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Temporal binding errors are redistributed by the attentional blink

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When one searches for a target among nontargets appearing in rapid serial visual presentation (RSVP), one's errors in performance typically involve the misreporting of neighboring nontargets. Such illusory conjunctions or intrusion errors are distributed differently around the target, depending on task or stimulus variables. It is shown here that shifts in intrusion error patterns can be produced by the manipulation of attention alone. In a dual-task paradigm, the magnitude and distribution of intrusion errors changed systematically as a function of available attentional resources. Intrusion errors in RSVP tasks reflect internal capacity limitations for binding independent features. The present results support a two-stage model of RSVP target processing.

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 fixation). For random lists of stimuli (e.g., letters, digits, words, etc.), this presentation rate quickly exceeds the cognitive system's ability to process these items to a level sufficient for report. To a considerable extent, attentional mechanisms allow the observer to select relevant items (targets) for enhanced processing.

Visual attention is involved in the processing and subsequent integration of independent visual attributes of selected items (Treisman & Gelade, 1980). This can be examined by requiring observers to report a single target appearing among distractors in RSVP. The target is typically defined by an attribute (such as color or letter case) that differentiates it from the distractors, and observers report another independent attribute of the target (e.g., the form identity). In an early RSVP study, Lawrence (1971) showed that one could report a single uppercase target word presented among lowercase distractor words with rather high accuracy. The results indicated that although the rates of presentation used in RSVP may be too rapid for all presented items to be fully processed, the visual system is able to utilize an independent feature cue such as letter case to *select* single targets for full processing. Observers may also use categorical identity (e.g., animal words among non–animal words) to select targets from an RSVP stream. Nevertheless, there is a limitation to the number of targets that can be reliably reported (Broadbent & Broadbent, 1987; Weichselgartner & Sperling, 1987), and performance drops as a function of increasing presentation rate (Lawrence, 1971). Thus, RSVP target search reveals a bottleneck in the processing of rapidly presented visual items (Broadbent & Broadbent, 1987; Chun & Potter, 1995) which forces the system to employ attentional selection of target events (Raymond, Shapiro, & Arnell, 1992).

In addition to examining the effects of task variables such as selection cues or stimulus parameters such as presentation rate, analysis of the pattern of *errors* made in these RSVP tasks is useful for inferring the visual processes underlying performance. Errors can be grouped into three types: observers can miss the target; they can misreport an item not even presented on a trial; or they can report the wrong item from the neighboring RSVP sequence. The latter error, which occurs frequently, is referred to as a *binding error* or an *illusory conjunction* (Treisman & Schmidt, 1982), because the feature defining the target is misconjoined with the to-be-reported feature of a distractor. The pattern of these binding errors is the main focus of the present study. Such errors have also been described in previous studies as *visual dissociations* (Intraub, 1985) or *intrusion errors* (Gathercole & Broadbent, 1984; Lawrence, 1971; McLean, Broadbent, & Broadbent, 1983; Raymond et al., 1992).

Before discussing previous results on illusory conjunctions in RSVP tasks, I introduce here 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

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target to be reported at the end of the trial is the *response feature*. *Intrusion errors* occur when a nontarget item that has 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 *posttarget intrusion*, whereas a *pretarget intrusion* comes from an item appearing before the target in the RSVP sequence. Depending on the relative proportion of posttarget or pretarget intrusions, the overall pattern of errors can be described as postpattern, prepattern, or symmetrical. For example, errors in Lawrence's (1971) study were postpattern, because posttarget intrusions were predominant.

The patterns of these intrusion errors have been used to infer the processes involved in target performance in RSVP tasks. Different patterns might either reflect different processing strategies employed by the observer (Gathercole & Broadbent, 1984; McLean et al., 1983) or reflect different relative processing times for the independent features involved (Botella & Eriksen, 1992). For instance, a postpattern result may result from the use of an active detect-then-identify search strategy which hypothesizes that processing resources "are devoted to the interrogation of the target-defining code to the exclusion of the to-be-reported code until a target detection is made" (McLean et al., 1983, p. 184). 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 and 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, observers produced each of the two patterns (Gathercole & Broadbent, 1984; McLean et al., 1983). A postpattern was obtained when observers were asked to report the color of a specified numeral embedded in a list of letters, and a symmetrical pattern was found for color report when the numeral was unspecified. Broadbent and his colleagues suggested that subjects employed different processing strategies: an active "detect-then-identify" strategy, producing postpatterns for specified target search, and a "wait-and-see" strategy, producing symmetrical patterns in the more difficult categorically defined target search.

More recently, Botella and Eriksen (1992) have argued that rather than postulate different processing strategies, a single parallel processing account could account for all three patterns of intrusion errors on the basis of relative processing times for each of the independent features involved as well as the amount of attention allocated to each feature dimension (Botella, 1992). Botella and his colleagues have presented several findings that argue against the need for postulating different processing strategies. One of the most critical results was shown in a task that required subjects to report the identity and/or color of a target uppercase word presented among lowercase words. Regardless of whether subjects reported one or both response dimensions, a postpattern was shown for color and a prepattern was shown for identity responses (Botella, Garcia, & Barriopedro, 1992).

Another key result relevant to the present study is Botella and Eriksen's (1991) demonstration 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 msec/item (no blank interstimulus interval), a symmetrical pattern was obtained, and intrusion errors were equally likely to occur from items appearing before the target and after the target. At shorter durations of 83 or 66 msec/item, a postpattern of intrusions was obtained: intrusions came predominantly from items appearing after the target. This pattern shift obtained within a single experiment is interesting, because it reflects inherent limitations in how key features and response features are processed and conjoined. Intrusions may reflect timing errors for integrating cue and response features, as well as the relative availability of the internal codes for these independent features. In either case, increasing presentation rate results in an increased probability of posttarget events' taking over the internal representations of the targets. This produces a corresponding shift in intrusion errors toward a postpattern. Because the presentation rates were randomized within blocks, the shift in intrusion patterns also argues against the possibility that different processing strategies could account for the effect.

With respect to Norman and Bobrow's (1975) theoretical framework, increasing presentation rate is a data-limiting manipulation. Could such pattern shifts in intrusion errors also be induced by a resource-limiting manipulation? The purpose of the present study is to examine whether such pattern shifts in intrusion errors could be induced without changing the stimulus parameters of presentation, but rather by manipulation of attention *alone*. Attention is required for feature binding and has recently been shown to be needed to prevent items from being overwritten by subsequent stimuli (Giesbrecht & Di Lollo, in press). Thus, one should be able to increase the likelihood of posttarget intrusions by providing a competing load on limited-capacity resources available for target processing and feature binding. The hypothesis is that increased task load will reduce available attentional resources, producing a shift toward proportionally more posttarget intrusion errors.

Attentional load can be increased by requiring observers 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 (T_1) produces interference on report of a second target (T_2) appearing within 200–500 msec. This effect, termed the "attentional blink" (AB) by Raymond et al. (1992), 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, 1997; Chun & Potter, 1995). In all of these AB studies, T_2 report performance was poorest at

Lags 2–3 (stimulus onset asynchrony, or SOA, of 200–300 msec) and improved systematically as the temporal separation between the two targets increased. When T_2 immediately follows T_1, there is little or no AB. Chun and Potter suggest, following Weichselgartner and Sperling, and Raymond et al., that in this case, T_1 and T_2 are processed together. Lag 1 represents a singularity, and any effects of attentional load are expected to be minimal at this lag.

The AB qualifies as an attentional effect because it occurs only when T_1 is attended to (Raymond et al., 1992). The impairment on T_2 is not observed when subjects are instructed to ignore T_1 in control conditions. In other words, the processing requirements of attending to and consolidating T_1 from the RSVP sequence is what reduces the capacity to process T_2. Performance on T_2 provides a direct measure of available attentional resources, which change as a function of time. The AB function indicates that the load or resource demands of T_1 processing are maximal around 200–300 msec from stimulus onset, recovering to baseline levels with increasing lag.

The main purpose of the present study was to examine the role of attention in intrusion error distributions. I employed the AB task, which provides a clear independent variable, lag, to explore the effects of reduced capacity. The prediction was that the proportion of intrusion errors should be greater during the AB interval and that the distribution of errors should shift toward a postpattern. Observers searched for one or two letter targets appearing in an RSVP stream of single letters. Each trial included two potential targets (T_1 and T_2), which were each defined by a colored (red or green) outline frame surrounding the letter: the nontarget letters were surrounded with white outline frames.[1] 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 T_1 or T_2) appearing with a prespecified color cue (e.g., report the letter that appeared with the red outline cue). In the dual-target experimental condition, they were required to report both color-cued targets. The lag between T_1 and T_2 was systematically varied from 1 to 7 (SOA = 120–840 msec). Target report performance and the distribution of intrusion errors for T_1 and T_2 was compared between the two conditions.

As has been shown previously, performance for a single target appearing in RSVP is relatively unaffected by other events that do not require selection for report. This corresponds to the control condition, in which performance on T_1 or T_2 was expected to be relatively unaffected by the temporal separation between the two. However, in dual-target search tasks, processing of T_1 produces a lag-dependent interference on T_2 performance. This AB effect can be taken as a measure of available attentional resources. Importantly, the AB effect diminishes as a function of increasing lag, allowing one to examine the dynamic effects of processing resources 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, such effects should also be found in the present task. Again, the lags that produce the AB should also produce the most asymmetric posttarget pattern of intrusions.

METHOD

Subjects

Twenty observers participated in the experiment. These 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 everyone was paid for their participation. None of the subjects was aware of the purpose of the experiment.

Materials and 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 T_1 was randomly permuted so that it appeared an equal number of times in Serial Positions 3–6. Seven lags between T_1 and T_2, Lag 1 (no intervening items, SOA = 120 msec) to Lag 7 (SOA = 840 msec), were crossed with the four serial positions of T_1. Each item in the RSVP stream appeared within an outline box (frame). The color of the outline frame was white for all of the nontargets and was red for one target and green for the other. The outline frame color was always different for the two targets, and the order of the colors was counterbalanced. T_1 color (red or green) was crossed with T_1 serial position (3–6) and T_2 lag (1–7), resulting in a total of 56 trials per block. This was replicated three times for a total of 168 trials in each condition.

Each subject was run in two main conditions, the order of which was counterbalanced across observers. In the single-target (control) condition, observers were instructed to report only the target that appeared in a designated target frame color, which would be T_1 on half of the trials and T_2 on the other half of the trials. Half of the observers 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, observers 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 msec at the center of the monitor screen. Three hundred sixty milliseconds after the fixation cross went off, the stream of letter stimuli appeared successively without interstimulus blanks at the same location, for 120 msec each. The two color cues and white frames on distractors appeared for the first 30 msec that each letter was displayed. The sequence was followed by a "&" mask for 120 msec, signaling the end of the trial. Subjects were encouraged to enter their best guess, typing their responses through the keyboard, and pressing the space bar for any targets that they missed. Each keypress response was flashed on the screen, but trial feedback was otherwise not given.[2] After the observer made two keypresses, the computer initiated the next trial after a pause of about 2 sec. Breaks were given every 56 trials, and the entire procedure lasted about 1 h. 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, and observers read these at their own pace. A summary of the instructions was also given by the experimenter, who

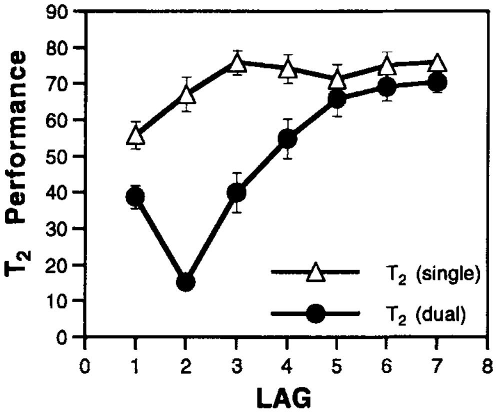

Figure 1. The attentional blink. The group mean of the proportion of trials on which T_2 was correctly reported is plotted as a function of lag between the two targets. Open triangles indicate performance in the single-target condition, and filled circles indicate performance on T_2 given that T_1 was correctly reported in the dual-target condition. Error bars represent the standard error of the mean.

remained in the room during the practice block to answer any questions about the procedure. The remainder of the experiment was self-paced.

Apparatus

The experiment was run on a Macintosh II computer with an Apple high-resolution RGB monitor. The software used for designing and running the experiments was MacProbe Version 1.5.0, developed by Aristometric Computers. The experiment was carried out under dim illumination provided by a 15-W lamp facing the rear white wall behind the computer. The letter stimuli were presented in 24-point Geneva font. Viewed from an average distance of 30 cm, the letter stimuli subtended approximately .95° × 1.34° of visual angle.

RESULTS

The AB Effect (T_2 Report Performance)

A comparison of T_2 report performance between the single-target control condition and the dual-target experimental condition is shown in Figure 1. T_2 performance in the single-target control condition was measured over the trials on which the target color framed the second item. T_2 performance in the dual-target condition represents the proportion of trials on which T_2 was correctly reported, given that T_1 was correctly reported. As is apparent in Figure 1, there were main effects of condition [$F(1,19) = 92.15, p < .001$] and lag [$F(6,114) = 30.48, p < .001$], and there was a significant interaction between condition and lag [$F(6,114) = 18.69, p < .001$]. Thus, when observers were required to report the identity of both targets, correct identification of T_1 clearly interfered with T_2 report. Indeed, correct identification of T_1 was not even a necessary condition for T_2 impairment in this experiment. As can be seen in Table 1, an AB effect was obtained regardless of whether T_1 was correctly conjoined with its color cue or not, as long as observers were required to report the first target and were thus engaging limited capacity mechanisms required for feature conjunction in this RSVP task. The interaction between condition and lag for T_2 performance not conditionalized on T_1 was also highly significant [$F(6,114) = 20.21, p < .001$].

In comparison, when selection was based on a specified color cue in the control condition, interference of the irrelevant T_1 cue color on report of the identity of T_2 was much weaker, although there was a main effect of lag in a separate analysis of T_2 report performance for the control condition [$F(6,114) = 6.02, p < .001$]. The interference effect at Lags 1 and 2 in the control condition may reflect (1) the demand of implicit color discrimination, (2) the perceptual difficulty to resolve the second of two very briefly presented color cues appearing in close succession, or (3) a failure to completely ignore T_1. The effect of the latter would be exacerbated by the use of a within-subjects design, since half of the subjects were exposed to the dual-target condition first and may have had some initial difficulty ignoring T_1 in the control condition. However, there appear to have been no such confounds or hysteresis effects. There was no main effect of order ($F < 1$), and order did not interact with condition [$F(1,18) = 1.56, p > .22$] or with any other factor (all Fs < 1). Though an interference effect was found with the shortest lags, of main interest here is the large difference between the two conditions, which shows that processing the form identity of T_1 impaired T_2 processing much more severely than did implicit color discrimination of the T_1 color cue. In sum, a robust AB effect was obtained in this task.

The raw proportion of intrusion errors from Relative Serial Positions −3, −2, −1, +1, +2, and +3, the proportion of other "random" intrusions, and the proportion of miss errors for each target in each condition for each lag is shown in Table 1. For the dual-target condition, the T_2 report data is shown for both the raw proportion of T_2 trials and the trials conditionalized on T_1 having been correctly reported. The following analyses are all based on the raw proportions, which are not conditionalized on whether T_1 was reported correctly or not. Corresponding analyses based on the T_2 data conditionalized on correct report of T_1 produced essentially identical results. The choice of an unconditionalized analysis was made in order to score any migration as an error. Note that since target report in dual-target tasks involves a high proportion of order inversion errors such as reporting "B, A" when T_1 = "A" and T_2 = "B" (Chun & Potter, 1995; Reeves & Sperling, 1986), the raw data will include a number of trials in which the cued targets were accurately identified, but their identification was scored as an intrusion because of a reversal in the order in which they were reported. For the present purposes, letters reported in the first position were scored as T_1 or an intrusion on T_1, and letters reported in the second as T_2 or as a T_2 intrusion.

Table 1
Percentage Distribution of Letter Report for RSVP targets

Lag	Relative Serial Position of the Letter Reported							Random Intrusions	Misses
	−3	−2	−1	0	+1	+2	+3		
				T_1: Single-Target Condition					
1	2	0	13	70	7	1	0	3	4
2	0	0	12	78	3	2	0	2	2
3	0	0	14	73	7	0	1	2	3
4	0	1	12	76	5	0	1	2	3
5	0	0	12	74	7	0	0	2	4
6	0	1	10	75	4	2	0	2	5
7	0	1	13	75	7	0	0	1	3
				T_1: Dual-Target Condition					
1	1	2	16	59	12	1	0	3	6
2	2	1	14	66	7	4	0	3	3
3	0	1	14	70	5	1	0	4	5
4	0	1	15	71	7	1	0	3	3
5	0	1	14	69	9	1	0	4	2
6	0	1	10	75	8	1	0	3	2
7	1	1	13	69	7	1	1	3	3
				T_2: Single-Target Condition					
1	0	1	22	56	10	0	0	3	7
2	0	4	5	67	16	1	0	4	2
3	1	0	7	76	10	0	0	3	2
4	0	0	13	74	5	2	0	2	3
5	0	1	14	71	6	0	1	2	3
6	0	0	13	75	5	0	0	4	3
7	0	1	9	76	8	0	0	3	2
				T_2: Single-Target Condition					
1	3	10	15	29	8	3	2	11	19
2	11	10	11	14	18	6	3	14	13
3	5	4	2	34	24	5	2	15	9
4	2	1	3	53	21	4	1	10	6
5	1	0	4	62	16	2	1	10	4
6	0	0	7	67	13	2	1	5	5
7	0	0	9	66	13	1	1	7	4
				$T_2 \mid T_1$: Dual-Target Condition					
1	3	14	*	39	10	3	3	12	15
2	15	*	13	15	18	7	5	14	11
3	*	4	2	40	26	7	2	16	4
4	3	1	3	55	22	4	1	8	4
5	0	0	5	66	16	4	1	7	2
6	0	1	7	69	13	2	1	4	3
7	0	1	9	70	13	0	0	5	2

*Undefined for the $T_2 \mid T_1$ conditional measure.

Intrusion Errors on T_2

Of main interest is the pattern of intrusion errors for T_2 at each lag. Here, lag is considered a variable of available attentional resources which change as a function of lag. To review the predictions, Botella and Eriksen (1991) found a shift from a symmetric pattern of intrusions to a postpattern (predominance of posttarget intrusions from Serial Positions +1, +2, +3) as the presentation rate was increased. In the present experiment, I compared intrusion error distributions for T_2 in the single-target condition (low attentional load) with those for T_2 in the dual-target condition (increased attentional load changing as a function of lag). The prediction is that there should be a symmetric or a pretarget intrusion pattern in the single-target condition and that a pattern shift toward posttarget intrusions should be found in the dual-target condition. Moreover, the proportion of posttarget intrusions should be greatest at Lags 2–5, where the AB effect is found, and this pattern should gradually shift toward the control baseline symmetrical distribution pattern as lag is increased.

Table 1 and Figure 2 show this pattern. The intrusion index plotted in Figure 2 was calculated by taking the average of responses in which correct responses were assigned a weight of 0, pretarget intrusions, −1, and posttarget intrusions, +1. This index was favored over a ratio measure, in order to avoid sampling fluctuations that exaggerate ratio values when the percentage of intrusions is small.

A significant increase in posttarget intrusions was found in the dual-target condition in comparison with the single-target control condition especially at Lags 3, 4, and 5. An ANOVA of the intrusion index confirmed what is apparent in Figure 2. There were main effects of condition [$F(1,19) = 25.89$, $p < .001$] and lag [$F(6,114) =$

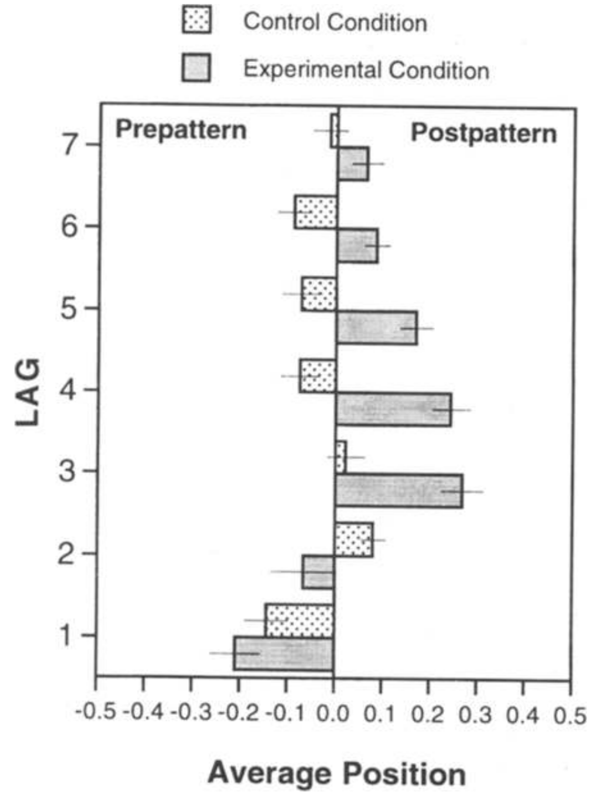

Figure 2. Intrusion index scores for T_2 as a function of lag and condition. Positive scores indicate posttarget intrusion patterns; negative scores indicate prepatterns. Error bars represent the standard error of the mean.

15.39, $p < .001$], and there was a significant interaction of condition × lag [$F(6,114) = 12.99, p < .001$]. In sum, a sharp increase in posttarget intrusions was obtained at the AB lags. One exception is the symmetrical to pretarget intrusion pattern at Lags 1 and 2. This was due to the large increase in intrusions from T_1 and its neighboring positions. A large proportion of these intrusions included trials in which T_1 was reported as T_2. These inversion errors occur frequently in RSVP tasks (Reeves & Sperling, 1986), and their proportion is always highest at Lag 1, typically diminishing by Lag 3 (Chun and Potter, 1995). Although these represent true errors in the order of report of the two targets, it is unclear how to classify them, since in many cases, typically the order and not the identity of the two targets is misreported. Attentional allocation to T_1 also appears to enhance its immediately neighboring items, increasing the likelihood of pretarget intrusions on T_2's appearing at Lags 1 and 2. As noted in the introduction, the processing of T_1 and its neighboring events (Lag 1) represents a singularity in the AB function. Lags 1 and 2 aside, the dominant pattern in the present results is a dramatic increase of posttarget intrusions at AB lags.

An ANOVA was performed on the intrusion errors, with condition (single target, dual target), lag, intrusion type (pretarget intrusions vs. posttarget intrusions) and relative serial position (1–3) as factors. There was a main effect of condition [$F(1,19) = 33.76, p < .001$], confirming that an increase in attentional load produces a higher proportion of intrusion errors. Overall, a symmetrical pattern of intrusions was observed, as is indicated by the lack of a main effect of type [$F(1,19) < 1$]. Of focal interest is the significant interaction of condition × type [$F(1,19) = 29.80, p < .001$], consistent with the hypothesis that there would be an increase of posttarget intrusions in the dual-target condition. Most importantly, as shown in Table 1 and Figure 2, this increase of posttarget intrusions in the dual-target condition was dependent on lag, as supported by a significant three-way interaction of condition × intrusion type × lag [$F(6,114) = 10.76, p < .001$].

The overall proportion of intrusion errors decreased as a function of lag [$F(6,114) = 21.30, p < .001$]. The effect of lag on intrusion errors was greater in the dual-target condition, as is indicated by the significant interaction of condition × lag [$F(6,114) = 8.99, p < .001$]. The interaction of lag × type of intrusion errors was also significant [$F(6,114) = 13.11, p < .001$].

Most of the intrusions were of nontarget items that appeared immediately before or after the cued target item, replicating previous findings (Botella & Eriksen, 1991, 1992; Gathercole & Broadbent, 1984; Lawrence, 1971; McLean et al., 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 $+1$. There was a main effect of relative serial position [$F(2,38) = 458.71, p < .001$]. Relative serial position interacted with lag [$F(12,228) = 1.92, p < .05$] as well as intrusion type [$F(2,38) = 4.92, p < .05$]. The interaction of condition × relative serial position was not significant [$F(2,38) = 1.04, p > .36$]. There were significant three-way interactions of relative serial position × condition × lag [$F(12,228) = 3.46, p < .001$], relative serial position × condition × intrusion type [$F(2,38) = 44.94, p < .001$], and relative serial position × lag × intrusion type [$F(12,228) = 12.99, p < .001$]. The four-way interaction of relative serial position × condition × lag × intrusion type was also significant [$F(12,228) = 5.10, p < .001$].

Overall, the requirement to report T_1 produced an AB interference effect on detection and recall of T_2, resulting in lower accuracy than in the single-target condition at Lags 1–4. As predicted, the effects on T_2 accuracy, misses, and intrusion error types all showed gradual recovery to baseline performance for single targets, as the lag increased.

T_1 Report and Intrusion Errors

As is shown in Table 1, having to report both targets in the dual-target condition also affected performance on T_1. T_1 was correctly reported on 68.2% of the trials in the dual-target condition and on 74.5% of the trials in the single-target condition [$F(1,19) = 20.94, p < .001$]. There was a main effect of lag [$F(6,114) = 3.53, p < .005$], with reduced performance on T_1 at Lag 1, when T_1 was immediately followed by T_2. The interaction between condition and lag was not significant [$F(6,114) = 1.16, p > .33$]. Excluding Lag 1, there was a main effect of condition [$F(1,19) = 13.03, p < .005$], but no effect of lag ($F < 1$), nor an interaction between condition and lag [$F(5,95) = 1.19, p > .32$]. Thus, except at Lag 1, AB is largely unidirectional, with T_1 affecting T_2.

The pattern of intrusion errors for T_1 was similar for both the single- and dual-target conditions. There was a main effect of condition [$F(1,19) = 18.13, p < .001$], lag [$F(6,114) = 2.75, p < .05$], intrusion type [$F(1,19) = 6.33, p < .05$], and relative serial position [$F(2,38) = 199.84, p < .001$]. In contrast with the results shown for T_2, the interaction of condition × type for T_1 intrusions was not significant ($F < 1$), and neither was the three-way interaction of condition × type of intrusions × lag ($F < 1$). Relative serial position interacted with condition [$F(2,38) = 10.06, p < .001$], lag [$F(12,228) = 2.31, p < .01$], and intrusion type [$F(2,38) = 9.19, p < .001$]. None of the other two-way, three-way, or four-way interactions were significant in the T_1 intrusion error analysis.

DISCUSSION

The present study examined the effect of attention on binding errors in RSVP. Attentional load was increased by using a dual-task procedure in which observers searched for two targets versus one letter target defined by colored frame cues. The amount of attentional resources available was manipulated by varying the temporal lag between the two targets. 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 processing T_1 produces interference with report of T_2 appearing within 200–500 msec (Broadbent & Broadbent, 1987; Chun & Potter, 1995; Raymond et al., 1992; Ward, Duncan, & Shapiro, 1996; Weichselgartner & Sperling, 1987). This AB effect was replicated in the present task, using targets defined by color cues. In the single-target condition, observers had little difficulty in selecting the target with a specified frame color and, except at Lag 1, performance was relatively unaffected by the lag between the two targets. In contrast, when observers had to report both targets in the dual-target condition, T_2 report was significantly impaired by report of T_1, with performance gradually improving as a function of increasing temporal lag. This impairment is the direct result of the attentional demands of processing T_1, which are maximal at Lag 2 and recovers with increasing lag.

Errors in target report comprised mostly intrusion errors, and earlier studies using RSVP have shown that such distributions 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 (116, 100, 83, and 66 msec/item). Their main finding was that as presentation rate increased, the distribution of intrusion errors changed from a symmetrical pattern (equivalent proportions of pretarget vs. posttarget intrusions) to a posttarget pattern (larger proportion of posttarget intrusions).

A similar pattern shift was found in the present study as a function of available attentional resources (which covary with lag) while holding presentation rate constant. The strongest pattern was an increase in posttarget intrusions in comparison with the baseline control condition. Moreover, this distortion in intrusion error distributions was greatest at AB lags and gradually recovered to baseline as lag was increased, indicating a smooth mapping between available attentional resources and the predicted effects on intrusion error distributions.

Thus, the present results illustrate the effects of attention on the process of binding key features to response features. The resource-limited manipulations in the present study produced effects that were analogous to those produced by the increased presentation rate (data-limited) manipulations in Botella and Eriksen's (1991) study. This suggests that pattern shifts in intrusion errors reflect capacity limitations on higher level codes of processing rather than low-level sensory effects such as masking or temporal integration that may result from an increased presentation rate.

The demonstrated shift in intrusion errors can be readily explained by the two-stage model for RSVP target processing (Chun & Potter, 1995). According to this model, target identification and report proceeds in two stages. In Stage 1, items are rapidly identified and available in a postcategorical short-term buffer (a type of visual short-term memory or very short-term conceptual memory; Potter, 1993). However, representations at this stage cannot subserve conscious report and must be further consolidated by Stage 2. It is assumed that Stage 2 is limited in capacity and cannot process other targets while it is occupied by a previous target. Thus a second target appearing within 200–500 msec would have to wait for Stage 2 processing to be completed for T_1. Because representations in Stage 1 are ephemeral and rapidly overwritten by subsequent items, response features for T_2 appearing during bottleneck processing of T_1 will be overwritten by post-T_2 items. In other words, the internal code strength of post-T_2 items may be higher than that of T_2 by the time feature binding occurs. This would produce a predominance of posttarget intrusions during the attentional blink interval, and the proportion of these would change systematically as a function of lag, as found in the present experiment.

The results and model are also highly consistent with a recent finding demonstrating that attention is required to prevent target items from being overwritten by subsequent events (Giesbrecht & Di Lollo, in press). They employed two types of masks in a dual-target detection task.

Either T_2 was masked by a trailing event (interruption masking) or the mask was embedded with T_2 (interference masking). The AB deficit was obtained only in the interruption masking condition, indicating that AB results from the difficulty of recovering an unattended item that is overwritten by subsequent events. This not only provides direct support for the general two-stage account of AB (Chun & Potter, 1995), but clearly illustrates why posttarget intrusions increase during the AB interval. Since attention is required for one to capture visual events embedded within a rapidly changing sequence of items, a reduction of such attentional resources results in an increase in the proportion of targets overwritten by following items, producing the postpattern reported here.

The two-stage account for the results reported here is also consistent with the literature proposing that multiple attributes of each RSVP event may be analyzed in parallel, albeit at different processing efficiencies. 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). Focal attention is needed to correctly combine independent attributes, and diverting attention away from targets in spatial arrays gives rise to illusory conjunctions (Briand & Klein, 1987; Prinzmetal, Presti, & Posner, 1986; Treisman & Schmidt, 1982). For items appearing in RSVP, the codes for color (key feature) and form (response feature) may develop in parallel in Stage 1 and be subsequently integrated in Stage 2 of Chun and Potter's (1995) two-stage model. The response made corresponds to the response code that is most active at the time at which the key feature is positively identified. Intrusion errors occur when the response code activations of neighboring items are higher than that for the target stimulus during the process of binding with the key feature.

While the results clearly establish how the pattern of intrusion errors covaries with available attentional resources, a few issues in the intrusion error literature remain unresolved. One limitation regards predicting intrusion error patterns from the relative processing times of the key and response features. On a first-pass analysis, intrusion error patterns can be predicted as follows. Let $t(\text{key})$ represent the time required for processing the key feature, and $t(\text{response})$ be the time required for processing the response feature. When $t(\text{key}) > t(\text{response})$, a posttarget intrusion will occur, and when $t(\text{key}) < t(\text{response})$, a pretarget intrusion results. Although these predictions are straightforward, the empirical data from various studies do not corroborate the simple algebra. First, according to the relative timing logic, if a particular task produces a posttarget intrusion pattern, then reversing the key and response features should result in a pretarget intrusion pattern. However, this result was not obtained; a postpattern persisted (McLean et al., 1983). In addition, the relative timing hypothesis predicts a postpattern for categorically defined targets, if we presume that these are more difficult to detect than prespecified targets. However, a symmetrical pattern has been typically demonstrated for such tasks. Second, reaction times (RT) for detection of a key feature should correlate with intrusion error patterns. RTs for tasks on which a postpattern is obtained should be slower than RTs for tasks on which a symmetrical or pretarget intrusion pattern is obtained. Such a result was not observed (Botella, 1992). Finally, if one assumes that the impairment of target processing during the attentional blink interval in the present study would be correlated with increased internal processing time for those items, then an increased "pretarget" intrusion error pattern would be predicted, yet the opposite pattern was obtained here.

The major difficulty here is in getting valid estimates of the internal processing times of the key and response features. These are dependent on how limited attentional resources are proportionally allocated to each feature dimension (Botella, 1992), producing sets of relative processing times that vary somewhat from task to task and from study to study. Although a strict dichotomy between parallel and serial processing in RSVP target search does not likely exist, there may be some validity to Broadbent and his colleagues' proposal that different processing strategies may be employed from one task to the other, assuming here that a processing strategy entails differential allocation of attention to the key and response features in a task. In particular, although the increased difficulty of detecting categorically defined targets over prespecified targets should produce a postpattern according to the relative timing logic and the resource limitation effects shown here, this is not necessarily the case. Observers may be allocating more attentional resources to efficiently process the key feature, which would increase the relative processing time of the response feature and would result in a symmetrical pattern instead (Botella, 1992). Different processing strategies should not be inferred as an umbrella explanation for different intrusion patterns, however, especially since these are shown to change within tasks, such as those in Botella and Eriksen (1991), Botella et al. (1992), and the present study. In sum, when top-down attentional allocation strategies are controlled for, intrusion error patterns show a strong dependency on data-driven factors such as presentation rate, and on resource limitations such as the effect of lag in dual tasks shown here.

The main difference between this study and previous studies in which task requirements and selective set have been varied is that a much more severe reduction in processing resources was imposed by the present dual task. Thus the intrusion errors on T_2 reflect the more robust effect of loss or substitution of a target appearing within the AB interval by subsequent events, consistent with proposals that attention is required to recover these events from Stage 1 into a more durable format (Chun & Potter, 1995; Giesbrecht & Di Lollo, in press).

The present study also demonstrates how the AB dual-target paradigm can be used to produce a resource-limiting 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 to operationally define the presence or absence of attentional resources. In these tasks, observers are required to actively attend to a primary task (or stimulus appearing in a target color) to the exclusion of a peripheral secondary task (or differently colored distractor). Performance decrements are typically shown for "unattended" stimuli, but how is one to determine that "no" attentional resources were available for the secondary task? Rather, it may be more useful to understand attention as a graded resource to be explored along a continuum, as has been 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 an avenue for further research (see Joseph, Chun, & Nakayama, 1997).

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NOTES

1. Similar patterns of results are obtained whether the key feature is integrated with the response feature or spatially separate as in the present experiment (Gathercole & Broadbent, 1984; McLean et al., 1983). In addition, Intraub (1985) has shown that binding errors cannot be attributed to spatial separation, because the same effect occurred whether the frame (key feature) surrounded the stimuli (response feature) or was presented in the center of the stimuli itself (which were pictures of scenes in her experiments).

2. Since penalty feedback was not given, subjects may have adopted a liberal criterion in making their responses. Thus caution should be taken in interpreting intrusion errors as truly perceptual illusory conjunctions. However, changes in the pattern of errors across conditions remain valid, because it is likely that the same criterion was used over the intermixed trials. Confidence rating measures may help resolve some ambiguity, yet would not add much to the interpretation of the present results. Thus, following the procedures of the majority of RSVP studies, confidence ratings were not obtained in the present experiment. Intraub (1985), who did collect confidence ratings, showed that observers made a reliable proportion of confident yet incorrect responses.

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