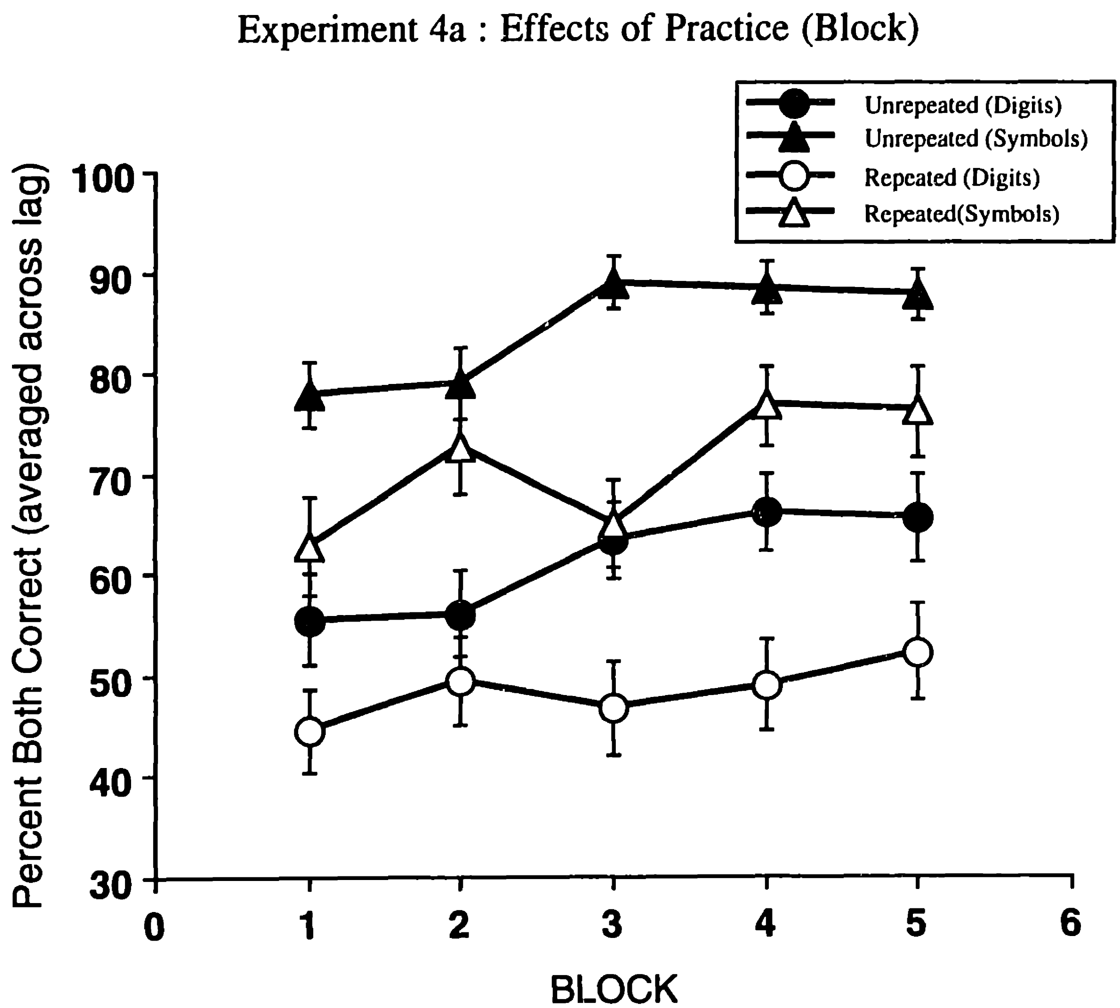


Figure 5. Percent both correct averaged across lags 2-6 shown as a function of block for each distractor condition: Experiment 4a

Experiment 4b

Method

Twelve subjects from the MIT subject pool were tested in Experiment 4b. Except where noted, the design and procedure of Experiment 4b was identical to that of Experiment 4a. In Experiment 4b, the subject's task was to report the colored letter targets (one or two) appearing among digit distractors (one half) or letter distractors (the other half). As before, the order of halves was counterbalanced across subjects.

Results of Experiment 4b

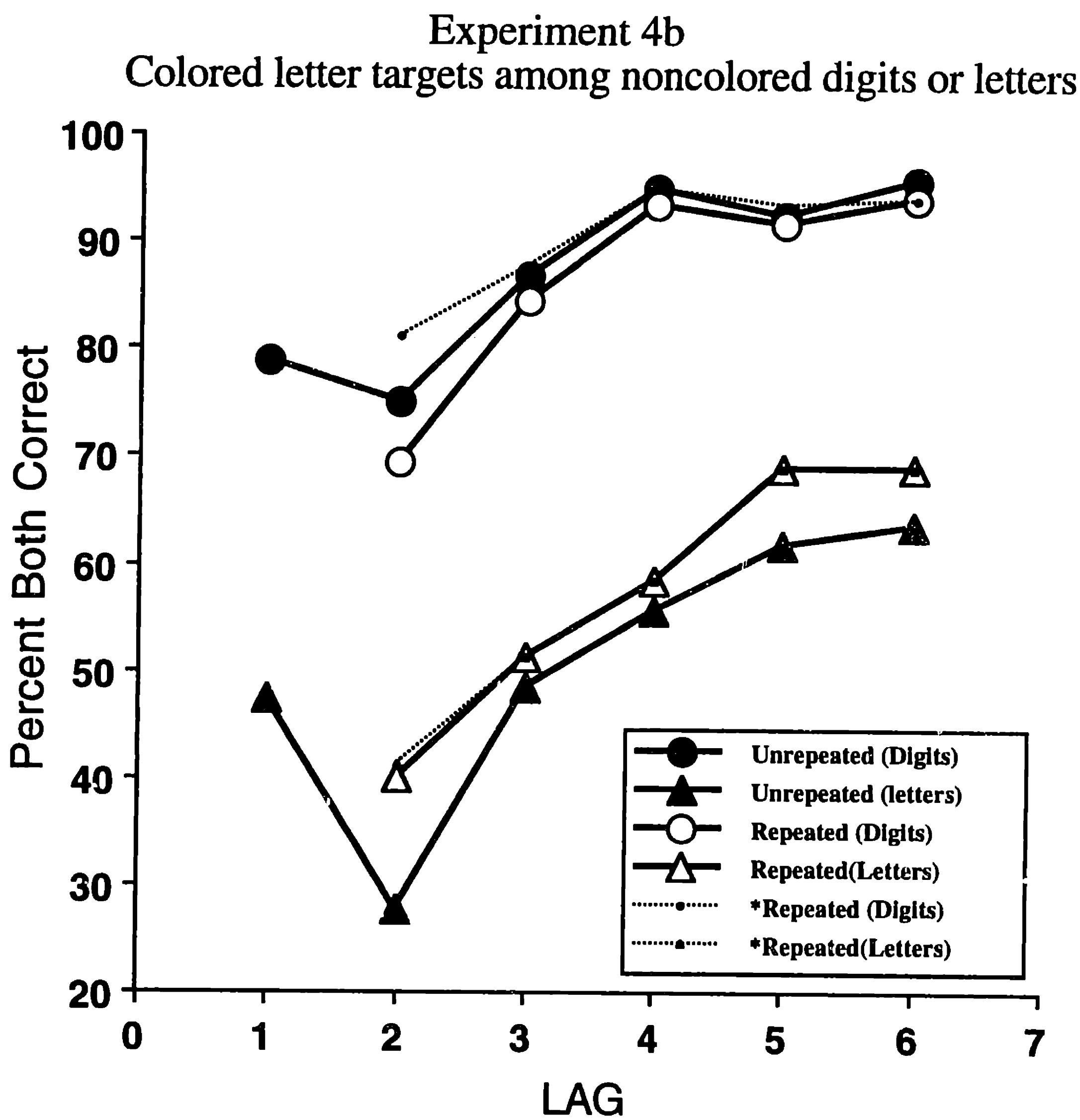


Figure 6. Percent both correct for unrepeated and repeated letter targets presented among either digit distractors or letter distractors across blocks : Experiment 4b. Targets were differently colored letters (red or green) among black distractors. Dashed lines (*Repeated) correspond to the uncorrected data for the repeated target conditions.

The figure and statistical analyses were based on data which were corrected for possible guessing biases that might have reduced RB (see Experiment 3). The results of Experiment 4b are shown in Figure 6. There was no main effect of target repetition, $p>.22$, replicating Experiment 3. There were main effects of distractor type, $F(1,11)=66.58$, $p<.001$, and lag, $F(4,44)=33.31$, $p<.001$. Distractor type interacted with repetition, $F(1,11)=5.47$, $p<.05$, and with lag, $F(4,44)=3.55$, $p<.05$. Although there appears to be an RB effect at lag 2 in the digit distractor condition, this difference was not statistically significant, $p>.26$.

Separate analyses were carried out for each distractor condition. For targets presented among digit distractors, there was a main effect of lag, $F(4,44)=20.38$, $p<.001$, but no main effect of target repetition ($p>.33$), nor an interaction between repetition and lag ($p>.89$). In the letter distractor condition, there was a main effect of lag, $F(4,44)=24.57$, $p<.001$, and also a main effect of repetition, $F(1,11)=6.99$, $p<.05$, suggesting repetition priming had occurred. The interaction between repetition and lag was not significant ($p>.60$).

Another interesting aspect of the data is that the redundant color cue in the digit distractor condition improved the overall level of performance in comparison to the digit distractor condition of Experiment 4a without color cues. The independent color cue not only eliminated RB, but also seems to have enhanced target report performance of the unrepeated letter targets. A significant AB effect persisted due to target-distractor discriminability, but comparison of Experiments 4a and 4b suggests that part of the AB effect may reflect difficulty in tokenization and consolidation of target items which is alleviated with additional episodic cues.

Experiment 4b
Effects of Practice (First Blocks)

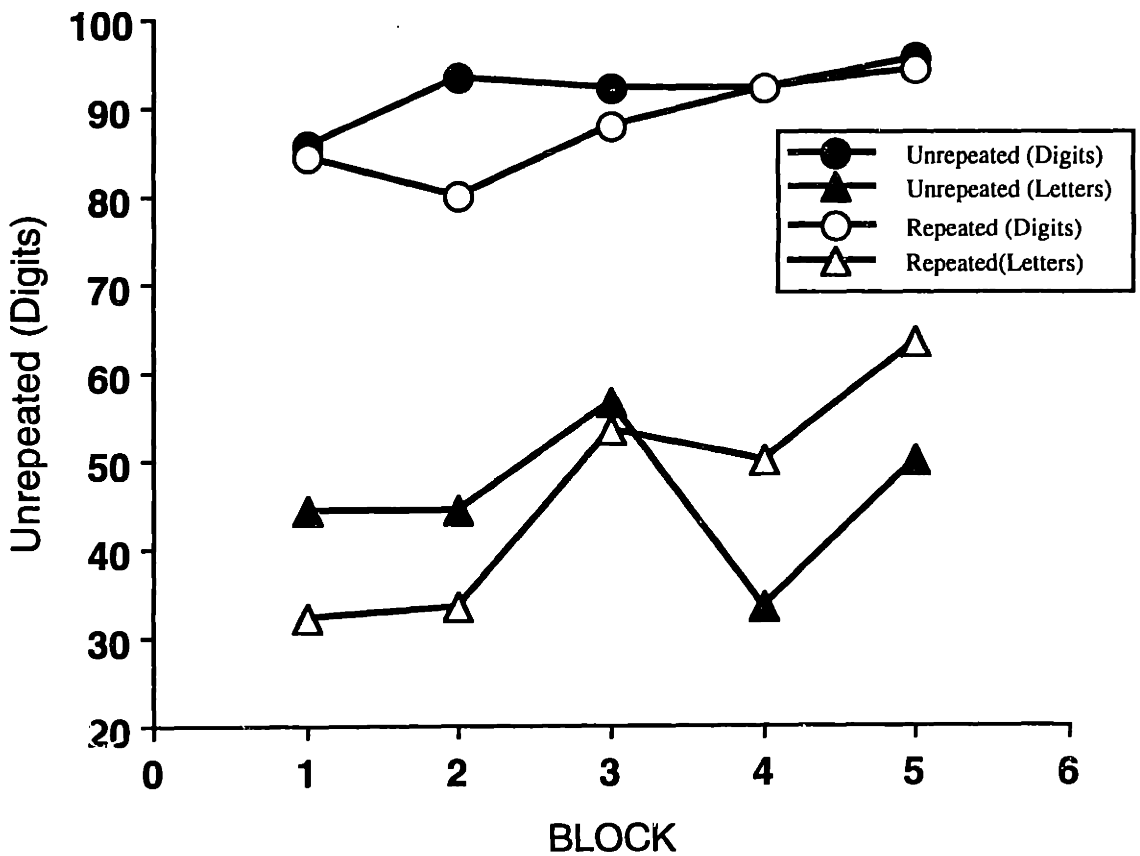


Figure 7. Percent both correct averaged across lags 2-6 shown as a function of block for each distractor condition: Experiment 4b

As in Experiment 4a, we averaged performance across all lags 2-6, and plotted this as a function of block, for the first half only. This made distractor type a between-subjects variable. The prediction here was that even though RB was not present in the average data compiled across the entire session, RB might be found in the earlier blocks before subjects learn to use the color cue to distinguish the two target events episodically. This analysis is shown in

Figure 7. While there was a hint of an RB effect for the first two blocks of a session, this difference diminished by the third and fourth blocks. In the letter distractor condition there was a shift from a repetition deficit (RB) in blocks 1 and 2 to a repetition benefit in blocks 4 and 5.

Discussion of Experiments 4a and 4b

The pattern of results replicates Experiments 1, 2 and 3. Experiment 4a shows that when targets are categorically defined and in the absence of additional episodic cues defining the targets, a robust RB effect was produced in both symbol and digit distractor conditions. Moreover, this RB effect persisted throughout the session, as indicated by the block analysis. When additional episodic cues (color) were provided in Experiment 4b, the RB effect disappeared. A block analysis of Experiment 4b revealed that RB was present in the first two blocks of trials in a session, but that subjects appeared to be learn to utilize the episodic cue to help individuate the target items, resulting in an overall null RB effect, or even slight positive priming. This finding explains the difference in results between our experiments and a previously reported experiment (Kanwisher, 1991, Experiment 6), and shows that episodic cues defining target events can be used under certain conditions to overcome RB. It is especially important to note that practice per se does not eliminate RB, because subjects in Experiments 4a and 4b had the same number of trials. Guessing strategies cannot explain the lack of RB in Experiments 3 and 4b, because the proportion of repetition intrusions was low, conservative guessing corrections were employed, and also because in all other respects the design, procedure, and the proportion of repeated vs. unrepeated target trials were identical for Experiments 4a and 4b. In sum, the hypothesis that color cues aid token individuation of repeated target items provides the most parsimonious explanation for the results.

General Discussion

The relationship between two deficits that occur for reporting targets presented in rapid serial visual presentation (RSVP) was examined in this study. In each experiment, subjects monitored an RSVP stream and were required to report two letter targets embedded among distractors. The two targets (T1, T2) were either unrepeated or repeated and the lag between T1 and T2 was varied systematically. When distractors (digits or other letters) were similar to the letter targets , correct identification of T1 produced a deficit for T2 appearing within 500 msec, the attentional blink. When T1 and T2 were two different types (the unrepeated target condition), performance was a U-shaped function of lag characteristic of the attentional blink. When T1 and T2 were of identical letter types, an additional deficit was obtained when T2 appeared within 300 msec (repetition blindness). When additional episodically distinct cues (colors) were used to define the targets, the RB deficit was eliminated.

In Experiment 1, subjects were asked to report one or two letter targets presented at various lags among digit distractors. Both a deficit for unrepeated targets (the attentional blink deficit, AB) and an additional deficit for repeated targets (repetition blindness, RB) was obtained. An AB deficit was found for unrepeated targets (lags 2-5) and an additional RB effect for repeated targets (lags 1-2) for AB and RB. The time course differences suggested that the two deficits are caused by independent processes. Further evidence for a dissociation between AB and RB was provided in the following three experiments. In Experiment 2, RB was shown to occur under conditions where there was no AB. Letter targets were presented among keyboard symbol distractors. As had been previously shown (Chun & Potter, in press), AB did not occur when the targets were presented among highly discriminable symbol distractors. RB, however, was still obtained under these conditions. In Experiment 3, AB was shown to occur without RB. The two targets were colored letters, the distractors were black letters. It was hypothesized that the color cues defining targets would provide information about the presence of two episodic target events, even though they gave no information about the identity of the two targets. As predicted, this manipulation eliminated RB while AB persisted. In the final Experiment 4, we compared AB and RB within subjects. In Experiment 4a, we replicated the results of Experiments 1 and 2 within subjects, showing that RB occurs both with easy-to-discriminate (keyboard symbols) and hard-to-discriminate (digits) distractors, while AB only occurs in the hard-to-discriminate condition. In Experiment 4b, we showed that RB is absent (after practice) when an additional episodic cue (color) is present, both with difficult-to-discriminate distractors (replicating Experiment 3) and with easier-to-discriminate distractors.

In sum, the time course differences and the double dissociation obtained between the two deficits across experiments strongly suggest that AB and RB are caused by different mechanisms. In the following sections, we will discuss the implications of the obtained double dissociation between AB and RB.

Object token instantiation

Our argument is that AB may be construed as a difficulty for linking correctly identified type information to an episodic object token which would mediate conscious availability of that perceptual event. It is hypothesized that the efficacy of this "binding" problem is dependent on the discriminability of a target event from its distractors. The role of type recognition is to categorize an input with its functional "label" or propositional node in long-term memory. Categorization is affected by the discriminability of an item from other items. In search tasks, the discriminability of the designated target from distractors determines the speed and accuracy of target categorization. Thus, recognizing the letter T among L's may be less efficient than search for a red patch among blue patches of color, as has been confirmed in numerous studies (Duncan & Humphreys, 1989; Treisman, 1988; Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989) . As in visual search of an array of items spread across space, the ability to detect items presented sequentially over time in RSVP is highly dependent on the discriminability between the targets and distractors (Chun & Potter, in press). In Experiments 1, 2 and 4a it was easier to search for two letters appearing among keyboard symbols than among less discriminable digits.

At the high presentation rates used in RSVP tasks, processing of T1 may briefly tie up limited-capacity resources involved to instantiate a durable object token representation of a correctly detected type. This may be conceived as a bottleneck during which T2 will be missed. A model of how this may occur is discussed in more detail elsewhere (Chun & Potter, in press). In this model, the lesser deficit for T2 at lag 1 reflects the joint processing of T1 and the stimulus immediately following it, be it a distractor or T2.

This characterization of the AB deficit assumes that processing of the "blinked" items is occurring. We hypothesize that successful target processing entails stabilization of a correctly identified type into a more durable object token representation; thus, it can be conceptualized as a tokenization or binding problem. This view should thus be contrasted with early selection filtering views of visual processing which propose that no analysis of the "unattended" input occurs at all. We assume that even items subsequently unavailable for report will have received some initial processing, often to the level of their type, but that further consolidation (a capacity-requiring process) is needed for report. A more detailed account of this two-stage model of visual processing for target search in RSVP paradigms is provided in Chun and Potter (in press). In sum, the AB deficit represents a failure to produce a durable (and tokenized) representation of T2 that can be accessed in report.

While the visual discriminability between targets and distractors has the strongest effect on performance, it is interesting to note that the AB effect also occurs for word strings in which targets are defined by semantic category (Chun, Bromberg, & Potter, 1994). Performance was poorer in a condition in which the target and distractor categories were similar (e.g., birds among four-footed animals) than when they were not (e.g., birds among fruits). Here, visual discriminability was constant, yet stronger AB effects were shown for the more difficult categorization condition in which the conceptual similarity was higher. Therefore, both visual features and concept similarity of targets and distractors appear to play a role in AB. These findings are also consistent interactions between types and tokens, and to specify how object files guide visual processing, the evidence from previous work and the present study suggests that the type-token framework has already proved its usefulness.

Chapter 3

Illusory Conjunction Errors are Redistributed by the Attentional Blink

How are limited capacity resources allocated to visual stimuli as a function of time? A useful technique for investigating this issue is the rapid serial visual presentation (RSVP) paradigm in which a series of items is presented at high rates (8-12 items/sec) at a single spatial locus (typically, at fixation). For random lists of stimuli (e.g. letters, digits, words, etc.), this presentation rate quickly exceeds the cognitive system's ability to fully process each item such that only a few items are available for subsequent report. To a considerable extent, attentional mechanisms allow the observer to select relevant items (targets) for further processing and later report.

A main issue is to understand how independent visual attributes such as color and form are processed and subsequently integrated for selected items. This question has been explored using a task in which subjects are asked to report a single target appearing among distractors, in RSVP. The target is typically defined by an attribute (key feature, such as color or lettercase) which differentiates it from the distractors, and subjects report another independent attribute of the target (response feature, e.g. the letter identity of the target). In an early RSVP study, Lawrence (1971) has shown that subjects could report a single uppercase target word presented among lowercase distractor words with relatively high accuracy. The results indicate that while the rates of presentation used in RSVP are too rapid for full processing of all items presented, the visual system is able to utilize an independent feature cue such as lettercase to select a target for full processing.

Errors are of two types : subjects either miss the target or report the wrong item from the RSVP sequence. The latter error is referred to as an illusory conjunction error because the feature defining the target is conjoined with the to-be-reported feature of a distractor. It is the pattern of these illusory conjunction errors which is the main focus of the present study. These illusory conjunction errors have also been described as visual dissociations (Intraub, 1985), intrusion errors, or binding errors.

Before discussing previous results on illusory conjunctions in RSVP tasks, it will be useful to define some terminology adopted from Botella and Eriksen (1992). In a search for a colored target letter appearing among non-colored letter distractors, the color feature defining the target to be reported is the *key feature,* while the identity of the target to be reported at the end of the trial is the *response feature. Intrusion errors* occur when a non-target item which had appeared in the RSVP stream is incorrectly reported as the target. An item appearing after the target that is misreported as the target is a *post-target intrusion* while a *pre-target intrusion* is from an item appearing before the target in the RSVP sequence. Depending on the relative proportion of post-target or pre-target intrusions, the overall pattern of errors can be described as *post-pattern, pre-pattern,* or *symmetrical* pattern. For example, errors in Lawrence's (Lawrence, 1971) study were post-pattern because post-target intrusions were predominant.

Botella and Eriksen (1991) have shown that the pattern of intrusion errors shifts systematically as a function of presentation rate. Errors increased with increasing presentation rate. At durations of 100 or 116 ms/item a symmetrical pattern was obtained, with intrusion errors equally likely to occur from items appearing before the target and after the target. At shorter durations of 83 or 66 ms/item, a post-pattern of intrusions was obtained:

intrusions came predominantly from items appearing after the target. The pattern shift with increasing presentation rates suggests that increasing the difficulty of the task produces an increase in post-target intrusion errors.

The results can be understood by analogy to a batter trying to hit a pitched baseball. Timing of the swing is critical in hitting the ball correctly. If the batter times his or her swing according to the release of the baseball (corresponding to the cue) from the pitcher's hand, then the speed of the pitch will affect the direction to which the ball is batted. A ball batted into play can be considered a correct target response. As the speed of the ball increases, the ball will get pushed into the right foul area. This may correspond to a post-target intrusion. If the pitch is relatively slow, it will get pulled to the left foul area, corresponding to a pre-target intrusion. The Botella and Eriksen (1991) results indicate that increasing the presentation rates of items in RSVP may correspond to increasing the speed of a fastball pitch, resulting in a predominance of post-target intrusion errors, or balls fouled to the right.

Increasing presentation rate is a data-limiting manipulation. Could such pattern shifts in intrusion errors also be induced by a resource-limiting manipulation? That is, if intrusion errors reflect timing errors for integrating cue and response features, then one should also be able to demonstrate such effects by providing a competing load on limited-capacity resources available for target processing.

The purpose of the current study is to examine whether such pattern shifts in intrusion errors could be induced without changing the stimulus parameters of stimulus presentation, but rather by manipulation of attentional load. The hypothesis is that increasing attentional load should also produce a shift towards more proportionally more post-target intrusion errors.

Attentional load can be increased by asking subjects to report two targets rather than one. Previous studies have shown that when two targets are presented in RSVP, correct identification of the first target (T1) produces interference on a second target (T2) appearing within 200~500ms. This effect has been termed the "Attentional Blink" (AB) by Raymond, Shapiro, and Arnell (1992), and has been shown to occur across a variety of tasks and stimuli including uppercase words (Broadbent & Broadbent, 1987), sequences of digits (Weichselgartner & Sperling, 1987), letter detection (Raymond et al., 1992), and categorically defined targets (Chun & Potter, in press). In all of these AB studies, T2 report performance was poorest at lags 2~3 (SOA=200~300 ms), and improved systematically as the temporal separation between the two targets increased. When T2 immediately follows T1 (lag 1) there is little or no AB, and it is generally assumed that it represents a singularity where T1 and T2 are processed together (Chun and Potter, in press; Raymond et al., 1992; Weichselgartner & Sperling, 1987).

Thus the AB function (from lag 2 on) is a monotonic function of attentional load. The main purpose of the present study is to examine the effect of attentional load on intrusion error distributions. The prediction is that the proportion of intrusion errors should be greater during the AB interval and should show a shift in the pattern of errors. Subjects searched for one or two letter targets appearing in an RSVP stream of single letters. Each trial included two potential targets (T1 and T2) which were each defined by a colored (red or green) outline frame surrounding the letter: the non-target letters were surrounded with white outline frames. Subjects were tested in two conditions across blocks. Different task instructions were given in each, but the stimulus sequences were identical in the two conditions. In the single target control condition, subjects were asked to report only one target letter (which could be either T1 or T2) appearing with a prespecified color cue (e.g., report the letter which appeared with the red outline cue). In the dual target experimental condition, they were required to report both color-cued targets. The lag between T1 and T2 was systematically varied from 1 to 7 (SOA=120~840ms). Target report performance and the distribution of intrusion errors for T1 and T2 was compared between the two conditions.

As has been previously shown, performance for a single target appearing in RSVP is relatively unaffected by other events which are not attended to. This corresponds to the control condition, where performance on T1 or T2 was expected to be relatively unaffected by the temporal separation between the two. However, in dual target search tasks processing of T1 produces a lag-dependent interference on T2 performance. This AB effect can be taken as a measure of attentional load. Importantly, the AB effect diminishes as a function of increasing lag allowing one to examine the dynamical effects of attentional load on target report and especially the pattern of intrusion errors made. If pattern changes in intrusion error distributions reflect internal resource capacity limitations for processing and integrating visual attributes of a target, then such effects should also be found in the current task. The prediction is that the lags that produce the greatest AB will also produce the most asymmetric post-target pattern. The direction of this effect will be examined by comparing performance between the control condition and experimental condition for each lag, and also across different lags within the experimental condition.

Method

Subjects. Eighteen subjects participated in Experiment 1. The subjects were recruited from the Massachusetts Institute of Technology volunteer subject pool. All observers reported normal or corrected-to-normal visual acuity and normal color vision. Informed consent was obtained at the beginning of the session and subjects were paid for their participation. None of the subjects was aware of the purpose of the experiment.

Design. Each trial consisted of 17 letters, selected randomly and without repetition from a total set of 24 capital letters (excluding W and Q). Two of these letters were designated as targets. The serial position of T1 was randomly permuted so that it appeared an equal number of times in serial positions 3 to 6. Seven lags between T1 and T2, lag 1 (no intervening items, SOA=120ms) to lag 7 (SOA=840ms), were crossed with the four serial positions of T1. Each item in the RSVP stream appeared within an outline box (frame). This frame appeared together with the onset of each item and the frame duration was 30ms after which it went off. The color of the outline frame was white for all of the non-targets and was red and green for the two targets. The outline frame color was always different for the two targets, and the order of the colors was counterbalanced. T1 color was crossed with T1 serial position and T2 lag resulting in a total of 56 trials per block. This was replicated 3 times for a total of 168 trials in each condition. The order of the conditions was counterbalanced across subjects. In the single target (control) condition, subjects were instructed to report only the target which appeared in a designated target frame color. Half of the subjects were asked to report the target defined by the red colored frame, the other half reported targets appearing with the green cue. In the dual target (experimental) condition, subjects were required to report both color-cued targets. Note that only the task instructions differed between each condition; the stimulus sequences were identical (though randomized separately) in the two conditions.

Procedure. Each trial began with a "+" sign for fixation appearing for 360 ms at the center of the monitor screen. 360 ms after the fixation cross went off, the stream of letter stimuli appeared successively without interstimulus blanks at the same location for 120 ms each. The two color cues and white frames on distractors appeared for the first 30ms that each letter was displayed. The sequence was followed by a "&" mask for 120 ms, signaling the end of the trial. Subjects typed their responses on the keyboard, pressing the space bar for any targets which they missed. Each keypress response was flashed on the screen, but trial feedback was otherwise not given. After the subject made two keypresses, the computer initiated the next trial after a pause of 3 seconds. Computer initiated breaks were given every 56 trials and the entire procedure lasted about one hour. The experiment was preceded by a practice block of 10 trials for which subjects were instructed to try to report both targets. Instructions for the experiment were shown on the computer screen, on which subjects could read at their own pace. A summary of the instructions was also given by the experimenter, who remained in the room during the practice block to answer any questions about the procedure. The remainder of the experiment was self-paced.

Apparatus. Experiment 1 was run on a Macintosh II computer with an AppleColor High Resolution RGB monitor. The software used for designing and running the experiments was MacProbe v1.5.0 developed by Steven Hunt, Aristometric Computers. The experiment was carried out under dim illumination provided by a 15watt lamp facing the rear white wall behind the computer. The letter stimuli were presented in point 24 Geneva font.

Results

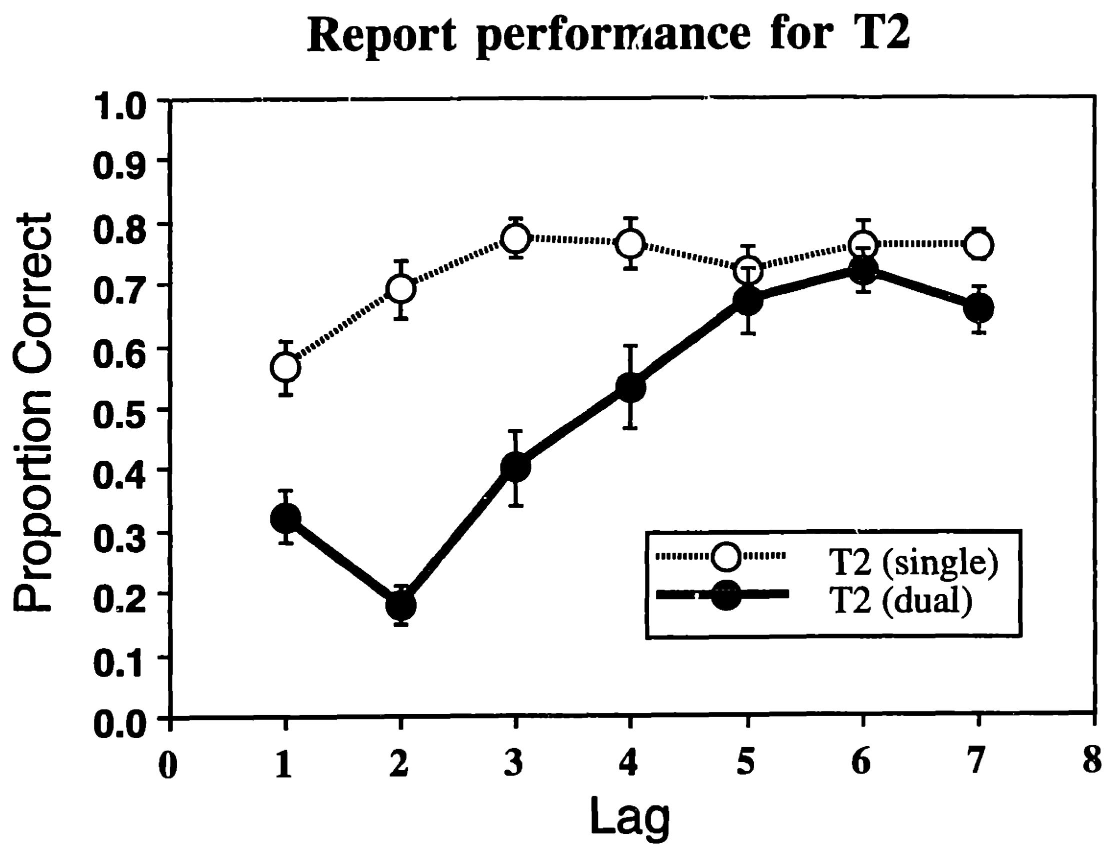


Figure 1. Percent correct for reporting T2 in the single target condition compared to T2 given T1 in the dual target condition, shown as a function of lag.

The AB effect (T2 report performance) A comparison of T2 report performance between the control and experimental conditions is shown in Figure 1. In the single target control condition, T2 corresponds to the half of all trials in which T2 had appeared in a given subject's target color. This was compared with the trials in the dual target condition in which T2 had appeared in the same target color. T2 performance was measured as the proportion of the trials in which T2 was correctly reported, given that T1 was correctly reported. As is apparent in Figure 1, there were main effects of condition, $\underline{F}(1,17)=86.70$, $\underline{p}<.001$, and lag, $\underline{F}(6,102)=24.00$, $\underline{p}<.001$, and a significant interaction between condition and lag, $\underline{F}(6,102)=12.37$, $\underline{p}<.001$. When subjects were required to report the identity of both targets, correct identification of T1 clearly interfered with T2 report. In the control condition in which subjects looked for a specified color cue, interference of the irrelevant T1 on report of the identity of T2 was much weaker, although there was a main effect of lag in a separate analysis of T2 report performance for the control condition, $\underline{F}(6,102)=5.35$, $\underline{p}<.001$. The large difference between the two conditions shows that processing the form of T1 impaired T2 report much more severely than T1 color cue discrimination did. This is the first study to generalize the AB effect to two targets defined by feature cues which were both spatially separate (outline frames) and dimension independent (color).

Table 1 shows the proportion of correct hits, intrusion errors from relative serial positions -3, -2, -1, +1, +2, and +3, and other misses ("random" guesses other than letters +/- 3 positions from the target, plus omissions) for each target in each condition at each lag. In an analysis of the number of T2 targets that were "other" misses, more were missed in the dual target condition than in the single target condition, $\underline{F}(1,17)=14.99$, $\underline{p}<.01$. There was a main effect of lag, $\underline{F}(6,102)=11.09$, $\underline{p}<.001$, and a significant interaction between condition and lag, $\underline{F}(6,102)=6.71$, $\underline{p}<.001$. A separate analysis of misses in the dual target condition revealed a significant main effect of lag, $\underline{F}(6,102)=10.57$, $\underline{p}<.001$, showing that the proportion of misses decreased with increasing lag, up to lag 4 or 5.

Table 1. Mean percent responses as a function of relative serial position for T1 and T2 in the Single Target Condition and Dual Target Condition over Lags 1 to 7 (Rounded to the nearest whole number).

	Relative Serial Position of the Letter Reported							Misses + Random
Lag	- 3	- 2	- 1	0	+ 1	+ 2	+3	Intrusions
			T1 : Single Target Condition					
Lag 1	2	0	13	68	7	1	0	8
Lag 2	0	0	13	78	3	2	0	3
Lag 3	0	0	15	72	6	0	1	5
Lag 4	0	1	11	77	5	0	1	5
Lag 5	0	0	13	74	7	0	0	6
Lag 6	0	1	11	75	4	2	0	7
Lag 7	0	1	13	75	6	0	0	5
			T1 : Dual Target Condition					
Lag 1	1	2	19	58	9	0	1	8
Lag 2	2	1	14	67	5	3	0	7
Lag 3	0	1	14	69	6	1	1	8
Lag 4	0	1	16	68	6	1	1	6
Lag 5	0	2	16	66	10	0	0	6
Lag 6	0	0	12	75	6	0	0	6
Lag 7	1	1	11	73	8	1	0	5
			T2 : Single Target Condition					
Lag 1	0	1	24	56	8	0	0	10
Lag 2	0	4	5	69	15	1	0	5
Lag 3	1	0	7	77	8	0	0	6
Lag 4	0	0	13	76	4	2	0	5
Lag 5	0	0	15	72	6	0	1	5
Lag 6	0	0	14	76	4	0	0	6
Lag 7	0	1	10	76	7	0	0	5
			T2 : Dual Target Condition					
Lag 1	5	10	1	32	12	2	1	37
Lag 2	15	0	12	18	25	7	3	20
Lag 3	0	5	2	40	26	7	0	19
Lag 4	3	1	6	53	21	5	1	9
Lag 5	0	0	6	67	14	8	0	5
Lag 6	0	0	7	72	10	1	1	8
Lag 7	0	2	10	65	15	0	1	5

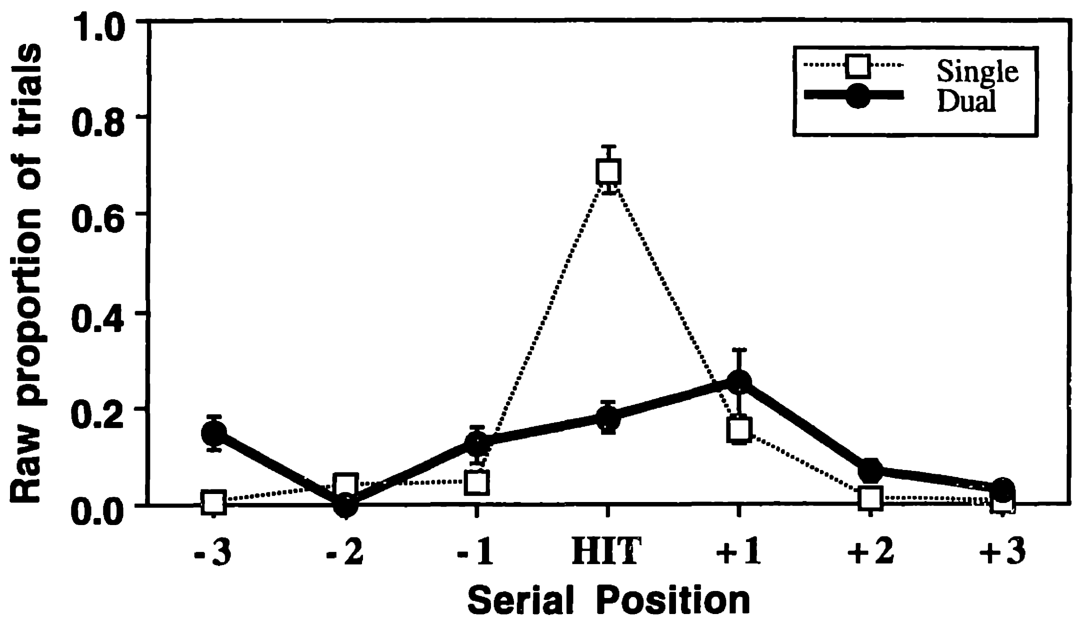
T1 report . As shown in Table 1, having to report both targets in the dual target condition also affected performance on T1. T1 was correctly reported on 67.9% of the trials in the dual target condition, compared with

74.3% of the trials in the single target condition, $\underline{F}(1,17)=13.53$, $\underline{p}<.01$. There was a main effect of lag, $\underline{F}(6,102)=3.45$, $\underline{p}<.01$, with reduced performance on T1 at lag 1, when T1 was immediately followed by T2. Thus, except for lag 1, AB is largely unidirectional, with T1 affecting T2.

Intrusion errors. Of main interest is the pattern of intrusion errors for T2 at each lag. Lag can be considered to be a manipulation of attentional load, which decreases with increasing lag. Botella and Eriksen (1991) found a shift from a symmetric pattern of intrusions to a post-pattern (predominance of post-target intrusions from serial positions +1, +2, +3) as the presentation rate was increased. In the current experiment, we compared intrusion error distributions for T2 in the single target condition (no attentional load) and the dual target condition (in which attentional load changes as a function of lag). The prediction is that there should be a symmetric or a pre-target intrusion pattern in the single target condition and that a pattern shift towards post-target intrusions should be found in the dual target condition. Moreover, the proportion of post-target intrusions should be greatest at lags 2-4, where the AB effect is found, and this pattern should gradually shift towards the control baseline symmetrical distribution pattern as lag is increased. Table 1 and Figure 2 show this pattern.

A

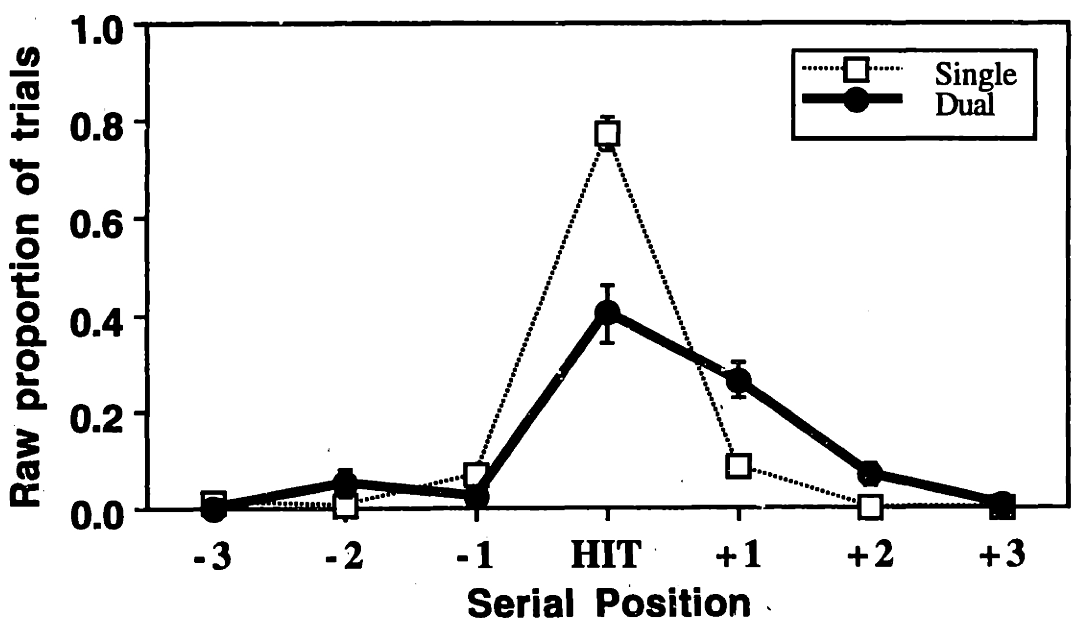
Lag 2



Single
Dual
1.0
0.8
0.6
0.4
0.2
0.0
Raw proportion of trials
-3
-2
-1
HIT
+1
+2
+3
Serial Position

B

Lag 3



Single
Dual
1.0
0.8
0.6
0.4
0.2
0.0
Raw proportion of trials
-3
-2
-1
HIT
+1
+2
+3
Serial Position

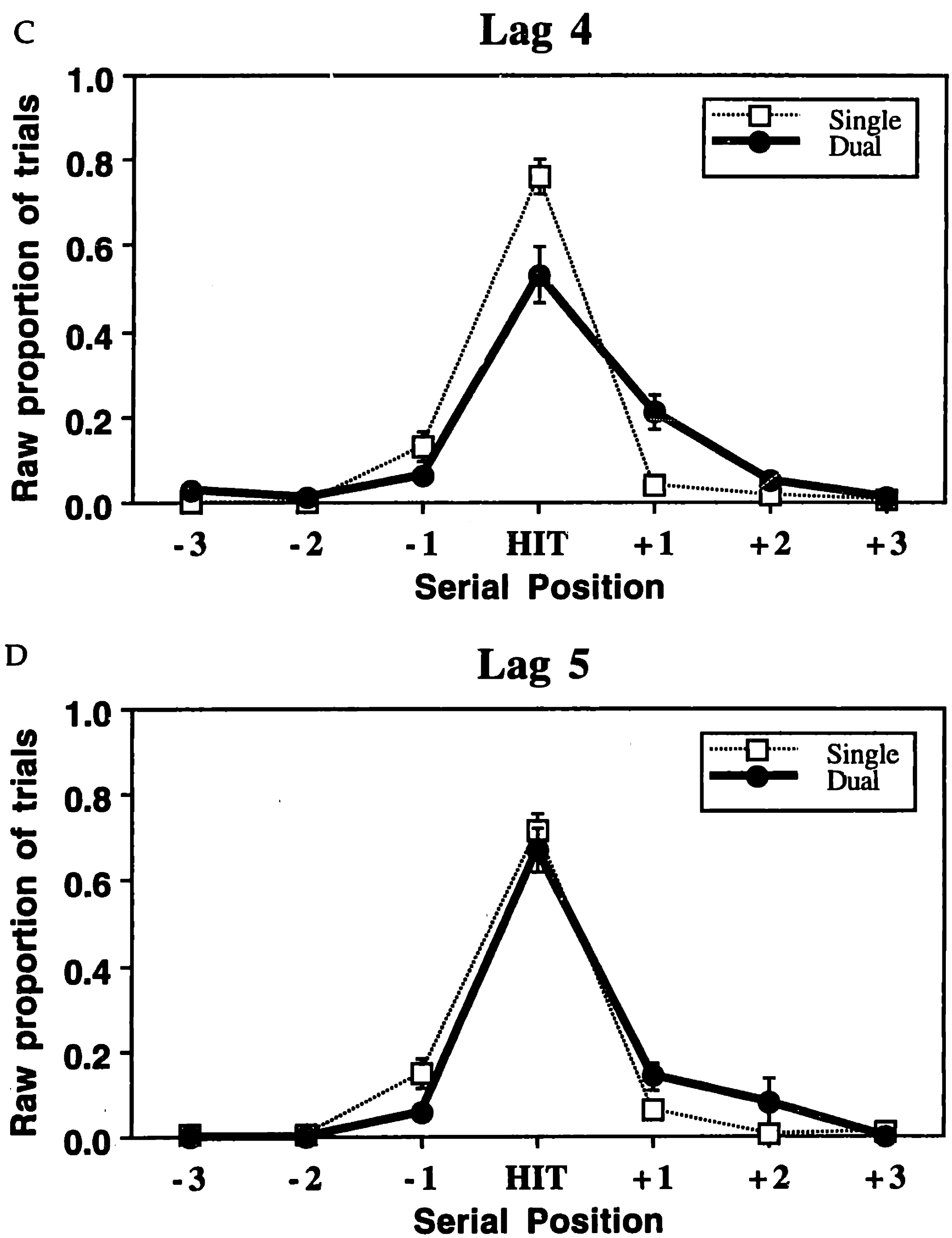


Figure 4. Distribution of raw proportion of trials of target responses for T2 as a function of relative serial position in the single target condition (bold solid lines) and the dual target condition (thin dotted lines), shown separately for lags 2 (panel A), 3 (panel B), 4 (panel C) and 5 (panel D). Asterisks for the dual target condition at relative serial position -2 (Panel A) and serial position -3 (Panel B) mark cells where intrusions were not possible.

An ANOVA was performed on the post-target intrusion errors (proportion of responses coming from relative serial positions +1, +2, and +3) for the two conditions across all lags. Subjects made significantly more post-target intrusions in the dual target condition than they did in the single target condition, $\underline{F}(1,17)=46.99$, $\underline{p}<.001$, there was a main effect of lag, $\underline{F}(6,102)=6.89$, $\underline{p}<.001$, and an interaction between condition and lag, $\underline{F}(6, 102)=2.52$, $\underline{p}<.05$. There was also a main effect of relative serial position, $\underline{F}(2,34)=67.90$, $\underline{p}<.001$, with more intrusion errors from relative serial positions closer to T2. Relative serial position also interacted with condition, $\underline{F}(2,34)=10.87$, $\underline{p}<.001$, and with lag, $\underline{F}(12,204)=2.69$, $\underline{p}<.01$. While intrusion errors were more likely for lag +1 in both single and dual target conditions, the effect was substantially greater for the dual target condition, particularly at lags 2-4.

Overall, correct identification and retention of T1 produced an AB interference effect on detection and recall of T2, resulting in lower accuracy than in the single target condition at lags 1~4. As predicted, the effects on T2 accuracy, misses, and intrusion error patterns all showed gradual recovery to baseline performance for single targets, as the lag increased.

Discussion

The current study examined target report performance for items appearing in RSVP. Subjects searched for one (single target control condition) or two (dual target experimental condition) letter targets defined by colored frame cues appearing in an RSVP stream of other letter items surrounded by non-colored frames. The temporal lag was varied between the two targets and the stimulus sequences for the single and dual target conditions were identical. Previous studies using dual targets in an RSVP search task have shown that correct identification of T1 produces interference with report of T2 appearing within 200-500ms. This AB effect was replicated in the present task, in which the targets were defined by a color cue. In the single target condition, subjects had little difficulty in selecting the target with a specified frame color and performance was relatively unaffected by the lag between the two potential targets. In contrast, when subjects had to report both targets in the dual target condition, T2 report was significantly affected by T1, with performance gradually improving as a function of increasing temporal lag.

Errors in target report consisted of both misses and intrusion errors. Intrusion errors are defined as errors in which non-target items up to three items earlier or later than the target were mistakenly reported as the target. Although a small proportion of these errors were probably random guesses, most are cases in which the target-defining cue (frame box) was misconjoined with the to-be-reported feature (letter identity) of temporally close non-target items. Such binding errors were produced more frequently than misses or random guesses. Most of the intrusions were of non-target items that appeared immediately before or after the cued target item, replicating previous findings (Botella & Eriksen, 1991, 1992; Gathercole & Broadbent, 1984; Intraub, 1985; Lawrence, 1971; McLean, Broadbent, & Broadbent, 1983). Thus, a plot of the distribution of responses for each RSVP target as a function of relative serial position followed a bell-shaped curve, with the highest proportion of responses (in most cases) being the correct target item, and with intrusion errors from neighboring items predominantly drawn from relative serial positions -1 and +1.

Previous studies have shown that the distribution of intrusion errors change as a function of task difficulty and task requirements. Because most of these studies compared intrusion error distributions across different tasks and different experiments, it is unclear how to interpret these pattern shifts. However, Botella and Eriksen (1991) showed pattern shifts within a single experiment using trials of single colored letter targets presented in RSVP at different rates (113~66ms/item). Their main finding was that as presentation rate increased (increasing target processing difficulty), the distribution of intrusion errors changed from a symmetrical pattern (equivalent proportions of pre-target vs. post-target intrusions) to a post-target pattern (larger proportion of post-target intrusions).

A similar pattern shift was found in the current study as a function of attentional load, holding presentation rate constant and requiring report of just one of the targets (specified by a given color), or both of them. As Chun and Potter (in press) hypothesized, the attentional requirement of processing T1 was maximal when T2 appeared at lag 2 and then diminished as lag increased. Most importantly, a pattern shift in intrusion errors was obtained at lags 2-4. At these lags, an increase in the proportion of post-target intrusions was found, compared to the control condition. Moreover, this post-target intrusion pattern was strongest at lags 2 and 3, and gradually recovered to baseline as lag was increased, indicating a smooth mapping between attentional load and the predicted effects on intrusion error distributions.

The overall pattern of results has several implications for previous RSVP studies. In comparison to Botella and Eriksen (1991), the present results illustrate effects of attentional load on the mechanisms binding key features to response features. Because the resource-limited manipulations in the current study produced effects that were analogous to those with manipulations of Botella and Eriksen's study, one can conclude that pattern shifts in intrusion errors reflect capacity limitations on higher-level codes of processing rather than low-level masking or other sensory effects such as temporal integration that may result from an increased presentation rate.

Because lag was randomized across trials in the current study, it is unlikely that the shifts in intrusion errors reflect changes in strategy for processing items in RSVP, contrary to sugestions of Broadbent and his colleagues (Gathercole & Broadbent, 1984; McLean et al., 1983). They hypothesized that symmetrical patterns vs. post-target patterns reflect two different strategies of processing available for identifying targets in RSVP. An active "detect-then-identify" strategy hypothesizes that processing resources "are devoted to the interrogation of the target-defining code to the exclusion to the to-be-reported code until a target detection is made". Such a two-stage mode of serial processing predicts a predominance of post-target intrusions. Another strategy available to the observer may be a "wait and see" mode of parallel processing which allocates resources to both target-defining and to-be-reported codes allowing them to develop concurrently, subsequently coordinating (binding) the two codes for target report. Such a parallel mode of processing generally predicts a symmetrical pattern of intrusions occurring from serial positions before and after the target. In different experiments, subjects produced each of the two patterns, leading Broadbent and his colleagues to suggest that subjects employed different processing strategies according to task difficulty and task requirements (Gathercole & Broadbent, 1984; McLean et al., 1983) .

Botella and Eriksen (1991, 1992) argued that a parallel-processing account can predict both patterns of intrusion errors, suggesting that such a model based on the relative speeds at which parallel codes develop is sufficient to describe the data, without resorting to an explanation which proposes different modes of processing. Our results complement their ideas, additionally showing how attentional load in the AB task may selectively affect processing of letter identity, relative to processing of the color cue. This produced an increase in post-target intrusions in the current study.

According to the parallel processing account, color and form are processed independently and these simultaneously active codes are subsequently integrated into a coherent percept (Keele & Neill, 1978; Treisman, 1977; Treisman & Gelade, 1980; Treisman & Schmidt, 1982). Serial attention is needed to correctly combine independent attributes, and diverting attention away from targets presented in spatial arrays gives rise to illusory conjunctions (Briand & Klein, 1987; Prinzmetal, Presti, & Poster, 1986; Treisman & Schmidt, 1982). It is unclear whether the present shift towards post-target intrusion errors at critical lags reflects an increase in conjunction errors, an increase in feature errors for letter identity, or both. An illusory conjunction interpretation would be that these errors are miscombinations of correctly perceived features and should be distinguished from errors arising from reduced accuracy in perceiving the actual features involved. There is still some debate about whether the illusory conjunctions obtained in previous studies involved only miscombination errors (Briand & Klein, 1989; Tsal, 1989a; Tsal, 1989b). Nevertheless, the data presented in the current study clearly show how binding errors are influenced by attentional load alone, without reducing the integrity of the perceptual input by increased masking or shortened duration of the stimuli. Moreover, attentional load (or divided attention) as a function of lag produced systematic effects on both target report accuracy and the pattern of intrusion errors.

The results are consistent with parallel accounts of RSVP target detection which predict that the codes for color (key feature) and form (response feature) develop in parallel and are subsequently integrated. The response made corresponds to the response code which was most active at the time the key feature was positively identified. Intrusion errors occur when there is a mismatch between the key and response feature codes. Post-target intrusions would be produced under conditions when the response codes for letter form are not simultaneously available at the time of color key feature detection. Chun and Potter (Chun & Potter, in press) proposed that the AB effect may reflect a "bottleneck" in target processing. Correct identification of the form of T1 may tie up limited-capacity processes during which processing of T2 appearing within AB lags would be delayed. This delay in the onset of processing for T2 would be most prominent at shorter lags (excluding lag 1), accounting for the higher proportion of post-target intrusion errors.

In sum, the results show how attentional load affects the pattern of intrusion errors (illusory conjunctions) in RSVP target search tasks, and demonstrate how the AB dual target paradigm can be used to produce a resource-limited manipulation of attention which in turn produces systematic effects as a function of lag. There have been previous attempts to introduce a dichotomy between "inattention" and "attentive processing" (Braun & Sagi, 1990; Rock & Gutman, 1981) which invite controversy over how attention should be operationally defined (e.g., how is one to determine that "no" attentional resources were available for a secondary task?). Rather, it may be more useful to understand attention as a graded resource to be explored along a continuum, as shown here for binding errors. Whether the dual-target AB paradigm can be extended to examine the graded effects of attention in other tasks is a question for further research.

References

Bavelier, D. (1992). *Phonological repetition blindness.* Unpublished doctoral dissertation, Massachusetts Institute of Technology, Cambridge.

Bavelier, D. (1994). Repetition blindness between visually different items : the case of pictures and words. *Cognition, 51,* 199-236.

Bavelier, D., & Potter, M. C. (1992). Visual and phonological codes in repetition blindness. *Journal of Experimental Psychology : Human Perception & Performance,* 18, 134-147.

Baylis, G. C., & Driver, J. (1993). Visual attention and objects: Evidence for hierarchical coding of location. *19*(3), 451-470.

Baylis, G. C., Driver, J., & Rafal, R. D. (1993). Visual extinction and stimulus repetition. *Journal of Cognitive Neuroscience, 5*(4), 453-466.

Botella, J., & Eriksen, C. (1992). Filtering versus parallel processing in RSVP tasks. *Perception & Psychophysics, 51*(4), 334-343.

Botella, J., & Eriksen, C. W. (1991). Pattern changes in rapid serial visual presentation tasks without strategic shifts. *Bulletin of the Psychonomic Society, 29*(2), 105-108.

Braun, J., & Sagi, D. (1990). Vision outside the focus of attention. *Perception & Psychophysics, 48*(1), 45-58.

Briand, K. A., & Klein, R. M. (1987). Is Posner's "beam" the same as Treisman's "glue"?: On the relation between visual orienting and feature integration theory. *Journal of Experimental Psychology: Human Perception and Performance, 13*(2), 228-241.

Briand, K. A., & Klein, R. M. (1989). Has feature integration theory come unglued? A reply to Tsal. *Journal of Experimental Psychology: Human Perception & Performunce, 15*(2), 401-406.

Broadbent, D. E., & Broadbent, M. H. P. (1987). From detection to identification : Response to multiple targets in rapid serial visual presentation. *Perception & Psychophysics, 42*(2), 105-113.

Chun, M.M. (1994). Illusory conjunctions are redistributed by the attentional blink. *Investigative Ophthalmology and Visual Science, 35*, 1621, (abs #1710) (Poster presentation at ARVO)

Chun, M. M., Bromberg, H. S., & Potter, M. C. (1994). *The effect of conceptual discriminability of targets and distractors in the attentional blink.* Manuscript in preparation.

Chun, M. M., & Potter, M. C. (1992). *Interference in detecting multiple RSVP targets : Effects of similarity.* Poster presented at the 1992 Annual Meeting of the Psychonomics Society, St. Louis, Missouri.

Chun, M.M. & Potter, M.C. (1993). Interference in detecting multiple targets in a sequence : A dissociation between the Attentional Blink and Repetition Blindness. *Investigative Ophthalmology and Visual Science, 34*, 1232 (abs #2592). (Poster presentation at ARVO).

Chun, M.M., & Potter, M. C. (1993b). *The attentional blink and repetition blindness.* Unpublished raw data.

Chun, M. M., & Potter, M. C. (in press). A two-stage model for multiple target detection in RSVP. *Journal of Experimental Psychology : Human Perception & Performance,*.

Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological Review, 87*(3), 272-300.

Desimone, R., & Ungerleider, L. G. (1989). Neural mechanisms of visual processing in monkeys. In F. Boller, & G. J. (Ed.), *Handbook of neuropsychology* (pp. 267-299). Amsterdam: Elsevier.

Duncan, J. (1983). Perceptual selection based on alphanumeric class : Evidence from partial reports. *Perception & Psychophysics, 33*(6), 533-547.

Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology : General, 113*(4), 501-517.

Duncan, J. (1985). Visual search and visual attention. In M. I. Posner, & O. S. M. Marin (Ed.), *Attention and Perception XI* (pp. 85-105). Hillsdale, NJ: Erlbaum.

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

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

Farah, M. J. (1990). *Visual Agnosia.* Cambridge, MA: MIT Press.

Gardner, G. T. (1973). Evidence for independent parallel channels in tachistoscopic presentation. *Cognitive Psychology, 4*(130-155), 130-155.

Gathercole, S. E., & Broadbent, D. E. (1984). Combining attributes in specified and categorized target search : Further evidence for strategic differences. *Memory & Cognition, 12*(4), 329-337.

Hoffman, J. E. (1978). Search through a sequentially presented visual display. *Perception & Psychophysics, 23*(1), 1-11.

Horlitz, K. L., Johnston, J. C., & Remington, R. W. (1992). *What makes it difficult to process multiple targets in rapid serial visual presentation (RSVP)?* Paper presented at the 1992 Annual Meeting of the Psychonomics Society, St. Louis, Missouri.

Intraub, H. (1985). Visual dissociation: An illusory conjunction of pictures and forms. *Journal of Experimental Psychology : Human Perception & Performance, 11*(4), 431-442.

Jonides, J., Smith, E. E., Koeppe, R. A., Awh, E., Minoshima, S., & Mintun, M. A. (1993). Spatial working memory in humans as revealed in PET. *Nature, 363,* 623-625.

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

Kahneman, D. (1973). *Attention and effort* . New York: Prentice Hall.

Kahneman, D., & Treisman, A. (1984). Changing views of attention and automaticity. In R. Parasuraman, & D. R. Davies (Ed.), *Varieties of Attention* (pp. 29-61). Orlando, FA: Academic Press.

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files : Object-specific integration of information. *Cognitive Psychology, 24,* 175-219.

Kanwihser, N. G. (1986). *Repetition blindness: Type recognition without token individuation.* Unpublished doctoral dissertation, Massachusetts Institute of Technology, Cambridge.

Kanwisher, N. G. (1987). Repetition Blindness : Type recognition without token individuation. *Cognition, 27,* 117-143.

Kanwisher, N. (1991). Repetition blindness and illusory conjunctions : Errors in binding visual types with visual tokens. *Journal of Experimental Psychology : Human Perception and Performance, 17*(2), 404-421.

Kanwisher, N., & Driver, J. (1992). Objects, Attributes, and Visual Attention: Which, What and Where. *Current Directions in Psychological Science, 1*(1), 26-31.

Kanwisher, N., Driver, J., & Machadol, L. (1993). Spatial repetition blindness is modulated by selective attention to color or shape. *manuscript in preparation.*

Kanwisher, N., & Potter, M. C. (1989). Repetition blindness : The effects of stimulus modality and spatial displacement. *Memory & Cognition, 17*(2), 117-124.

Kanwisher, N. G., & Potter, M. C. (1990). Repetition blindness : Levels of processing. *Journal of Experimental Psychology : Human Perception and Performance, 16*(1), 30-47.

Keele, S. W., & Neill, W. T. (1978). Mechanisms of attention. In E. C. Carterette, & M. P. Friedman (Ed.), *Handbook of Perception, Vol. IX* (pp. 3-47). New York: Academic Press.

Krueger, L. E. (1984). The category effect in visual search depends on physical rather than conceptual differences. *Perception & Psychophysics, 35*, 558-564.

Lawrence, D. H. (1971). Two studies of visual search for word targets with controlled rates of presentation. *Perception & Psychophysics, 10*(2), 85-89.

Luo, C. R., & Caramazza, A. (1994). Temporal and spatial repetition blindness : Effects of presentation mode and repetition lag on the perception of repeated items. *Manuscript submitted for publication.*

Marr, D. (1982). *Vision* . San Francisco: Freeman.

McCann, R. S., & Johnston, J. C. (1992). Locus of the single-channel bottleneck in dual-task interference. *Journal of Experimental Psychology : Human Perception and Performance, 18*(2), 471-484.

McLean, J. P., Broadbent, D. E., & Broadbent, M. H. P. (1983). Combining attributes in rapid serial visual presentation tasks. *Quarterly Journal of Experimental Psychology, 35A*, 171-186.

Mishkin, M., Ungerleider, L. G., & Macko, K. A. (1983). Object vision and spatial vision : Two cortical pathways. *Trends in the Neurosciences, 6*, 414-417.

Mozer, M. (1989). Types and tokens in visual letter recognition. *Journal of Experimental Psychology : Human Perception and Performance, 15*, 287-303.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research, 29*(11), 1631-1647.

Park, J., & Kanwisher, N. (1994). Repetition blindness : Effects of timing, load and stimulus configuration. *Journal of Experimental Psychology: Human Perception and Performance, 20*(3), 500-519.

Pashler, H. (1984). Processing stages in overlapping tasks : Evidence for a central bottleneck. *Journal of Experimental Psychology : Human Perception & Performance, 10*(3), 358-377.

Pashler, H. (1989). Dissociations and dependencies between speed and accuracy : evidence for a two-component theory of divided attention in simple tasks. *Cognitive Psychology, 21*, 469-514.

Pashler, H. (1992). Attentional limitations in doing two tasks at the same time. *Current Directions in Psychological Science, 1*(2), 44-48.

Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *The Quarterly Journal of Experimental Psychology, 41A*(1), 19-45.

Pfafflin, S. M. (1974). The total time hypothesis, recall strategies, and memory for rapidly presented word strings. *Memory & Cognition, 2*, 236-240.

Potter, M. C. (1975). Meaning in visual search. *Science, 187*, 965-966.

Potter, M. C. (1976). Short-term conceptual memory for pictures. *Journal of Experimental Psychology : Human Learning and Memory, 2*(5), 509-522.

Potter, M. C. (1993). Very Short-Term Conceptual Memory. *Memory and Cognition, 21*(2), 156-161.

Potter, M. C., & Levy, E. I. (1969). Recognition memory for a rapid sequence of pictures. *Journal of Experimental Psychology, 81*, 10-15.

Potter, M. C. (1983). Representational buffers : The eye-mind hypothesis in picture perception, reading and visual search. In K. Rayner (Ed.), *Eye movements in reading : Perceptual and language processes* (pp. 423-437). New York: Academic Press.

Potter, M. C. (1984). Rapid serial visual presentation (RSVP) : A method for studying language processing. In D. E. Kieras, & M. A. Just (Ed.), *New Methods in Reading Comprehension Research* (pp. 91-118). Hillsdale, NJ: Erlbaum.

Prinzmetal, W., Presti, D. E., & Poster, M. I. (1986). Does attention affect visual feature integration? *Journal of Experimental Psychology: Human Perception and Performance, 12*(3), 361-369.

Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets : Evidence for a parallel tracking mechanism. *Spatial Vision, 3*(3), 179-197.

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*(3), 849-860.

Reeves, A., & Sperling, G. (1986). Attention gating in short-term visual memory. *Psychological Review, 93*(2), 180-206.

Rock, I., & Gutman, D. (1981). The effect of inattention on form perception. *Journal of Experimental Psychology : Human Perception and Perormance,* 7(2), 275-285.

Scarborough, D. L., & Sternberg, S. (1967). *Processing items and their order in sequential visual displays.* Paper presented at the 1967 Annual Meeting of the Eastern Psychological Association, Boston, MA.

Shapiro, K., Arnell, K., & Drake, S. (1991). Stimulus complexity mediates target detection in visual attention search. *Investigative Ophthalmology and Visual Science, 32,* (Abs #1827).

Shapiro, K. L., & Raymond, J. E. (in press). Temporal allocation of visual attention : Inhibition or interference? In D. Dagenbach, & T. H. Carr (Ed.), *Inhibitory mechanisms in attention, memory and language .*

Shiffrin, R. M., & Gardner, G. T. (1972). Visual processing capacity and attentional control. *Journal of Experimental Psychology, 93*(1), 72-82.

Sperling, G., Budiansky, J., Spivak, J. G., & Johnson, M. C. (1971). Extremely rapid visual search : The maximum rate of scanning letters for the presence of a numeral. *Science, 174,* 307-311.

Tipper, S. P., Driver, J., & Weaver, B. (1991). Object-centred inhibition of return of visual attention. *The Quarterly Journal of Experimental Psychology, 43A*(2), 289-298.

Treisman, A. (1977). Focused attention in the perception and retrieval of multidimensional stimuli. *Perception & Psychophysics, 22,* 1-11.

Treisman, A. (1988). Features and objects: The fourteenth Bartlett memorial lecture. *The Quarterly Journal of Experimental Psychology, 40A*(2), 201-237.

Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12,* 97-136.

Treisman, A., & Sato, S. (1990). Conjunction search revisited. *Journal of Experimental Psychology : Human Perception & Performance, 16*(3), 459-478.

Treisman, A., & Schmidt, H. (1982). Illusory conjunctions in the perception of objects. *Cognitive Psychology, 14,* 107-141.

Tsal, Y. (1989a). Do illusory conjunctions support the feature integration theory? A critical review of theory and findings. *Journal of Experimental Psychology: Human Perception & Performance, 15*(2), 394-400.

Tsal, Y. (1989b). Further comments on feature integration: A reply to Briand and Klein. *Journal of Experimental Psychology: Human Perception & Performance, 15*(2), 407-410.

Ungerleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. In D. J. Ingle, M. A. Goodale, & R. J. W. Mansfield (Ed.), *Analysis of Visual Behaviour* (pp. 549-586). Cambridge, MA: MIT Press.

Vecera, S. P., & Farah, M. J. (1994). Does visual attention select objects or locations? *Journal of Experimental Psychology: General, 123*(2), 146-160.

Volkman, F. C., Riggs, L. A., & Moore, R. K. (1980). Eyeblinks and visual suppression. *Science, 207,* 900-922.

Ward, R., Duncan, J., & Shapiro, K. (1992). *The attentional blink does not require selection among a nontarget stream..* Paper presented at the 1992 Annual Meeting of the Psychonomics Society. St. Louis, Missouri.

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

Welford, A. T. (1952). The "psychological refractory period" and the timing of high-speed performance : A review and theory. *British Journal of Psychology, 43,* 2-19.

Wilson, F. A. W., O Scalaidhe, S. P., & Goldman-Rakic, P. S. (1993). Dissociation of object and spatial processing domains in primate prefrontral cortex. *Science, 260,* 1955-1958.

Wolfe, J. M. (1994). Guided Search 2.0 : A revised model of guided search. *Psychonomic Bulletin & Review, 1*(2), 202-238.

Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search : An alternative to the feature integration model for visual search. *Journal of Experimental Psychology : Human Perception and Performance, 15*(3), 419-433.

Xu, F., & Carey, S. (1994). *Infant metaphysics: the case of numerical identity.* Manuscript submitted for publication.