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Reducing the Effects of Adjacent Distractors by Narrowing Attention

David LaBerge, Vincent Brown, Marc Carter, and David Bash
Department of Cognitive Sciences
University of California at Irvine

Alan Hartley
Claremont Graduate School

Three experiments explored the gradual narrowing of visual attention to a letter target when other letters were positioned close by. The method by which attention was narrowed involved presenting a digit target immediately prior to the letter target and in the same location for progressively shorter durations and requiring the subject to identify both the digit target and the letter target before responding. The response time data from the first 2 experiments indicated that shorter durations of the digit target reduced the amount of information processed from noise letters positioned on either side of the letter target. In the third experiment, in which separation of letters was increased slightly, the response times indicated that the information from flanking noise letters may have been virtually eliminated.

One aspect of attention that has been the subject of considerable recent study concerns the privileged processing of information arising from a particular location in the visual field (for recent reviews, see Broadbent, 1982; Johnston & Dark, 1986; Shiffrin, 1988). Usually referred to as spatial attention, the operation that facilitates processing at a particular area in the visual field has at times been described as a spotlight or searchlight (for reviews, see C. W. Eriksen & Murphy, 1987; Yantis, 1988), a filter channel (LaBerge & Brown, 1989), a zoom lens (C. W. Eriksen & St. James, 1986), and as a distribution of processing resources (e.g., Downing & Pinker, 1985; LaBerge & Brown, 1989; Shaw, 1978; Shulman, Wilson, & Sheehy, 1985). The first two of these four descriptions usually imply that the attended area has a closed configuration with a relatively sharp boundary, whereas the last two imply a relatively sharp boundary only for those cases in which the resource distribution has a small variance. All four descriptions allow meaningful specifications of the location of the attended area. While the first two descriptions should easily yield specifications of the size of the attended area for a particular task, the last two descriptions should do so under conditions in which attention is believed to be relatively concentrated in a small area of the visual field. Because the present study is concerned mainly with a relatively narrow spread of attention, the term *attended area* should be meaningful under any of the four theoretical descriptions. In the interest of generality, then, attended area will be used to denote the area of the visual field in which processing is most concentrated.

Several studies in the literature have demonstrated that the size of the attended area can be varied by experimental manipulations (e.g., Egeth, 1977; C. W. Eriksen & St. James, 1986; Jonides, 1983; LaBerge, 1983; Sperling & Melchner, 1978). In one study (LaBerge, 1983) two displays were presented successively on a trial: the purpose of the first display was to induce subjects to form an attended area of a particular size at a particular location; the response time to a second display was used as a measure of that size and location. For example, in one condition the first display was a five-letter word whose center letter was to be identified; in another condition the first display was a five-letter word which the subject was to categorize. During a trial the first display was replaced by a probe display made up of the digit 7 which appeared equally often in each of the five locations occupied by the letters of the word; the remaining spaces were occupied by + signs. The resulting response time curve (response time to the probe as a function of the five target positions) for the condition in which subjects first identified the center letter showed a distinct V-shape, while the response time curve for the condition in which subjects identified the entire word showed a relatively flat shape. Since a V-shaped curve indicated that subjects had processed the probe most rapidly when it appeared in the center location, and a flat curve indicated that subjects processed the probe at the same rate across the five locations, it was concluded that attention had been narrowed to the center letter in the former case and had been spread across the five-letter words in the latter case. Apparently, subjects had modified the width of the attended area in anticipation of the type of identification they were required to perform on the first display, and when the second (probe) display appeared, it presumably was processed under approximately the same attentional conditions as that of the first display.

Given that the size of the attended area can be varied, one may inquire into the upper and lower limits of this variation. But before the question of limits can be answered, a means must be found to measure the size of the attended area. One method is to hypothesize the location of a boundary around an attended area, and then to place objects, such as letters, inside and outside the assumed boundary, and then show that an object inside the boundary is processed to a greater extent than objects outside the boundary. If the object outside the

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Correspondence concerning this article should be addressed to David LaBerge, Department of Cognitive Sciences, University of California, Irvine, California 92717.

hypothesized boundary is being processed at all, then one can conclude that the attended area extends beyond that boundary.

This general method was employed by B. A. Eriksen and C. W. Eriksen (1974), who varied the spacing between a central target item and the neighboring items on the left and right of the target. Subjects were shown a target letter taken from the two sets (C, S) and (H, K), and pressed a lever to the left or right, depending upon the set to which the target belonged. Each display consisted of seven letters arranged along a horizontal line, with three letters to the left and three letters to the right of the target letter. Of particular interest for present purposes are the response times to the displays in which the flanking letters were assigned either to the same response as that of the target, or to a different response from that of the target. Their results showed that when target and flankers were assigned to different responses (the Incompatible displays), mean response times were found to be greater than when the target and flankers were assigned to the same response (the Compatible displays), even though the subjects were instructed to respond only to the center letter of the display. More generally, Miller (1987) found that this Incompatible–Compatible response time difference was a function of the extent to which the flankers were correlated with either the same or the opposite response as that of the target. In the Eriksen and Eriksen study, when the spacing between letters in the displays was 0.06°, the difference between the response times to the incompatible and compatible displays (hereafter abbreviated I–C) was approximately 80 ms. At a between-letter spacing of one degree, I–C was approximately 20 ms. The fact that I–C did not approach zero at the one-degree spacing was taken as evidence that the minimum width of the attended area was at least one degree (Eriksen & Schultz, 1979).

The Eriksen and Eriksen (1974) study showed that target–flanker spacing affected I–C, which implies that their subjects identified flankers more effectively (or conversely, filtered them less effectively) the closer the flankers were located to the target letter. However, Eriksen and Eriksen did not attempt to vary I–C while holding target–flanker separation constant. Thus, their results do not address the question of whether the area in which flanking letters are processed sufficiently to produce interference can be changed. One way to demonstrate that the spread of attention can be changed in this situation is to reduce the size of the attended area while the target–flanker spacing is held constant. In the limiting case in which I–C is reduced to zero, one could assume that the information from flanking items is not being processed, with the implication that the boundary of the attended area was located somewhere in the spaces between the target and the flankers. Thus, the purpose of the present study is twofold: By using the flankered-letter identification task as an indicator of the attended area, we first attempt to vary the effective size of the attended area; then we attempt to reduce the size sufficiently to eliminate effects of the flanking letters.

The experiments reported here combine the compatible–incompatible flanker procedure developed by Eriksen and Eriksen (1974) with the method for controlling the location and size of the attended area developed by LaBerge (1983). The goal is to vary the size of the attended area without changing the sizes of the objects or the distances between the objects. In the present experimental design, a trial consists of three events: a warning signal indicating the location of the targets, a flankered first target (the digit 7) that must be identified against nontargets (the letters T and Z), and a flankered second target (C, H, K, or S). Subjects are to respond to a second-target letter only when the digit 7 appears in the first display.

The variable used to alter the effective size of the attended area is the duration of the first target. If one assumes that a certain amount of processing is required in order for subjects to be able accurately to identify a target letter, then a reduction in the duration of the first target display (the digit 7) may require that subjects increase the rate of processing of information at the location of the target. Under briefer first target presentation times, a reasonable strategy for the subject would be to attend more carefully to the location of the target letter. For the models referred to above, "attending more carefully" to the area of the first target would be described as a smaller spotlight width, channel size, zoom lens size, or a smaller variance in the distribution of processing resources.

If the reduction in first target duration were sufficiently effective in reducing the size of the attended area, the flanking letters of the second target display would fall outside the boundary of the attended area established by the first target (because the second target follows immediately after, and in the same location as, the first target). Thus, the important effect of manipulating first target duration is to have control over the size of the attended area at the onset of the second target. Over a block of trials, flankers falling outside the attended area would receive little or no processing, and thus a reduction in size of the attended area would be evidenced as a reduction in I–C.

Another variable of possible relevance in the present method is the duration of the second target. It is possible that longer durations of the second target provide increased opportunities to shift attention from the target to a flanker prior to responding, leading to an increase in I–C. On the other hand, it is possible that longer second target durations could enable the subjects to concentrate attention more narrowly on the target before responding, thus producing a smaller I–C value. In either case, if first target duration is effective in controlling the size of the attended area, and subjects respond promptly, then a longer presentation time of the second target should have less of an effect on the Incompatible–Compatible difference.

Manipulations of both first and second target durations are tested in the first experiment. The primary expectation is that I–C will decrease as the duration of the first target decreases. It is left to the data to inform us whether the duration of the second target has an effect on I–C.

Experiment 1

Method

Subjects. Twenty-four undergraduate students from the University of California, Irvine, served as subjects in partial fulfillment of a course requirement. All had normal or corrected-to-normal vision.

Apparatus. An IBM-AT computer equipped with an EGA graphics card generated displays and recorded response measures. All stimuli were white letters on the dark screen of an NEC Multisync monitor; viewing distance was maintained at 48 cm by use of an adjustable head- and chinrest. At this distance a character (5 pixels) subtended approximately 0.23° of visual angle; character center-to-center distance (8 pixels) was 0.31 cm, subtending approximately 0.37°; character edge-to-edge distance (3 pixels) was 0.11 cm, for a visual angle of 0.14°. Subjects responded with two 2.5-cm buttons arranged side by side 7.6 cm apart on a 28-cm × 36-cm response panel located directly in front of them.

Stimuli. There were four events on a trial: a warning signal, a first target (T1), a second target (T2), and a postmask. Each display was 17 characters long and was presented consecutively in the same location, with interstimulus intervals of 50 ms. The warning signal was a string of number signs with an asterisk in the center (########*########), which was displayed for 1,000 ms. T1 was a row of alternating Ts and Zs, with either a 7, a T, or a Z in the center (e.g., TZTZTZTZ7TZTZTZTZ). Subjects were required to identify a 7 as the center character of T1 before responding to T2. There were three different durations for T1: 83, 350, and 600 ms. T2 was a character from the set (C, H, S, K) surrounded by eight identical characters on each side from the set C, H, S, K, X (e.g., HHHHHHHHCHHHHHHHH). There were two different timings for T2: 100 and 600 ms. First and second target duration were varied orthogonally; thus there were six separate conditions. The second target was followed by a 300-ms postmask identical to the warning signal.

Response assignments. Each subject was assigned two of the letters for a right-hand response, and two for a left-hand response. The target letter (C, H, S, K) was surrounded by either Xs (*Neutral* condition), the same letter (*Same* condition), or one of the remaining letters (*Incompatible* or *Compatible* conditions). For example, a subject in the CH-left SK-right group would make a right-hand response on a trial in which the T1 contained a 7 in the center position, and was followed by an S in the center position of the T2. There were four left-hand/right-hand response assignments: CH/SK, SK/CH, CK/SH, and SH/CK. Response assignments were counterbalanced between subjects for hand (left or right) and letter shape—curved (C and S) or straight (H and K).

Procedure. Subjects were run individually in a normally lighted room. All displays were viewed binocularly. Each subject ran all six conditions (3 T1 durations × 2 T2 durations) in separate sessions, one session per day for 6 days; session order was determined via a 6 × 6 Latin square. A session consisted of two blocks of 120 trials, with a brief rest every 40 trials, and a longer rest between blocks. Two-thirds of the trials required a response; one-third were catch trials in which the T1 did not contain a 7 as the center letter. Of the 80 trials requiring a response, 16 contained Neutral flanker T2s, 16 were Same flankers, 16 were Compatible flankers, and 32 were Incompatible flankers. The four different target letters were presented an equal number of times in each block. Response time and accuracy to the second target were measured.

Errors were indicated by the display "ERROR" immediately after an incorrect response; misses were indicated by a "MISSED" message if no response was made within 1,000 ms after the onset of the T2. The intertrial interval was 750 ms.

Results

Figure 1 shows mean response time as a function of T1 duration for the four flanker–target conditions (Incompatible, Neutral, Same, Compatible). The top panel shows data for T2=100 ms and the bottom panel shows data for T2=600 ms.

The Neutral, Compatible, and Same data points are based on approximately 728 response times, while the Incompatible points are based on approximately 1,456 response times. It is clear that, overall, mean response time (RT) decreases as T1 duration increases, with a slight increase in response time at the longest T1. Also, it is apparent that the difference between the Incompatible and Compatible conditions increases as T1 duration increases. This effect is presented and analyzed separately (see Figure 2).

An analysis of variance compared response times across the factors of T1 duration, T2 duration, flanker–target condition, and block (first vs. second). The main effect of first target was significant, $F(2, 46) = 15.5$, $p < .01$, indicating a decrease in RT with increasing duration of T1. The effect of flanker–target condition was significant, $F(3, 69) = 20.6$, $p < .01$, indicating response times to the Incompatible displays were longer than those to the Compatible displays. The interaction of T1 duration with flanker–target condition was also significant, $F(6, 138) = 3.37$, $p < .01$, supporting the observation that the difference in RT between the Incompatible and Compatible conditions increases with T1 duration. The three-way T1 Duration × Flanker–Target Condition × Block interaction was also significant, $F(6, 138)=2.68$, $p < .05$. A closer examination of the data reveals a difference in the Incompatible–Compatible differences between blocks. In Block 1 the largest difference occurs when T1=600 ms. In Block 2, the largest difference occurs when T1=350 ms. However, in both blocks the smallest difference occurs when T1=83 ms.

Figure 2 shows the difference in mean RT between the incompatible and Compatible conditions (I–C) as a function of T1 duration for T2=100 ms and T2=600 ms. The metric I–C increases from T1=83 ms to T1=350 ms and appears to remain unchanged at T1=600 ms. When T2=600 ms I–C appears to be slightly higher than when T2=100 ms.

A second analysis of variance compared the values of I–C over the factors of T1 duration, T2 duration, and block. Only the main effect of T1 duration was significant, $F(2, 46) = 3.41$, $p < .05$, supporting the observed increase in I–C with duration of T1. The apparent effect of T2 duration was not significant, $F(1, 23) = 1.08$, $p = .31$, nor was the effect of block, $F(1, 23) = 0.22$, $p = .64$. No interactions were significant.

Although the overall error rates were low, some important trends were evident in the error data. Table 1 shows the proportion of wrong responses as a function of T1 duration for the four flanker–target conditions. A wrong response was made when the subject pressed the wrong button in response to the second target. As would be expected, the greatest proportion of wrong responses were made to the Incompatible condition. Table 2 gives the proportion of misses. A miss was recorded whenever the subject failed to respond to the second target within 1,000 ms of onset. Subjects made the greatest number of misses when T1 duration was very short (83 ms). Both wrong responses and misses are contingent upon the appearance of the 7 in T1. Errors occurred when subjects responded when the first target did not contain a 7. Because of a problem with the data collection routine, error rates could

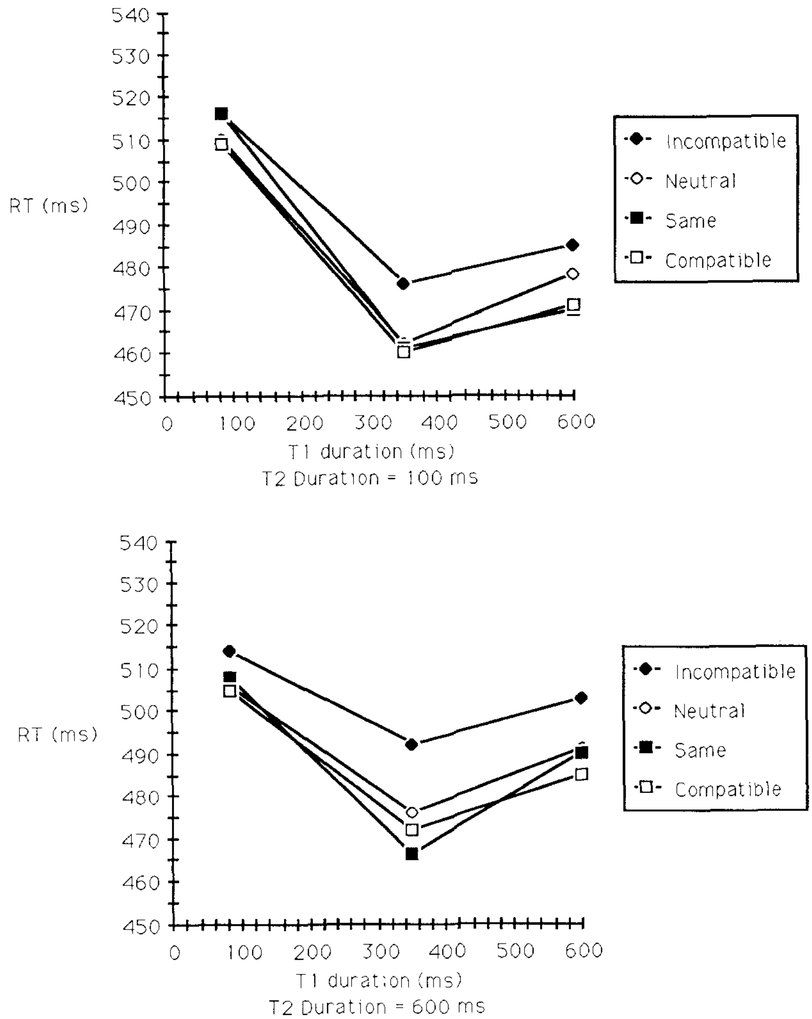

Figure 1. Experiment 1: Mean response times to the second target as a function of first target duration for the four flanker–target conditions. (For the top panel, second target duration is 100 ms; for the bottom panel, second target duration is 600 ms.)

not be calculated for the individual flanker–target conditions. Table 3 gives proportion of errors as a function of T1 duration for both T2 durations. Errors were rare except at the 83-ms first target duration.

An analysis of variance that compared wrong responses across the factors of T1 duration, T2 duration, flanker–target condition, and block indicated only one significant effect, the main effect of flanker–target condition, $F(3, 69) = 9.69$, $p < .01$; Incompatible wrong responses are clearly greater than wrong responses to the Compatible and Same conditions. A similar analysis of misses indicated a main effect of T1 duration, $F(2, 46) = 19.9$, $p < .01$, and a main effect of flanker–target condition, $F(3, 69) = 3.64$, $p < .05$. An analysis of variance of errors comparing the factors of T1 duration, T2 duration, and block indicated a main effect of T1 duration, $F(2, 46) = 36.2$, $p < .01$, and a significant interaction of T1 duration, T2 duration, and block, $F(2, 46) = 3.71$, $p < .05$. Closer examination of the data shows that errors are highest in the second block when T1=83 ms and T2=100 ms (i.e., the most difficult condition). Although not statistically significant, there are consistent increases in wrong responses, misses, and errors from the first to the second blocks.

Discussion

The principal result of Experiment 1 is that the indicator of flanker processing, the difference between the response times to the Incompatible and Compatible displays, decreases significantly as the duration of the first target display decreases. The range in which I–C exhibits the greatest change appears to be between the durations of 83 and 350 ms. Apparently, increases in the duration of the first target beyond 350 up to 600 ms appear to have little or no effect. It is also apparent from the data in Tables 2 and 3 that the errors and misses increase disproportionately as the duration of the first target decreases to 83 ms. In contrast to the effect of changing

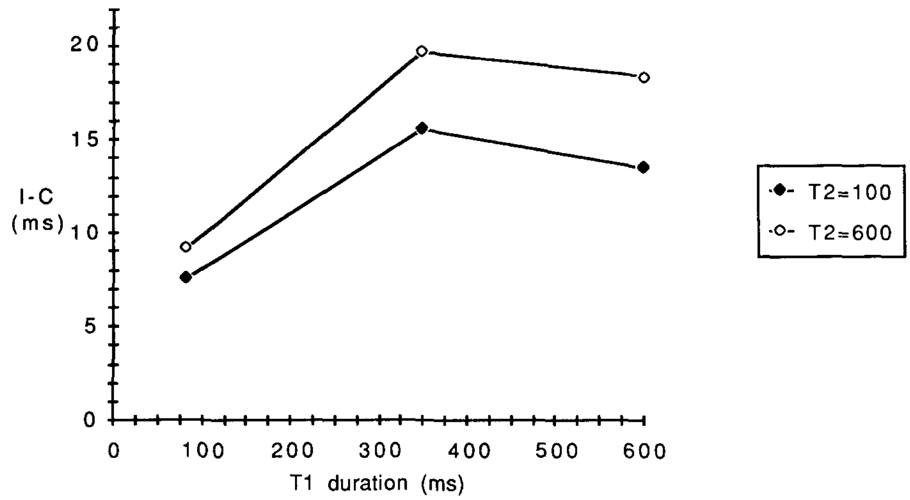

Figure 2. Experiment 1: I–C as a function of first target duration for the two second target durations.

the duration of the first target, changing the duration of the second target did not produce a statistically significant difference in I–C, even though a trend is shown in Figure 1.

There is a rather large discrepancy between the I–C values obtained in the present experiment and those obtained by Eriksen and Eriksen (1974). In Experiment 1 the largest I–C value is approximately 20 ms at a target–flanker separation of 0.14°, when T1 = 350 ms and T2 = 600 ms (see Figure 2). Eriksen and Eriksen obtained a maximum value of about 80 ms for a target–flanker separation of 0.06° and a minimum value of about 20 ms at separations of 0.5° and 1.0°. Linear interpolation of the Eriksen and Eriksen data (which gives an underestimate in this case) yields an I–C value of about 64 ms at 0.14°. Four important differences between the two studies should be noted. First, Eriksen and Eriksen's target–flanker displays were preceded by a fixation cross (that appeared below the center target letter), whereas the present targets were preceded by two displays that appeared in the same location as the target display and were designed to induce the subject to attend narrowly at the location of the upcoming target. Second, Eriksen and Eriksen did not mask their displays, whereas our second target was followed by a postmask. Third, in the Eriksen and Eriksen study the target–flanker display was presented for 1,000 ms, whereas in the present study the display was presented for at most 600 ms. And fourth, our subjects responded by pressing one of two buttons using one hand for each button, whereas Eriksen and Eriksen's subjects used a single hand to press a single lever to the left or right. Although it is possible to press two buttons simultaneously, it is not possible to press a lever both to the left and to the right simultaneously. So a subject initiating an incorrect button press may take less time to reverse the mistake than a subject initiating an incorrect lever press.

To strengthen the finding that the duration of the first target has a systematic effect on the Incompatible–Compatible response time differences, and to determine more precisely the durations at which there is the greatest effect, we carried out a second experiment similar in procedure to that of the first experiment, but with more first target durations (six timings between 67 ms and 450 ms) and a constant second target duration (200 ms). In an attempt to obtain a lower minimum value of I–C we decreased the shortest T1 duration to 67 ms.

Table 1
Mean Proportion Wrong Responses by T1 and T2 Duration for the Target-Flanker Conditions of Experiment 1

T1 duration (in ms)	Target–flanker condition I	C	S	N
	T2 duration = 100 ms			
83	.0410	.0273	.0274	.0417
350	.0573	.0287	.0260	.0378
600	.0521	.0299	.0313	.0443
	T2 duration = 600 ms			
83	.0469	.0339	.0365	.0391
350	.0573	.0339	.0352	.0391
600	.0493	.0365	.0313	.0391

Note. I = Incompatible, C = Compatible, S = Same, and N = Neutral.

Experiment 2

Method

Subjects. Subjects were 24 undergraduate students from the University of California, Irvine, who agreed to participate in partial fulfillment of course requirements. All had normal or corrected-to-normal vision. None of the subjects had participated in the first experiment.

Apparatus and stimuli. The apparatus and stimuli were identical to those of Experiment 1, with the exception that the number of T1 durations was increased to six (67, 100, 150, 250, 350, and 450 ms) and the T2 duration was held constant at 200 ms. Thus, the number of experimental conditions remained six.

Table 2
Experiment 1 Mean Proportion Misses by T1 and T2 Duration for the Target–Flanker Conditions

T1 duration (in ms)	Target-flanker condition I	C	S	N
	T2 duration = 100 ms			
83	.0234	.0182	.0326	.0182
350	.0039	.0039	.0078	.0052
600	.0020	.0013	.0039	.0039
	T2 duration = 600 ms			
83	.0280	.0182	.0274	.0352
350	.0046	.0013	.0065	.0026
600	.0098	.0065	.0143	.0052

Note. I = Incompatible, C = Compatible, S = Same, and N = Neutral.

Procedure. Response assignments were the same as in Experiment 1. As in Experiment 1, subjects ran each condition in a separate session (one session per day) and each session contained two 120-trial blocks composed of the same flanker-target conditions as in Experiment 1. Session order was determined by means of a balanced Latin square.

Results

Figure 3 shows mean response time as a function of T1 duration for the four flanker-target combinations. The means for the Neutral, Compatible, and Same conditions are based on approximately 728 observations per point. The means for the Incompatible condition are based on approximately 1,456 observations per point.

Two clear trends are evident in the data. Response time decreases as a function of the duration of the first target for all flanker-target conditions, and the difference between the Incompatible condition and the other conditions (most important the Compatible condition) increases as T1 duration increases. Figure 4 shows I–C as a function of T1 duration: Clearly, I–C decreases as T1 duration decreases but is still greater than zero.

An analysis of variance compared response times across the factors of T1 duration, flanker-target condition, and block.

Table 3
Experiment 1 Mean Proportion Errors by T1 and T2 Durations Collapsed Across Target–Flanker Conditions

T1 duration (in ms)	Proportion errors
T2 duration = 100 ms	
83	.0385
350	.0021
600	.0016
T2 duration = 600 ms	
83	.0297
350	.0031
600	.0016

The main effect of T1 duration was significant, $F(5, 115) = 18.1$, $p < .01$, again indicating decreasing response time as a function of increasing T1 duration. The effect of flanker–target condition was significant, $F(3, 69) = 60.5$, $p < .01$, and the T1 × Flanker–Target interaction was significant, $F(15, 345) = 2.11$, $p < .01$, confirming the observation that the differences between the Incompatible and Compatible conditions increase with T1 duration. The effect of block was not significant, $F(1, 23) = 0.3$, $p = .59$. No other interactions were significant.

A second analysis of variance compared I–C for the factors of T1 duration, flanker–target condition, and block. Only the main effect of target duration was significant, $F(5, 115) = 3.1$, $p < .05$, indicating a significant reduction in I–C with decreasing T1 duration.

As in Experiment 1, the overall error rates were low, but there are several trends discernable in the error data. Table 4 shows the proportion of wrong responses as a function of T1 duration. As in Experiment 1, wrong responses are clearly greater for the Incompatible condition than for the other conditions. Wrong responses to the Incompatible condition appear to increase with T1 duration. Table 5 shows proportion of misses; the 67-ms first target duration proved relatively difficult for the subjects, generating the greatest number of misses. Table 6 shows proportion of errors to the first target. The greatest number of errors occurred at a first target duration of 67 ms.

An analysis of variance comparing wrong responses over the factors of T1 duration, flanker-target condition, and block showed a main effect of flanker-target condition, $F(3, 69) = 7.88$, $p < .01$, and an interaction of T1 duration with target–flanker condition, $F(15, 345) = 1.92$, $p < .05$, supporting the observation that subjects made more wrong responses to the Incompatible condition and the number increased with T1 duration. A similar comparison of misses indicated a main effect of T1 duration, $F(5, 115) = 24.2$, $p < .01$, showing a significantly greater number of misses when the T1 duration was 67 ms. The main effect of block was also significant, $F(1, 23) = 12.4$, $p < .01$. Subjects missed a greater number of responses during the second block at all T1 durations. And as in Experiment 1, though not statistically significant, there is a slight increase in wrong responses and errors from the first to the second block. The comparison of error rates indicated that the observed effect of T1 duration was significant, $F(5, 115) = 16.7$, $p < .01$. The analysis also indicated an unexpected effect for the flanker-target conditions, $F(3, 69) = 3.74$, $p < .05$. Apparently subjects made more errors (to the first target) when the second target was of the incompatible type.

Because Experiments 1 and 2 both show that mean RT increases as T1 duration decreases, it is possible that this increase in RT is somehow responsible for the observed decrease in I–C, that is, that the increase in RT causes the decrease in I–C. We conducted further analyses in an attempt to rule out this possibility.

The first analysis is statistical in nature. To obtain as accurate an estimate as possible of each subject's mean response time to each of the six T1 durations in Experiment 2, the mean of all four flanker–target conditions for each T1

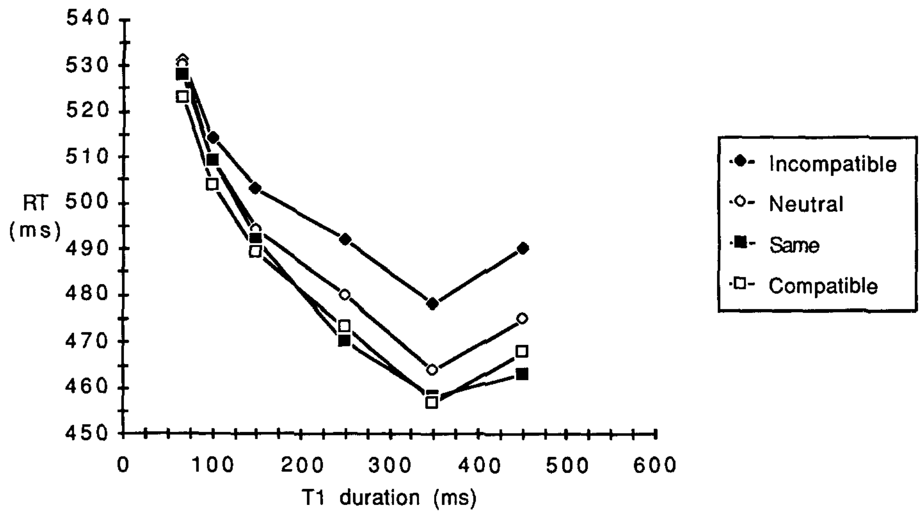

Figure 3. Experiment 2: Mean response time as a function of first target duration for the four flanker–target conditions. (Second target duration was constant at 200 ms.)

duration was used. The slope of the least squares regression line through these six points was then computed for each subject. This slope provided a reasonable estimate of the tendency of each subject's mean RT to vary systematically with the duration of the first target. Similarly, for each subject, we obtained the slope of the least-squares line through the I–C and T1 duration points. This slope provided an estimate of how much each subject's I–C values vary with the duration of the first target. If RT is causally related to I–C, we would expect increasingly large RTs to give rise to increasingly small I–C values; that is, I–C should be a monotonically decreasing function of RT. If there were a tendency for I–C to decrease monotonically as RT increases, then the RT slope should be negatively correlated with the I–C slope.

Comparing the pairs of slopes for 24 subjects showed no evidence of a correlation, $r = -.08$, $p = .71$. The lack of

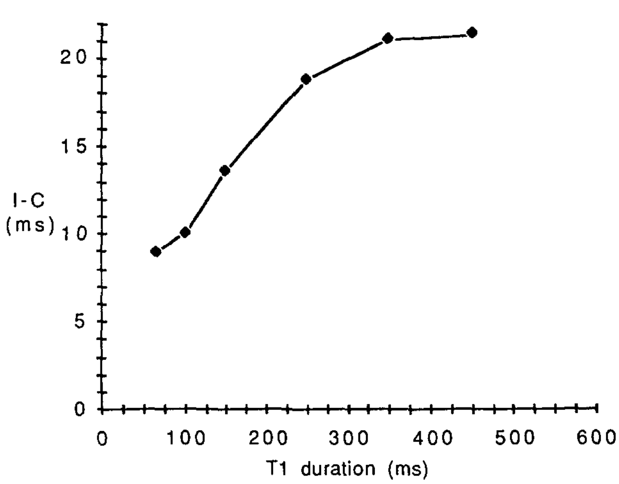

Figure 4. Experiment 2: I–C as a function of first target duration. (Second target duration is constant at 200 ms.)

correlation is clear from the scatterplot shown in Figure 5. To allow for the possibility that the longest T1 duration (450 ms) constrained the overall RT slope estimate, we analyzed the data without these points. The correlation based on five T1 values was a positive $r = .13$, $p = .54$. We also examined the correlation for each subject between RT and I–C for each T1 condition. The correlation coefficients for the 67-, 100-, 150-, 250-, 350-, and 450-ms T1 conditions were −.27, .24, .12, −.16, .19, and .09, respectively. None was statistically significant. It appears that the data do not support the hypothesis that the decrease in I–C is the direct result of factors that increase the absolute RT values.

It may appear inconsistent that the observed increase in RT and decrease in I–C with decreasing T1 duration is not associated with a correlation between rate of increase in RT and rate of decrease in I–C at the individual subject level. However, the only requirement to generate the observed pattern of results is that individual subjects show an increase in RT and a decrease in I–C with decreasing T1 duration. (Figure 5 shows that 19 of 24 subjects had negative RT slopes and positive I–C slopes.) This fact says nothing about how these slopes are related within subjects. Several patterns of individual I–C and RT slopes could produce the same overall results.

Experiment 2b

Since increasing (decreasing) the amount of time in which subjects are allowed a response is known to increase (decrease) response time, we ran a control experiment in which we manipulated response time by varying the "deadline" time, the amount of time within which a response must occur to be counted as correct. The message "MISSED" signaled the deadline; trials in which the subjects responded after the deadline were counted as misses.

Ten subjects were run with the same procedure as Experiments 1 and 2, except that the T2 letters were changed to C, H, D, and F (rather than C, H, S, and K), and only Compatible and Incompatible displays were used. T1 duration was constant at 100 ms, and the two deadlines were 650 and 1,300 ms. Each subject ran 48 practice trials and 96 test trials under each deadline condition in two sessions, separated by at least 2 hr. The order of sessions was balanced between two groups of 5 subjects.

The response time results are shown in Table 7. The 650-ms deadline condition produced substantially more wrong responses and misses than the 1,300-ms condition; therefore the RT data were corrected to offset possible biases. The procedure for correcting each subject's raw response time scores was to match each wrong response time with a correct response time near the wrong response value, and remove these correct scores from the distribution, an adaptation to medians of Yellott's (1967, 1971) procedure for correcting for fast (and slow) guesses. The number of misses were then added onto the tail of the distribution, and medians were computed for each subject. The mean response time data and the uncorrected and corrected medians are shown in Table 7. Proportions of wrong responses and misses to the second target are shown in Table 8. Error proportions to the first target were .059 and .072 for the 650- and 1,300-ms deadline conditions, respectively.

A sign test of the corrected medians showed the effect of deadline time to be significant ($p < .001$). A t test of the I–C values that was based on corrected medians was not significant, $t(9) = 1.49$, *ns*, indicating that although the I–C values appeared to increase from the 650- to the 1,300-ms deadline conditions, the present data do not lend clear support for this increase. Though the change in I–C for the corrected medians was not significant, the uncorrected mean change in I–C was significant, $t(9) = 2.35$, $p < .05$, as was the change in I–C between the uncorrected median response times, $t(9) = 2.29$, $p < .05$.

The change in response deadline from 650 to 1,300 ms had a consistent effect on overall response times. In fact, for every subject and display type the mean and median (both corrected and uncorrected) response times showed a consistent increase. The increase in response time did not produce a decrease in I–C, but rather the trend of the data indicates that increasing response time produces a corresponding increase in I–C. Additional evidence for the validity of this control experiment is engendered by the fact that the I–C value and the means of the medians for the Incompatible and Compatible conditions for the 650-ms deadline were quite close to the mean response times and I–C values obtained for the 100-ms T1 duration condition of Experiment 2, shown in Figure 3.

In summary, both statistical analysis and additional data indicate that the decrease in I–C shown in the results of Experiments 1 and 2 is not due to the increase in absolute response time produced by a decrease in T1 duration.

Table 4
Mean Proportion Wrong Responses by T1 Duration and Display Type for Experiment 2

T1 duration (in ms)	Display type			
	I	C	S	N
67	.0267	.0117	.0169	.0208
100	.0176	.0300	.0300	.0182
150	.0300	.0143	.0078	.0182
250	.0339	.0130	.0182	.0169
350	.0397	.0143	.0117	.0234
450	.0358	.0260	.0221	.0234

Note. I = Incompatible, C = Compatible, S = Same, and N = Neutral.

Table 5
Mean Proportion Misses by T1 Duration and Display Type for Experiment 2

T1 duration (in ms)	Display type			
	I	C	S	N
67	.0436	.0443	.0169	.0494
100	.0130	.0078	.0300	.0169
150	.0046	.0052	.0078	.0039
250	.0026	.0026	.0182	.0039
350	.0000	.0013	.0117	.0013
450	.0013	.0000	.0221	.0039

Note. I = Incompatible, C = Compatible, S = Same, and N = Neutral.

Discussion

The results of Experiment 2 confirm and strengthen the main finding of Experiment 1. The duration of the first target shows a clear and orderly effect upon the response time difference between the Incompatible and Compatible displays. Both the initial value and asymptotic values indicated by the curve shown in Figure 4 conform to the values obtained in Experiment 1 (cf. Figure 2).

The general interpretation of the finding that the duration of the first target affects the processing of the flankers in the second target is that the duration of the first target influences the effective size of the attended area, which in turn influences the processing of information at the location of the flankers. A short duration presumably induces the subject to decrease the size of the attended area at the location of the target, and consequently the information at the location of the flankers is less likely to be processed, resulting in an overall decrease in the response time difference between the Incompatible and Compatible displays. This conclusion is strengthened further by the convergence of absolute response time curves for the Same and Neutral displays shown in Figure 3. The Same displays show response time values very close to those for the Compatible displays across the range of durations, and the Neutral displays fall almost midway between the values of the Incompatible and Same displays, as would be expected if the Neutral displays carried information that is relatively unbiased with respect to a response.

We note at this point that because the interstimulus interval between T1 and T2 was constant at 50 ms, T1 duration covaries with the total time between the onset of T1 and the onset of T2 (stimulus onset asynchrony [SOA]). It is possible that T1 duration does not affect the initial spread of attention, but that initially identical spreads of attention broaden with increasing SOA. This explanation is also consistent with the

Table 6
Mean Proportion Errors by T1 Duration and Display Type for Experiment 2

T1 duration (in ms)	Display type			
	I	C	S	N
67	.1340	.1610	.1280	.1060
100	.0195	.0339	.0104	.0104
150	.0039	.0052	.0000	.0026
250	.0026	.0000	.0000	.0000
350	.0026	.0000	.0000	.0000
450	.0013	.0078	.0000	.0026

Note. I = Incompatible, C = Compatible, S = Same, and N = Neutral.

finding that I–C increases with T1 duration. However, as noted earlier, the significance of the present design is that it measures the size of attention at the onset of T2. Thus, the fact that I–C can be changed independently of target–flanker separation is evidence that the effective size of the attended area has changed. The question of what is the precise mechanism that produces that change is currently under investigation (Hartley, Carter, Brown, & LaBerge, 1991). Recall, however, that the LaBerge (1983) study discussed earlier provides independent evidence that the initial spread of attention can be changed: Response time patterns to the second target differed between the letter and word first target conditions, although the first target/second target SOA was the same in both conditions.

Since the response time difference between the Incompatible and Compatible displays did not reach zero at the shortest duration, the implication is that the minimum effective size of the attended area was greater than the width of a target letter plus one space on either side, or for subjects in this task, approximately 0.5° of visual angle. However, for a difference between the Incompatible and Compatible displays greater than zero, there is no unambiguous indication of where a boundary of the attended area may be located along the string of letters in a display.

It is obvious that I–C could be reduced to zero if we radically increased the spacing between the target and flanking letters. With sufficient distance between the letters (e.g., 25°) the flankers would not be identified, so the response times to the Incompatible and Compatible displays would be equal. But retinal locations 25° from the fovea are considerably impoverished in terms of acuity, so a failure to process flankers at such an eccentricity could be attributed to acuity rather than to attention. Therefore, in an attempt to reveal effects of attention rather than acuity, the distance between target and flankers should be kept to a minimum.

However, at the between-character spacing used in Experiments 1 and 2, errors were greater than 10% at a first target duration of 67 ms, compared to 3% at 100 ms (Experiment 2) and 3% to 4% at 83 ms (Experiment 1). Thus, it appears unlikely that reducing T1 further while holding spacing constant would give fruitful results. To reduce T1 duration without a sharp increase in errors, we increased the spacing between characters from 0.14° to 0.32° (half of a character space).

Another problem that arises in attempting to demonstrate an I–C of zero is the difficulty of providing statistical support to observed differences of zero. However, by accumulating many observations one can reduce the confidence interval associated with an obtained mean near zero. To obtain a large number of observations under approximately constant and more highly controlled conditions, we decided to run many trials on a few subjects rather than relatively few trials on many subjects.

To obtain roughly equal numbers of observations for the Compatible and Incompatible conditions and still maintain a reasonable number of trials for subjects to run, only Compatible and Incompatible displays were used. The number of trials per session was reduced due to the increase in errors and misses from first to second blocks noted in Experiments 1 and 2. Also, because individual differences in spatial and temporal acuity as well as in ability to focus attention become increasingly important at short display durations, an attempt was made to find the minimum effective display duration for each subject.

Experiment 3

Method

Subjects. Four subjects participated in this experiment. Each subject was assigned one of the four response assignments used in Experiments 1 and 2.

Apparatus and stimuli. Apparatus and stimuli were identical to those used in Experiments 1 and 2, except that only Compatible and Incompatible second targets were used and the spacing between the characters in each of the displays was increased to half of a character space (7 pixels, 0.32°).

Procedure. The trial events were as in the previous experiments. Two T1 durations were used and T2 was held constant at 100 ms. The fastest duration at which each subject was able to identify the first target 7 on better than 85% of the trials was chosen for the "short" T1 condition. This apparently low cutoff was chosen so that subjects would be forced to concentrate attention at the center location of the first target because of the difficulty of the task. For 3 subjects this was 50 ms and for 1 subject 33 ms. The "long" T1 condition was determined by adding 200 ms to the duration of the

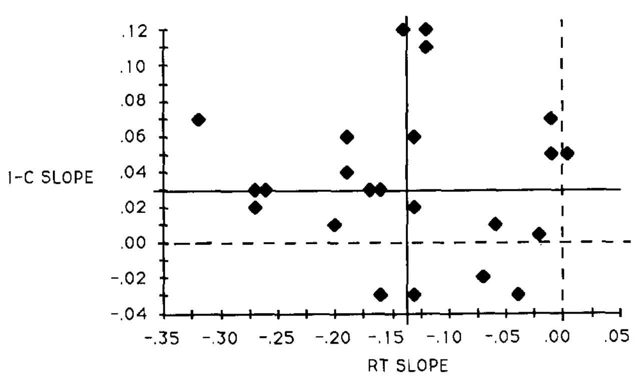

Figure 5. Experiment 2: Scatterplot of I–C slopes versus RT slopes for 24 subjects. (Dashed lines indicate zero points; solid lines indicate median values.)

Table 7
Uncorrected and Corrected Compatible and Incompatible Response Times and I–C Values for the 650-ms and 1,300-ms Deadline Conditions of Experiment 2b

	Deadline condition					
	650 ms			1,300 ms		
RT measure	C	I	I–C	C	I	I–C
Uncorrected mean of means (in ms)	487	490	3	596	617	21
Mean of medians (in ms)						
Uncorrected	486	491	5	569	594	25
Corrected	499	511	12	580	605	25

Note. C = Compatible displays; I = Incompatible displays.

short T1. Each subject ran a total of 24 sessions each containing a practice block of 24 trials and a test block of 96 trials. Sessions were run two per day for 12 days. Two subjects ran six short T1 sessions followed by 12 long T1 sessions followed again by six short T1 sessions. The order was inverted for the other 2 subjects. Each block contained equal numbers of Compatible and Incompatible trials and two-thirds of the trials required a response.

Results

The mean reaction times of each subject to the Compatible and Incompatible second targets for the short and long T1 durations are shown in Figure 6. Each point is based on approximately 384 observations. The I–C values are given in Figure 7.

On average, the results of Experiment 3 are consistent with the results of the first two experiments. For 2 subjects I–C increases as T1 increases. For 2 subjects there is no apparent change in I–C from the short T1 to the long T1. The most important observation about the data is that at the short T1 duration none of the I–C values appear to be significantly greater than zero (the measured values for the 4 subjects are 0, 2, 0, and 1).

The mean RTs, I–C values, and standard errors for the I–C values are presented in Table 9. For all subjects the standard errors at the short T1 duration overlap zero, whereas for 2 subjects the standard errors at the long duration do not overlap zero.

As in Experiments 1 and 2, more wrong responses were made to the Incompatible condition than were made to the Compatible condition. The combined proportion of wrong responses are 6.0% and 5.5% for the Incompatible short and long T1 durations, respectively, and 4.1% and 4.0% for the Compatible short and long T1 durations, respectively. The combined proportion of misses are much greater for the short T1 duration than for the long T1 duration: 6.3% and 6.5% for the short Incompatible and Compatible conditions, respectively, and 0.7% and 0.5% for the long Incompatible and Compatible conditions, respectively. Although no subject made a single error at the long T1 duration, as expected, errors were high at the short T1 duration: 11.5% for the Incompatible condition and 14.4% for the Compatible condition.

Table 8
Proportion Wrong Responses and Misses by Condition for Experiment 2b

	Deadline condition			
	650 ms		1,300 ms	
Error type	C	I	C	I
Wrong responses	.069	.103	.053	.047
Misses (in ms)	.091	.119	.084	.047

Note. C = Compatible displays; I = Incompatible displays.

Discussion

It appears that the 4 subjects' I–C values were at or very near zero for the short T1 duration, indicating that they had successfully filtered the flankers in that condition. However, the size of the standard errors leaves room for the possibility that the actual values of I–C were positive. We note that in this experimental procedure an occasional "lapse" of narrowed attention could result in sampling information from the location of a flanker. ("Lapses of attention" cannot be ruled out even under less demanding conditions in which the target and flankers are separated by two or three spaces.) Because the occurrence of an incompatible flanker is as likely as a compatible flanker, such a lapse will move the mean response time difference away from zero in the positive direction. There is no compensating factor to move the mean response time difference away from zero in the negative direction, and chance variation moves the differences in both directions. Because the likelihood of maintaining an invariant attention state from trial to trial decreases as the number of trials increases, the benefit gained by increasing the number of observations (to reduce standard error) will be at least partially offset by the cost incurred with the increased probability that the mean difference in response times will not be greater than zero. Therefore, even if subjects were able to narrow attention sufficiently to filter out flanking information on a vast majority of the trials, their overall I–C difference would be likely to be greater than zero. However, the I–C data from Experiment 3 appear to be sufficiently close to zero to be taken as serious support for the claim that the subjects, on a reasonable number of trials, have indeed narrowed attention to an area whose width is approximately the width of the target letter plus half a space on either side (approximately 0.87°).

General Discussion

The first main finding, provided by the first two experiments, showed that the effective size of an area of attention could be narrowed by reducing the duration of an identified digit occurring immediately prior to the onset of a target letter. The second main finding, obtained from an extended series of trials by 4 subjects in Experiment 3, indicated that the effect of the flankers could be virtually eliminated. When the results of Experiment 3 are interpreted within the context

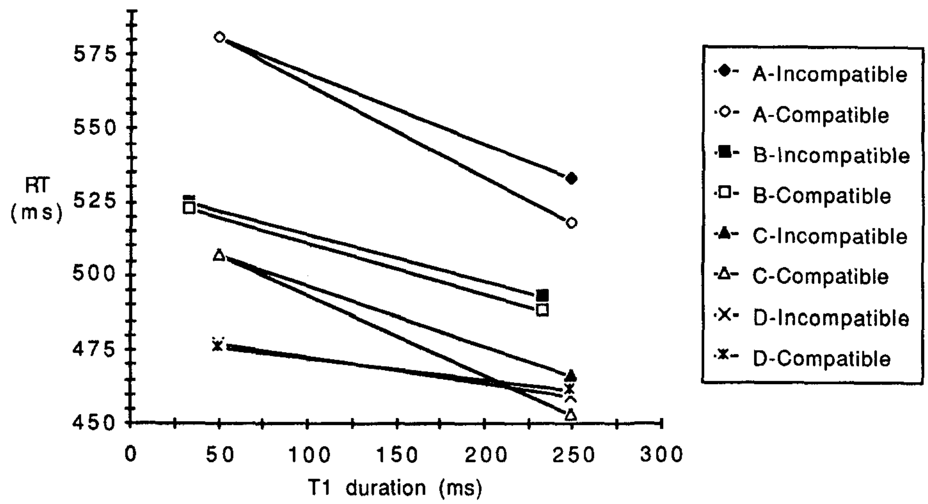

Figure 6. Experiment 3: Mean response times for the 4 subjects (A, B, C, D) as a function of first target duration for the Incompatible and Compatible flanker–target conditions. (Second target duration is constant at 100 ms.)

of the results of Experiments 1 and 2, it would appear that the major factors contributing to the elimination of flanker influence on response time were the very short first target durations and the increase of the space between a target and flanker from 0.14° to 0.32°.

Is the finding of the change in amount of flanker processing as duration of the first target varied consistent with each of the four models of the attended area described at the beginning of this article? From the viewpoints of the zoom lens and resource distribution models, one could account for the present findings by assuming that shorter durations of the first target simply narrow the focus of the lens or reduce the area in which resources are most concentrated. For cases in which I–C is effectively zero, the values of the distribution at flanker locations would approach zero, and such a distribution would be indistinguishable from a spotlight or filter channel. From the viewpoints of the spotlight and filter-channel models, shorter durations of the first target would have the effect of contracting the boundaries of the attended area. Therefore, all four models under consideration apparently give straightforward accounts of the present results.

However, the spotlight and filter-channel models conceivably encounter problems with the findings of the present experiments if the assumption is made that complete filtering of flankers is required to identify a target letter. Whenever I–C is not zero for some value of the independent variable, we infer that subjects were processing information from flanker items along with the information from target items.

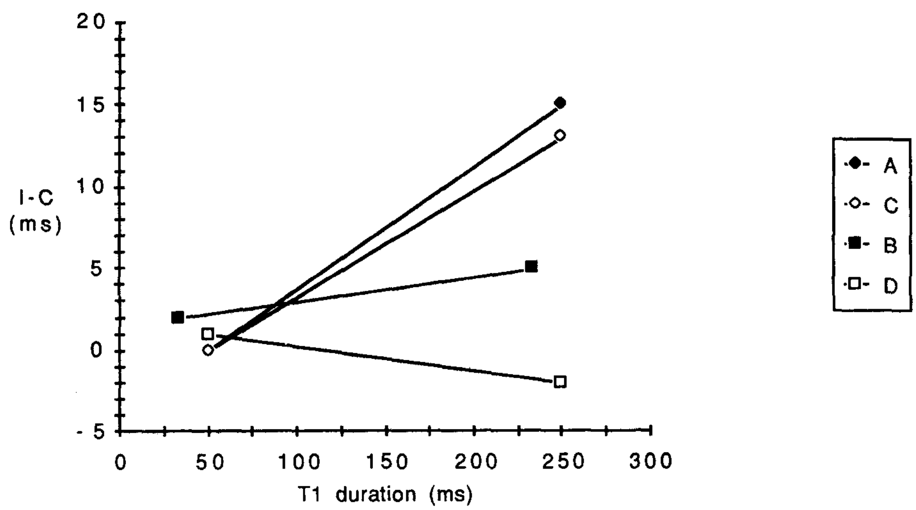

Figure 7. Experiment 3: I–C for the 4 subjects (A, B, C, D) as a function of first target duration. (Second target duration is constant at 100 ms.)

Table 9
Mean Response Times for the Short and Long T1 Durations, I–C, and the Standard Errors of the Difference Between Means

T1 duration	Subject	I	C	I–C	*SE*
Short					
50	A	581	581	0	6.2
33	B	525	523	2	6.2
50	C	507	507	0	5.9
50	D	477	476	1	6.0
Long					
250	A	533	518	15	5.3
233	B	493	488	5	5.1
250	C	459	461	−2	6.0
250	D	466	453	13	4.3

Note. C = Compatible displays; I = Incompatible displays. All figures are in milliseconds.

Yet, in such cases, the subjects were able to identify the target items with high levels of accuracy. LaBerge and Brown (1989) treat this problem by assuming that to identify a letter item, the channel must, at some moment, assume a size small enough to filter out the flanker information. However, the channel may quickly open and close at target and flanker locations many times during a typical display. Exactly where the channel is likely to open at a given time after the display appears is determined by the shape of a distribution of resources across locations of the display.

The shape of the distribution is assumed to be influenced by the duration of the first target. Because the warning signal display contained a distinct object at the central location, the subjects could use this object to concentrate attention in anticipation of the briefly exposed digit that followed the warning signal. When the duration of the digit display was relatively short, the subject concentrated more information flow at the central location, forming a distribution that was high in the center, and falling off rapidly to the left and right of center. When the duration of the digit display was relatively long, the subject concentrated less information flow at the central location, forming a distribution that was lower in the center, and falling off less rapidly to the left and right of center.

Therefore, according to the LaBerge and Brown (1989) account, the operation of attention in these experiments involves two main mechanisms: a fast-acting filter that repeatedly opens and closes at locations of the target and flanker objects, and a distribution of resources that determines probabilistically the location at which the channel will open at any given time.

References

Broadbent, D. A. (1982). Task combination and selective intake of information. *Acta Psychologica, 50,* 253–290.

Downing, C., & Pinker, S. (1985). The spatial structure of visual attention. In M. Posner & O. Martin (Eds.), *Attention and performance XI* (pp. 171–187). Hillsdale, NJ: Erlbaum.

Egeth, H. (1977). Attention and preattention. In G. Bower (Ed.), *The psychology of learning and motivation* (Vol. 2, pp. 277–320). New York: Academic Press.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16,* 143–149.

Eriksen, C. W., & Murphy, T. D. (1987). Movement of attentional focus across the visual field: A critical look at the evidence. *Perception & Psychophysics, 42,* 299–305.

Eriksen, C. W., & St. James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics, 40,* 225–240.

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

Hartley, A., Carter, M., Brown, V., & LaBerge, D. (1991). *Controlling the focus of visual attention.* Unpublished manuscript.

Johnston, W. A., & Dark, V. J. (1986). Selective attention. *Annual Review of Psychology, 37,* 43–75.

Jonides, J. (1983). Further toward a model of the mind's eye's movement. *Bulletin of the Psychonomic Society, 21,* 247–250.

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

LaBerge, D. L., & Brown, V. R. (1989). Theory of attentional operations in shape identification. *Psychological Review, 96,* 101–124.

Miller, J. (1987). Priming is not necessary for selective-attention failures: Semantic effects of unattended, unprimed letters. *Perception & Psychophysics, 41,* 419–434.

Shaw, M. L. (1978). A capacity allocation model for reaction times. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 586–598.

Shiffrin, R. M. (1988). Attention. In R. C. Atkinson, J. R. Herrnstein, G. Lindzey, & R. D. Luce (Eds.), *Stevens's handbook of experimental psychology* (pp. 739–811). New York: Wiley.

Shulman, G. L., Wilson, J., & Sheehy, J. B. (1985). Spatial determinants of the distribution of attention. *Perception & Psychophysics, 37,* 59–65.

Sperling, G., & Melchner, M. J. (1978). Visual search, visual attention, and the attention operating characteristic. In J. Requin (Ed.), *Attention and performance VII* (pp. 675–686). Hillsdale, NJ: Erlbaum.

Yantis, S. (1988). On analog movements of visual attention. *Perception & Psychophysics, 43,* 203–206.

Yellott, J. I. (1967). Correction for guessing in choice reaction time. *Psychonomic Science, 8,* 321–322.

Yellott, J. I. (1971). Correction for fast guessing and the speed–accuracy tradeoff in choice reaction time. *Journal of Mathematical Psychology, 8,* 159–199.

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