

Linear Changes in the Spatial Extent of the Focus of Attention Across Time

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This research examined changes in the spatial extent of focal attention over time. The Attentional Blink (impaired perception of the second of two targets) and Lag-1 sparing (the seemingly paradoxical finding that second-target accuracy is high when the second target immediately follows the first) were employed in a dual-stream paradigm to index spatiotemporal changes in focal attention. Lag-1 sparing occurs to targets in different streams if the second target falls within the focus of attention. Focal attention is assumed to initially encompass both streams but to shrink rapidly to the first-target stream, thus withdrawing from the second target if it appears in the opposite stream. The time available for the focus to shrink before second target onset was manipulated by varying the stimulus-onset asynchrony (SOA) between successive items in the stream. There was a progressive transition from Lag-1 sparing to its converse (Lag-1 deficit) as the SOA was increased. This transition was related linearly to SOA, which suggests that the spatial extent of focal attention varies linearly over time.

Keywords: spatial attention, attentional blink, temporal dynamics of attention, Lag-1 sparing, attention shifts

Stimuli presented at attended locations are processed faster and more accurately than those presented at unattended locations (Helmholtz, 1866/1962; James, 1890/1950; LaBerge, 1995). A common metaphor to describe this finding is that attention functions like a spotlight: items that fall within the spotlight are processed faster and more accurately than items that fall outside. A characteristic that attentional processes share with a spotlight is that both can be directed at specific locations and can be moved rapidly to new locations. Pursuing this metaphor, Eriksen and colleagues (Eriksen & Yeh, 1985; Eriksen & St. James, 1986) proposed a model in which, to optimize performance, the focus of attention can be resized just like a spotlight equipped with a zoom lens.

How quickly attention can be moved from one object or location to another has been studied extensively with both behavioral (e.g., Weichselgartner & Sperling, 1987) and electrophysiologic (e.g., Müller, Teder-Salejari, & Hillyard, 1998) measures. In contrast, studies that investigated changes in the size of the focus of attention have been concerned mainly with the hypothesized inverse relationship between performance and the size of the attended area, with attention becoming more diffuse as the size of the attended

area is increased (Barriopedro & Botella, 1998; Egeth, 1977; Eriksen & St. James, 1986; Eriksen & Yeh, 1985; Jonides, 1983; LaBerge, 1983, 1995). Notably, there has been a dearth of studies of the *rate* at which the focus of attention expands or contracts.

An estimate of the time required to expand focal attention has been provided by Benso, Turatto, Mascetti, and Umiltà (1998), who used a pre-cue to draw attention from the center of the screen to a randomly chosen location, at which a cue was presented. The cue consisted of a ring with a diameter of either 2.5° or 7.5°. After a variable delay, a target was presented within the cued area. The critical assumption was that, upon presentation of the cue, the attentional focus expanded to cover the cued area. The results suggested that the process of expansion was completed within about 33 to 66 ms.

One limitation of Benso et al.'s (1998) study was that it was confined to the case in which the attentional spotlight was expanded. For both practical and conceptual reasons, it is equally important to obtain estimates of the rate at which the focus of attention contracts, and that was the main objective of the present work.

A phenomenon that can be used for this purpose is the *attentional blink (AB)*. When two targets are presented in rapid succession, correct identification of the second target is impaired. This second-target deficit is most pronounced when the temporal lag between the two targets is in the range of 100 to 500 ms (Raymond, Shapiro, & Arnell, 1992). The AB has been investigated with a paradigm known as rapid serial visual presentation (RSVP), in which two targets (e.g., letters) are inserted in a stream of distractors (e.g., digits). Typically, all the items are displayed sequentially in the same location at a rate of one every 100 ms or so.

The present work utilized an aspect of the AB known as *Lag-1 sparing* (Potter, Chun, Banks, and Muckenhoupt, 1998), in which the AB is much reduced when the second target is presented directly after the first (i.e., at Lag 1), without any intervening

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distractors, provided that the inter-target stimulus-onset asynchrony (SOA) is about 100 ms or longer (see Bowman & Wyble, 2007; Chun & Potter, 1995; Giesbrecht & Di Lollo, 1998; Maki, Couture, Frigen, & Lien, 1997; Raymond et al., 1992). Visser, Bischof, and Di Lollo (1999) defined Lag-1 sparing as a positive difference between second-target identification accuracy at Lag 1 *minus* the lowest level of second-target identification accuracy at any other lag. In the present work, the magnitude of Lag-1 sparing was estimated as a positive difference between performance at Lags 1 and 3 on the grounds that in many studies the lowest level of second-target accuracy was reached at Lag 3 or later (e.g., Arnell & Jolicœur, 1999; Chun & Potter, 1995; Duncan, Ward, & Shapiro, 1994; Giesbrecht & Di Lollo, 1998; Raymond, Shapiro, & Arnell, 1992; Seiffert & Di Lollo, 1997; Shapiro, Caldwell, & Sorensen, 1997; Shapiro, Raymond, & Arnell, 1994; Shih, 2000; Spalek, Falcon, & Di Lollo, 2006). A negative difference in second-target accuracy between Lags 1 and 3 was termed *Lag-1 deficit*.

Lag-1 Sparing Across Space

In the present research, we employed Lag-1 sparing and Lag-1 deficit as tools to investigate the temporal dynamics of changes in the spatial extent of attention over very brief intervals of time. In a survey of the literature, Visser et al. (1999) found that Lag-1 sparing never occurs when the two targets are displayed in different spatial locations. Recent examples of this rule have been provided by studies that employed two or more concurrent RSVP streams such that the two targets appear either in the same stream or in different streams (e.g., Dell'Acqua, Pascali, Jolicœur, & Sessa, 2003; Holländer, Corballis, & Hamm, 2005; Juola, Botella, & Palacios, 2004; Kristjansson & Nakayama, 2002; Peterson & Juola, 2000). In these studies, Lag-1 sparing was never found when the two targets were presented in different streams.

Recently, however, Jefferies, Ghorashi, Kawahara, and Di Lollo (2007) found substantial Lag-1 sparing when the two targets were presented in different streams, but only when the second target fell within the focus of attention. In that study, the size of the attentional focus was manipulated in two main conditions. In one, observers knew which of two streams would contain the first target, causing attention to be focused narrowly on that stream. In the other condition, the first target was presented unpredictably in either stream, leading to a broad focus of attention that encompassed both streams.

Of special interest to the present work was the condition in which the two targets appeared in opposite streams. In this case, if attention was narrowly focused on the stream containing the first target, the second target fell outside the attended area and Lag-1 sparing did not occur. If, however, the focus of attention encompassed both streams, the second target fell within the attended area, and Lag-1 sparing occurred. From this perspective, the incidence of Lag-1 sparing can provide a means for achieving the main objective of the present work. Namely, Lag-1 sparing to targets presented in opposite streams can be used to index the location and extent of the focus of attention. The presence of Lag-1 sparing would indicate that the focus of attention was set broadly to encompass both streams; the absence of Lag-1 sparing would indicate that attention was focused narrowly on one stream to the exclusion of the other. Thus, whereas Jefferies et al. (2007) used

the extent of the attentional focus to account for the incidence of Lag-1 sparing, in the present work Lag-1 sparing was used to index the extent of the focus of attention.

Control of Attention in the Spatiotemporal Domain

As noted above, the major objective of the present work was to provide an estimate of the rate at which the focus of attention changes in size. In practice, we used the magnitude of Lag-1 sparing to index the presence of attention at a given spatial location. To monitor changes in the size of the focus of attention over time, we varied the SOA between successive items in the RSVP streams. The importance of SOA becomes evident when one considers the changes in attentional focus that are likely to occur in the course of performing the experimental task. Those changes can be described in terms of an attentional focus the extent of which changes dynamically over time to optimize performance on the task at hand.

We assume that at the outset of any given trial, the observer is set to optimize performance on the first task, namely the identification of the first target. Support for this assumption comes from the findings of Shih (2000) and Jefferies et al. (2007) who employed a dual RSVP stream paradigm. Jefferies et al. hypothesized that when the observers did not know which stream contained the first target, the focus of attention was set broadly to encompass both streams. In contrast, when the location of the first target was known in advance, the focus of attention was hypothesized to be set narrowly on the relevant stream to maximize the probability of detecting the first target. This reasoning was supported by the finding that identification accuracy for the first target was significantly higher when the location of the first target was known in advance. From a theoretical standpoint, this finding is consistent with the hypothesis that attention was focused narrowly on the first target's location, resulting in a higher concentration of attentional resources than if attention had been distributed broadly (Barriopedro & Botella, 1998; Castiello & Umiltà, 1990; Egeth, 1977).

In the present work we employed two concurrent RSVP streams wherein the first target could appear unpredictably in either RSVP stream. In such a display, the optimal initial strategy would be to set a spatially broad focus of attention to encompass both streams. When the first target appeared, the attentional focus would begin to narrow to the stream containing the first target to optimize target identification. If the second target then appears in the same stream, it will fall within the focus of attention and its identification will be enhanced, resulting in Lag-1 sparing. If, however, the second target is presented in the opposite stream, it will not be encompassed within the attentional focus, and its identification will hinge on the length of the SOA, as follows.

If the SOA is short, there may not have been sufficient time for the focus to fully narrow on the stream containing the first target before the onset of the second target. In this case, both streams may still be encompassed within the focus, allowing the second target to be processed along with the first even when it appears in the opposite stream, resulting in Lag-1 sparing. If, on the other hand, the SOA is long, there is a greater probability that there has been sufficient time for the focus to narrow on the stream containing the first target. In this case, if the second target appears in the opposite stream, it will fall outside focal attention, and Lag-1 sparing will not occur.

To examine this hypothesis, we systematically varied the SOA between successive items in the RSVP stream. Six groups of observers were tested, each at a different SOA (53, 66, 80, 100, 118, and 133 ms), and each across three intertarget lags (1, 3, and 9). The changes in the width of the attentional focus expected based on the above hypothesis are illustrated in Figure 1. Each segmented box represents the width of the attentional focus at any given combination of SOA and Lag. The extent to which the second target (T2) is encompassed within the segmented box is proportional to the probability that the second target will fall within the focus of attention, thus yielding Lag-1 sparing. Take as an example the top and bottom rows of Figure 1, namely, SOAs of 53 and 133 ms, respectively.

Consider first an SOA of 53 ms. At Lag 1 (i.e., 53 ms after the onset of the first target, T1), the focus of attention has begun to narrow on the location of the first target, but it still encompasses a substantial portion of the stream containing the second target. This will result in the second target falling within focal attention and being processed along with the first target, thus yielding Lag-1 sparing. By Lag 3 (i.e., 159 ms after the offset of the first target) the focus has further narrowed on the first target's location, thereby reducing the extent to which the second target is attended. As a result, the accuracy of second-target identification is reduced and an AB deficit ensues. Finally, by Lag 9, 477 ms after the onset of the first target, sufficient time has elapsed for the attentional focus to have expanded to again encompass both target locations.

At an SOA of 133 ms (Figure 1, lowest row) sufficient time has elapsed from the T1 onset for the focus of attention to narrow almost completely on the first target, even at Lag 1, leaving the second target outside the attended area. As a result, the accuracy of second-target identification is reduced, and Lag-1 deficit ensues instead of Lag-1 sparing. By Lag 3, 399 ms after the onset of the first target, there has been sufficient time for the focus to widen again to encompass most of the second target. Needless to say, by Lag 9 the focus once again fully encompasses both target locations. With the appropriate changes, the contraction and expansion of the focus of attention follow a similar sequence at the intermediate SOAs.

Experiment 1

Experiment 1 was designed to test the predictions outlined above and illustrated in Figure 1.

Method

Observers

A total of 117 undergraduate students at both the University of British Columbia and Simon Fraser University participated for course credit. All participants were naïve as to the purpose of the experiment and reported normal or corrected-to-normal vision.

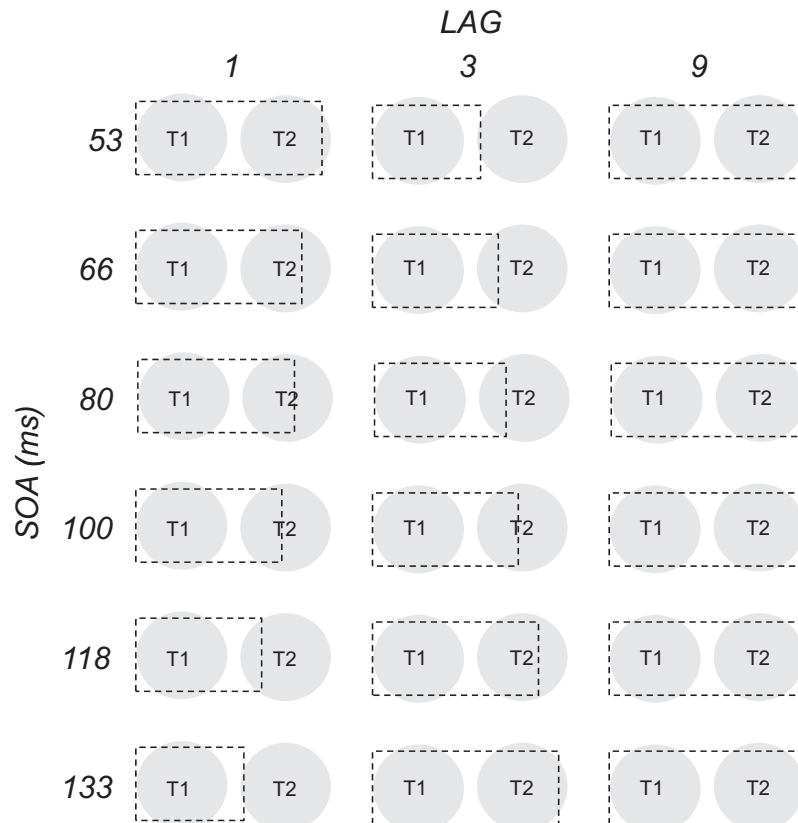


Figure 1. Schematic illustration of the progressive changes in the spatial extent of the focus of attention (segmented rectangles) as a joint function of stimulus-onset asynchrony (SOA) and Lag. See text for a detailed description.

The observers were allocated randomly to one of six groups (SOA: 53, 66, 80, 100, 118, and 133 ms). Each group was required to have a minimum of 17 observers, but because the data were collected concurrently at the two universities, the final number of observers in each group was 17, 22, 18, 19, 17, and 24, for SOAs of 53, 66, 80, 100, 118, and 133 ms, respectively.

Apparatus and Stimuli

All stimuli were presented on a computer monitor viewed from a distance of approximately 57 cm. A white fixation cross (0.25° by 0.25°) was displayed in the center of the screen throughout each trial. All other stimuli were white digits (0 - 9) or capital letters (excluding the letters I, O, Q, and Z), each of which subtended approximately 0.9° vertically. The luminance of all stimuli was 129 cd/m², and the luminance of the black background was 2.3 cd/m². To obtain the six SOAs of 53, 66, 80, 100, 118, and 133 ms, the screen refresh rate was set at 75, 75, 75, 60, 85, and 75 Hz, respectively.

Procedure

The observers initiated each trial by pressing the spacebar. The trial began with the onset of two synchronized RSVP streams, one centered 1.75° to the left and the other 1.75° to the right of fixation. Each stream contained an equal number of digit distractors and 0, 1, or 2 letter targets. Both streams contained 8 to 14 leading distractors selected from the digits 0 to 9, with the restriction that each digit differed from the previous two digits and from the digit in the opposite stream. The number of distractors presented before the first target varied randomly between trials, but it was always identical for both streams. A total of two target letters were presented on any given trial. The two letters were never the same on any given trial and appeared with equal probability in either the left or the right stream and in either the same or opposite stream. Each stream terminated with a single digit distractor, which acted as a backward mask for the second target.

The second target was presented at one of three intertarget lags: Lags 1, 3, and 9. At Lag 1, the second target was presented directly after the first; at Lag 3, two distractors intervened between the targets; at Lag 9, there were eight intervening distractors. Items continued to be displayed in both RSVP streams until the second target and its mask were presented. Intertarget lags occurred in random order and with equal frequency across trials. The actual amount of time (milliseconds) that elapsed from the onset of the first target to the onset of the second target at each lag depended on the SOA group as follows. The number of milliseconds at Lags 1, 3, and 9 was 53, 106, and 424 for the 53-ms SOA group; 66, 132, and 528 for the 66-ms SOA group; 80, 160, and 640 for the 80-ms group; 100, 200, and 800 for the 100-ms SOA group; 118, 236, and 944 for the 118-ms SOA group; and 133, 266, and 1064 for the 133-ms SOA group. The SOA between successive items in the RSVP stream consisted of approximately two-thirds exposure duration of the stimulus and one-third blank interstimulus interval (ISI). The actual proportions were constrained by the refresh rate of the monitor. The ratios of exposure duration to ISI were approximately 26.5:26.5, 40:26, 45:35, 70:30, 71:47, and 80:53 ms for SOAs of 53, 66, 80, 100, 118, and 133 ms, respectively.

The display sequence on any given trial is illustrated schematically in Figure 2. The observers' task was to identify the two target letters presented in each trial. Observers were required to press the appropriate keys on the keyboard in either order at the end of each trial.

Results and Discussion

Second-Target Accuracy

Only those trials in which the first target was identified correctly were included for analysis. This procedure is commonly adopted in AB experiments because, on trials in which the first target is identified incorrectly, the source of the error is unknown, and thus its effect on second-target processing cannot be estimated.

Figures 3A and 3B illustrate the percentage of correct second-target responses as a function of SOA and Lag, separately for the Same-stream and Different-stream conditions. The data were analyzed in a 2 × 3 × 6 ANOVA consisting of two within-subject factors and one between-subjects factor. The within-subject factors were Lag (1, 3, and 9), and Stream (Same and Different). The between-subjects factor was SOA (53, 66, 80, 100, 118, and 133 ms). The analysis revealed significant effects of Stream [$F(1, 111) = 84.93, p < .001, \eta_p^2 = .431$], Lag [$F(2, 222) = 78.21, p < .001, \eta_p^2 = .418$], and SOA [$F(5, 111) = 24.65, p < .001, \eta_p^2 = .521$]. There were two significant two-way interaction effects: Lag × SOA [$F(10, 222) = 5.78, p < .001, \eta_p^2 = .199$], and Stream × Lag [$F(2, 222) = 63.15, p < .001, \eta_p^2 = .362$]. The three-way interaction amongst Stream, Lag, and SOA was also significant [$F(10, 222) = 4.96, p < .001, \eta_p^2 = .182$]. The interaction effect between Stream and SOA was not significant [$F(5, 111) = .93, p = .46, \eta_p^2 = .041$].

As expected on the basis of earlier research (Jefferies et al., 2007; Shih, 2000; Visser et al., 1999), a comparison between the Same-stream and Different-stream conditions revealed Lag-1 sparing across all SOAs in the Same-stream condition. This is shown by the greater accuracy of second-target identification at Lag 1

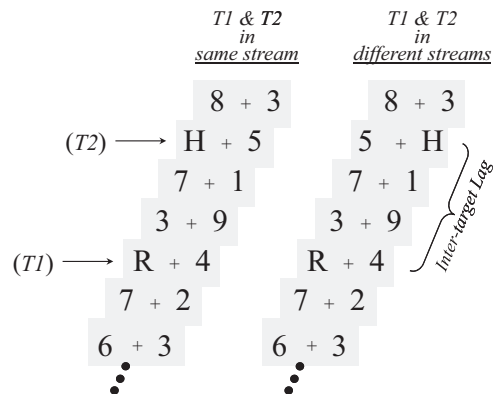


Figure 2. Schematic representation of the sequence of events within a trial in Experiment 1. The first and the second targets (T1 and T2) could appear in either the left or the right rapid serial visual presentation stream and in either the same or opposite streams. Illustrated in the figure is the case in which the second target was presented three frames after the first target (i.e., at Lag 3). At Lag 1, the second target was presented directly after the first, without intervening distractors.

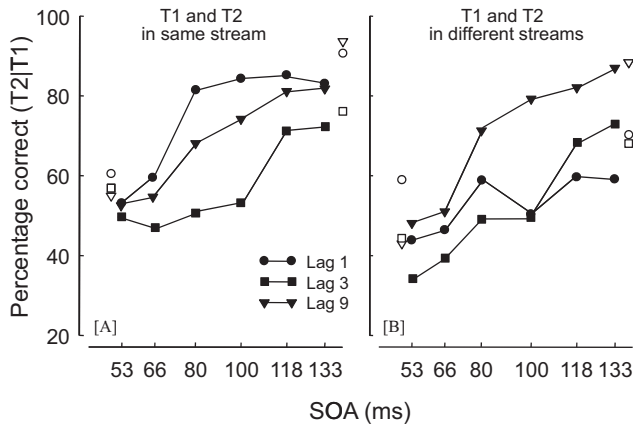


Figure 3. Mean percentages of correct identifications of the second target in Experiment 1. Panel (A): Both targets were presented in the same stream, the data have been collapsed across left and right streams. Panel (B): Both targets were presented in opposite streams. Each function represents performance at a different lag across stimulus-onset asynchronies (SOAs). The open symbols represent data from Experiment 2, in which the spatial separation between the rapid serial visual presentation streams was reduced.

than at Lag 3 in Figure 3A. In contrast, in the Different-stream condition, the incidence and magnitude of Lag-1 sparing depended critically on SOA, as illustrated in Figure 3B and discussed below.

Lag-1 sparing: Comparing predicted and obtained patterns. Critical to the major objective of the present work was an examination of Lag-1 sparing as a function of SOA in the condition in which the two targets were displayed in different streams. From the model outlined in Figure 1, Lag-1 sparing should occur when the SOA is short, but not when it is long. This is because at brief SOAs the second target is hypothesized to be still encompassed within the focus of attention. This prediction, illustrated in the first two columns of Figure 1 (Lags 1 and 3), is confirmed by the corresponding results for the different-stream condition in Figure 3B. The relationship between the relevant portions of Figures 1 and 3B is illustrated in Figure 4. The vertical bars in Figure 4 correspond to the segmented-line rectangles for Lags 1 and 3 in Figure 1, and represent the extent of the focus of attention across SOAs. The empirical functions in Figure 4 were transposed from Figure 3B.

There is a close match between the expected and obtained results in Figure 4. In both the expected and the obtained results, the functions for Lags 1 and 3 exhibit a cross-over as SOA is increased. In interpreting this cross-over, it should be emphasized that the height of each bar indexes the probability that the second target will fall within the focus of attention and, therefore, maps directly to the accuracy of second-target identification. The cross-over in the empirical data in Figure 4 is consistent with the outcome of the overall statistical analysis that revealed a significant three-way interaction amongst Stream, SOA, and Lag. To confirm this interpretation of the three-way interaction, a subsidiary ANOVA was performed on the empirical data illustrated in Figure 4. The analysis was a 2×6 ANOVA consisting of one within-subject factor, Lag (1 and 3), and one between-subjects factor, SOA (53, 66, 80, 100, 118, and 133 ms). The analysis

revealed a significant effect of SOA [$F(5, 111) = 12.41, p < .001, \eta_p^2 = .449$]. Interpretation of this effect, however, is constrained by the significant interaction between Lag and SOA [$F(5, 111) = 7.07, p < .001, \eta_p^2 = .217$], confirming the graphical evidence in Figure 4 that the accuracy of second-target identification was higher at Lag 1 than at Lag 3 when the SOA was short, but that the reverse was true when the SOA was long. Individual *t*-tests between performance at Lags 1 and 3, separately for each SOA, were as follows: SOA 53 ms: $t(16) = 2.53, p = .02$; SOA 66 ms: $t(21) = 2.13, p < .05$; SOA 80 ms: $t(17) = 2.29, p < .04$; SOA 100 ms: $t(18) = 0.13, p = .90$; SOA 118 ms: $t(16) = 2.11, p = .05$; SOA 133 ms: $t(23) = 4.29, p < .001$. In essence, the Lag-1 sparing observed at short SOAs turned into a Lag-1 deficit at long SOAs.

The effect of masking. Figure 5 provides a more conventional representation of Lag-1 sparing, and serves to illustrate an incidental yet important factor at work in the present experiment: masking. In Figure 5, each line represents second-target performance at a different SOA. Within each line, the first symbol represents performance at Lag 1, and the second symbol represents performance at Lag 3. A negative slope indicates Lag-1 sparing; a positive slope indicates Lag-1 deficit. As may be expected based on Figure 1, negative slopes in Figure 5 are associated with short SOAs whereas positive slopes are associated with long SOAs.

The effect of masking is illustrated by a progressive increment in the mean level of each line in Figure 5. Masking becomes progressively stronger—and performance correspondingly less accurate—as the SOA is reduced from 133 to 53 ms. The effect of masking is also seen in an apparent discrepancy between the empirical results illustrated in Figure 5 and the predicted patterns in Figure 1. Consider two data points in Figure 5: Lag 3 at an SOA of 53 ms and Lag 1 at an SOA of 133 ms. Performance is considerably less accurate in the former than in the latter. Refer-

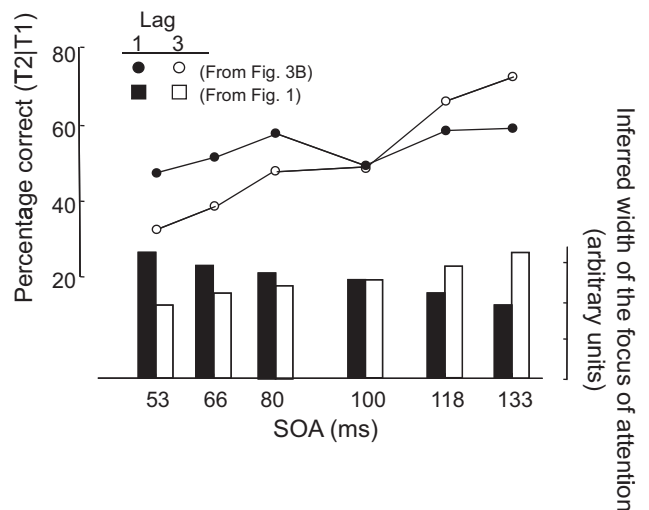


Figure 4. Comparison between the estimated spatial extent of the attentional focus at Lags 1 and 3 across stimulus-onset asynchronies (SOAs) (from Figure 1) and the corresponding empirical results from Figure 3B. The height of each vertical bar in the lower portion of the figure exactly matches the width of the corresponding segmented-line rectangle in Figure 1, and represents the extent of the focus of attention across SOAs.

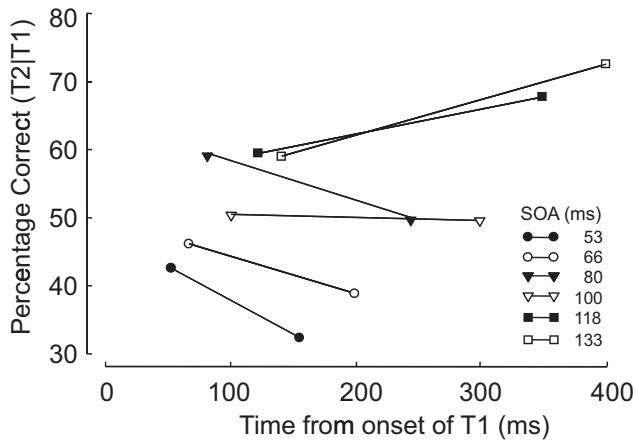


Figure 5. Progressive transition from Lag-1 sparing (negative slope) to Lag-1 deficit (positive slope) across stimulus-onset asynchronies (SOAs). In each function, the first symbol represents second-target performance at Lag 1, and the second symbol represents second-target performance at Lag 3. The data were redrawn from the data for Lags 1 and 3 in Figure 3B.

ence to the corresponding points in Figure 1, however, shows that the extent of the attentional focus is predicted to be exactly the same in the two cases. Were the extent of the attentional focus the only determining factor, accuracy of second-target identification should be the same in both cases. The fact that performance is lower at an SOA of 53 ms, however, is to be expected, based on the well-established principle that the strength of masking is inversely related to the period of time that elapses from the onset of a target to the onset of the trailing mask (Breitmeyer, 1984). That period of time covaried with SOA, being 53 ms for the 53-ms SOA group, and 133 ms for the 133-ms SOA group. It should be noted that the predictions in Figures 1 and 4 (vertical bars) illustrate the dynamic variation in the extent of the focus of attention independent of masking. The effect of masking is seen in the empirical results in Figure 4 in the progressive reduction in overall level of performance as the SOA is decreased from 133 to 53 ms.

First-Target Accuracy

Accuracy of first-target identification as a function of SOA in the Same-stream and Different-stream conditions is illustrated in Figure 6, separately for each lag. The data were analyzed in a 2 × 3 × 6 ANOVA consisting of two within-subject factors and one between-subjects factor. The within-subject factors were Lag (1, 3, and 9), and Stream (Same and Different). The between-subjects factor was SOA (53, 66, 80, 100, 118, and 133 ms). The analysis revealed significant effects of Stream [$F(1, 111) = 23.03, p < .001, \eta_p^2 = .191$], Lag [$F(2, 222) = 52.15, p < .001, \eta_p^2 = .337$], and SOA [$F(5, 111) = 48.76, p < .001, \eta_p^2 = .636$]. There was one significant interaction effect: Stream × Lag [$F(2, 222) = 30.30, p < .001, \eta_p^2 = .285$]. No other effects were significant.

As was the case for second-target accuracy, the progressive increment in first-target accuracy over SOA seen in Figure 6 can be attributed to masking. All functions in Figure 6 are parallel—as confirmed by the absence of any statistically significant interactions involving SOA—and overlap substantially with one another, except for the Same-stream condition at Lag 1. This means that the

strength of masking at any given SOA was the same across conditions and lags with the single exception of the Same-stream condition in which masking of the first target at Lag 1 was more pronounced across all SOAs. The relatively lower performance in the Same-stream condition was not unexpected and can be explained on the well-established finding that the strength of masking increases as a function of the structural similarity (Fehrer, 1966; Harmon & Julesz, 1973) and/or conceptual similarity (Dux & Coltheart, 2005; Enns, 2004; Intraub, 1981, 1984) between the target and the mask. In the present experiment, the first-target letter was always masked by a digit (relatively low categorical similarity) except in the Same-stream condition at Lag 1 in which it was masked by the second target (another letter; relatively high categorical similarity). As a consequence, masking was relatively stronger in that condition.

Temporal Dynamics of the Focus of Attention

Temporal changes in the spatial extent of the focus of attention can be estimated from the slopes of the functions in Figure 5 combined with the model illustrated in Figure 1. A negative slope (i.e., Lag-1 sparing) corresponds to a broad attentional focus whereas a positive slope (i.e., a Lag-1 deficit) corresponds to a focus of attention that is set narrowly on the location of the first target, thereby excluding the second target. As illustrated in Figure 5, there is a progressive increment in the slope of the functions as SOA is increased. This increment in slope across SOAs reflects the progressive transition from Lag-1 sparing to Lag-1 deficit, and indexes the corresponding changes in the extent of the focus of attention. This relationship provides a basis for estimating the time-course of the changes in the spatial extent of the focus of attention.

If the data in Figure 5 are to be used to estimate the time-course of the changes in the extent of the focus of attention, it is first necessary to partial out the effects of masking, which caused the mean level of the functions to vary with the SOA. This was

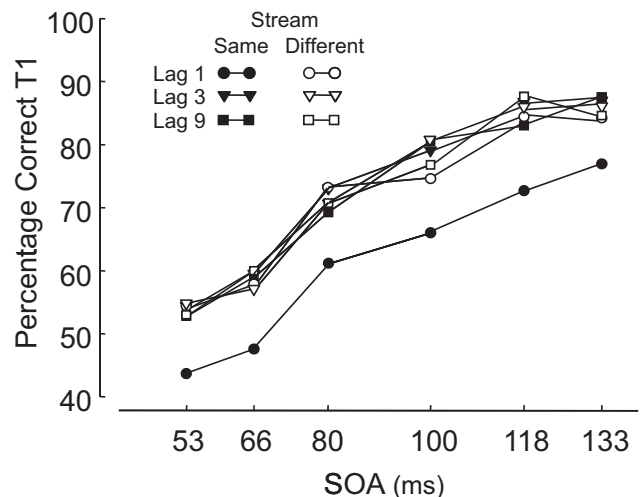


Figure 6. Mean percentages of correct identifications of the first target in Experiment 1 as a joint function of Stream (Same or Different), Lag, and stimulus-onset asynchrony (SOA).

accomplished by expressing the slope of each function in Figure 5 as the ratio of performance at Lag 3 to performance at Lag 1. By this method, the mean level of performance at each SOA, and therefore the effect of masking, is removed as a determining factor. This makes it possible to express the magnitude of Lag-1 sparing (or the lack thereof, i.e., a Lag-1 deficit) as a single value, independent of masking. To express the magnitude of Lag-1 sparing as positive values and the magnitude of Lag-1 deficit as negative values, we applied Equation (1) to the data in Figure 5

$$\text{Lag-1 sparing value} = 100 - [(\text{Lag3}/\text{Lag1}) * 100] \quad (1)$$

where positive values indicate Lag-1 sparing and negative values indicate a Lag-1 deficit. The AB values obtained from Equation (1) are illustrated in Figure 7. A linear fit through the points in Figure 7 by the method of least squares yielded the linear function:

$$y = 60.6 - .62x \quad (2)$$

Figure 7 reveals an approximately linear transition from Lag-1 sparing to Lag-1 deficit as the SOA is increased from 53 to 133 ms, mirroring the corresponding changes in the extent of the focus of attention illustrated in Figure 1. Equation (2) indicates that, under the conditions of the present study, Lag-1 sparing decreased (or Lag-1 deficit increased) by approximately 2.5% for every millisecond increment in SOA.

Experiment 2

The main message conveyed by the function in Figure 7 is that the spatial extent of the focus of attention, as indexed by the

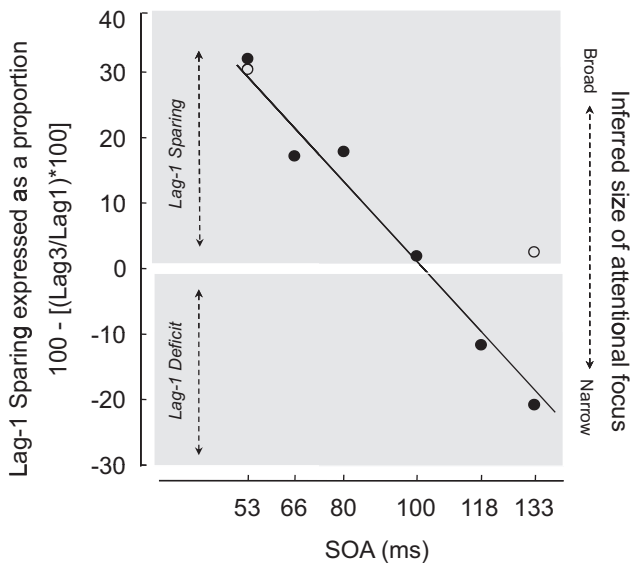


Figure 7. Variation in the magnitude of Lag-1 sparing (positive values) and Lag-1 deficit (negative values) as a function of stimulus-onset asynchrony (SOA). The effect of masking was partialled out by expressing the magnitude of Lag-1 sparing/Lag-1 deficit as the ratio of second-target accuracy at Lag 3 to that at Lag 1. See text for a detailed description. The closed symbols represent the data from Experiment 1; the open symbols represent the data from Experiment 2.

magnitude of Lag-1 sparing, varies linearly with SOA. We interpret this linear relationship as reflecting the time-course of the contraction and expansion of the focus of attention. When the SOA is short there is not sufficient time for the focus of attention to shrink to the location of the stream containing the first target. This causes the second target to remain within the focus of attention with consequent Lag-1 sparing. In contrast, when the SOA is long there is abundant time for the focus to shrink, leaving the second target unattended, resulting in a Lag-1 deficit.

Experiment 2 was designed to provide a test of this account. This was done by reducing the spatial separation between the two RSVP streams. Bringing the streams closer together should reduce the time required for the attentional focus to shrink to the first-target location. Similarly, closer spatial proximity should reduce the time required for the focus to re-expand to again encompass both streams. The hypothesized changes in the extent of the focus of attention as a function of SOA and spatial separation are illustrated in Figure 8.

An important comparison in Figure 8 is the extent to which the second target is encompassed within the focus of attention in the Far- and in the Close-stream conditions at different SOAs. At an SOA of 53 ms, the second target falls within the focus of attention in both the Far and the Close conditions. In contrast, at an SOA of 133 ms, the second target lies outside the focus in the Far condition but at least partly within it in the Close condition. This is because, in the Close-stream condition, the distance between the streams is sufficiently small to allow the focus to shrink to the first-target stream and then to re-expand towards the second-target stream. In practice, this means that approximately the same amount of Lag-1 sparing should be in evidence in both the Close and the Far conditions at an SOA of 53 ms, but Lag-1 sparing should occur only in the Close condition at an SOA of 133 ms.

Method

Observers

A total of 15 undergraduate students at both the University of British Columbia and Simon Fraser University participated for course credit. All participants were naïve as to the purpose of the experiment and reported normal or corrected-to-normal vision.

Procedure

The procedures in Experiment 2 were identical to those in the 53-ms and 133-ms SOA conditions in Experiment 1 with the single exception that the center-to-center separation between the two RSVP streams was reduced from 3.5° to 0.7°. Therefore, the design of Experiment 2 was a 3 (Lags 1, 3, or 9) × 2 (Same-stream, Different-stream) × 2 (SOA: 53 or 133 ms) factorial.

Results and Discussion

As in Experiment 1, only those trials in which the first target was identified correctly were included for analysis. The average accuracy scores for first-target identification, collapsed across lags, were 56.4% (SOA 53 ms, same stream), 59.7% (SOA 53 ms, different stream), 91.0% (SOA 133 ms, same stream), and 91.5% (SOA 133 ms, different stream). The corresponding scores when the streams were far apart (Experiment 1) were 50.5%, 54.1%,

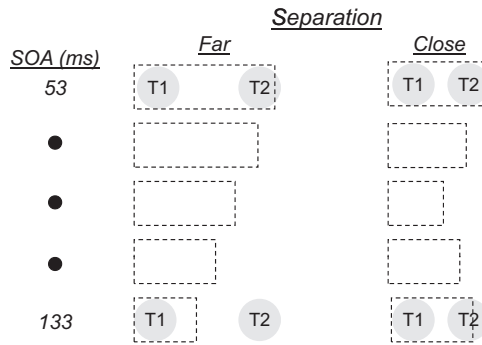


Figure 8. Schematic illustration of the progressive changes in the spatial extent of the focus of attention (segmented rectangles) as a joint function of stimulus-onset asynchrony (SOA) and Spatial Separation of the rapid serial visual presentation streams. See text for a detailed description.

84.0%, and 86.2%. This pattern of results is consistent with the hypothesis that first-target detectability was not impaired when the RSVP streams were close together. If anything, first-target detectability was better when the streams were close together (Experiment 2) than when they were far apart (Experiment 1).

The percentages of correct second-target responses for SOAs of 53 ms and 133 ms as a function of Lag and Same/Different stream conditions are illustrated as unconnected open symbols in Figures 3A and 3B. The data were analyzed in a 3 (Lag: 1, 3, or 9) \times 2 (Same or Different stream) \times 2 (SOA: 53 or 133 ms) within-subject ANOVA. The analysis revealed significant effects of Lag, $F(2, 28) = 4.47, p = .02, \eta_p^2 = .242$ Stream, $F(1, 14) = 32.528, p < .001, \eta_p^2 = .699$, and SOA, $F(1, 14) = 103.46, p < .001, \eta_p^2 = .881$. There was one significant two-way interaction effect between Lag and SOA, $F(2, 28) = 12.95, p < .001, \eta_p^2 = .48$. The three-way interaction effect among Lag, Stream, and SOA was also significant, $F(2, 28) = 8.10, p = .002, \eta_p^2 = .367$. The significance of the three main effects and the two-way interaction is qualified by the significant three-way interaction.

As was the case in Experiment 1, of particular interest in the present experiment was the condition in which the two targets were presented in opposite streams. For that reason, a separate 3 (Lags: 1, 3, or 9) \times 2 (SOAs: 53 ms or 133 ms) factorial analysis was performed on those data. The analysis revealed significant effects of Lag, $F(2, 28) = 3.51, p = .04, \eta_p^2 = .201$, SOA, $F(1, 14) = 60.7, p < .001, \eta_p^2 = .813$, and a significant interaction effect between Lag and SOA, $F(2, 28) = 17.75, p < .001, \eta_p^2 = .56$. The interaction effect reflects the finding that Lag-1 sparing was in evidence at an SOA of 53 ms, $t(17) = 2.25, p = .03$, but not at an SOA of 133 ms, $t(17) = 0.96, p = .35$. The important finding is that no Lag-1 deficit was in evidence at an SOA of 133 ms. This contrasts sharply with the corresponding result in the 133-ms SOA condition in Experiment 1 that revealed a highly significant Lag-1 deficit, $t(23) = 4.28, p < .001$.

Figure 7 permits a direct comparison between the magnitudes of Lag-1 sparing obtained at SOAs of 53 and 133 ms in Experiments 1 (far streams, filled symbols) and 2 (close streams, open symbols). Spatial separation between the streams made no difference to the magnitude of Lag-1 sparing when the SOA was 53 ms. When the SOA was 133 ms, however, a Lag-1 deficit was in evidence when the streams were far apart (Experiment 1) but not

when the streams were close together (Experiment 2). Indeed, if anything, at an SOA of 133 ms, the results of Experiment 2 revealed a small amount of Lag-1 sparing. This pattern of results matches the predictions from the model illustrated in Figure 8.

The results of Experiment 2 also speak to a potential alternative interpretation of the linear relationship between SOA and Lag-1 sparing obtained in Experiment 1 (Figure 7). It could be suggested that the inverse relationship may stem from a progressive increment in the detectability of the first target as the SOA is increased. The reasoning would be as follows: the first target may be less detectable when the SOA is short than when it is long, perhaps because at shorter SOAs the first-target mask occurs sooner and/or because there is less time to switch processing from the preceding item (Ghorashi, Zuvic, Visser, & Di Lollo, 2003). A less detectable first target would delay the signal that triggers the shrinking of focal attention. Thus, as the SOA is decreased, the trigger signal would be issued correspondingly later. In addition, the later the shrinking is triggered, the longer the second target would remain within the focus of attention. For example, at an SOA of 53 ms the detectability of the first target is low, the trigger is issued relatively late, and the focus remains broadly set causing the second target to remain within the focus of attention. Lag-1 sparing then follows. In contrast, at an SOA of 133 ms, first-target detectability is high and the trigger is issued promptly, leaving sufficient time for the focus to shrink, causing the second target to lie outside the focus of attention with consequent absence of Lag-1 sparing.

The results of Experiment 2 disconfirm this interpretation. According to the "first-target detectability" hypothesis, the relationship between Lag-1 sparing and SOA should be unaffected by spatial separation. This is because the factors that influence the detectability of the first target (masking, switch costs) are invariant with spatial separation. The prediction that stems directly from this hypothesis is that the slope of the function illustrated in Figure 7 should be invariant with spatial separation. This prediction is clearly disconfirmed by the results illustrated in Figure 7 showing that spatial separation had a strong effect on the slope of the function relating Lag-1 sparing to SOA.

Experiment 3

In Experiment 1, the stimuli were displayed for approximately 2/3 of the SOA, with the screen remaining blank for the remaining one third. This was done to maintain an approximately proportional relationship between stimulus duration and ISI. This procedure, however, might have introduced an unintended variation in the brightness of the stimuli. Because of Bloch's law, stimuli displayed for shorter durations might have been seen as dimmer than those shown for longer durations (Bloch, 1885). Experiment 3 was a control experiment designed to dismiss the option that the results might have been influenced by possible brightness differences. This was done by maintaining a fixed exposure duration for the stimuli and varying the duration of the blank ISI to obtain the required SOA.

Method

Observers

A total of 18 undergraduate students at both the University of British Columbia and Simon Fraser University participated for

course credit. All participants were naïve as to the purpose of the experiment and reported normal or corrected-to-normal vision.

Procedure

The procedures in Experiment 3 were identical to those in the 53-ms and 133-ms SOA conditions in Experiment 1 with the single exception that the exposure duration of all items in the RSVP streams was 26.5 ms. The balance of the time required to complete the SOA was filled by a blank ISI (26.5 ms for the 53-ms SOA condition, and 106.5 ms for the 133-ms condition). Therefore, the design of Experiment 2 was a 3 (Lags 1, 3, or 9) \times 2 (Same-stream, Different-stream) \times 2 (SOA: 53 or 133 ms) factorial.

Results and Discussion

As in Experiment 1, only those trials in which the first target was identified correctly were included for analysis. The average accuracy scores for first-target identification, collapsed across lags, were 51.1% (SOA 53 ms, same stream), 51.5% (SOA 53 ms, different stream), 78.2% (SOA 133 ms, same stream), and 79.3% (SOA 133 ms, different stream). The corresponding scores in Experiment 1, in which the exposure duration of each stimulus was proportional to the total SOA, were 50.5%, 54.1%, 84.0%, and 86.2%.

The percentages of correct second-target responses for SOAs of 53 ms and 133 ms as a function of Lag and Same/Different stream conditions are illustrated in Figure 9 (solid lines). The data were analyzed in a 3 (Lag: 1, 3, or 9) \times 2 (Same or Different stream) \times 2 (SOA: 53 or 133 ms) within-subject ANOVA. The analysis revealed significant effects of Lag, $F(2, 34) = 7.415$, $p = .002$, $\eta_p^2 = .304$, Stream, $F(1, 17) = 15.24$, $p = .001$, $\eta_p^2 = .473$, and

SOA, $F(1, 17) = 36.76$, $p < .001$, $\eta_p^2 = .684$. There were two significant two-way interaction effects, one between Lag and SOA, $F(2, 34) = 4.45$, $p = .02$, $\eta_p^2 = .21$, and one between Stream and SOA, $F(1, 17) = 4.17$, $p = .03$, $\eta_p^2 = .24$. The three-way interaction effect among Lag, Stream, and SOA was also significant, $F(2, 34) = 5.16$, $p = .01$, $\eta_p^2 = .233$. The pattern of results of Experiment 3 clearly parallels that of Experiment 1. This indicates that the same experimental outcome is obtained whether the relationship between stimulus duration and blank ISI is proportional (Experiment 1) or fixed (Experiment 3).

General Discussion

From a general standpoint, the present research examined the spatial and temporal dynamics of attentional control, as instantiated in the model illustrated in Figure 1. Specifically, we employed the incidence and magnitude of Lag-1 sparing to monitor changes in the spatial extent of the focus of attention. To this end, we used a dual-stream RSVP paradigm and manipulated the SOA between successive items in the stream. Of special interest were those trials in which the two targets appeared in opposite streams. At the beginning of each such trial, the focus of attention was presumed to be set widely to encompass both streams. Based on earlier evidence, however, we expected that upon the presentation of the first target, the focus of attention would narrow reflexively onto that location so as to optimize identification of the first target (Jefferies, Ghorashi, Kawahara, & Di Lollo, 2007; Visser, Bischof, & Di Lollo, 2004).

When both RSVP streams are encompassed within the focus of attention, the second target is processed accurately along with the first. This occurs when the SOA between successive items in

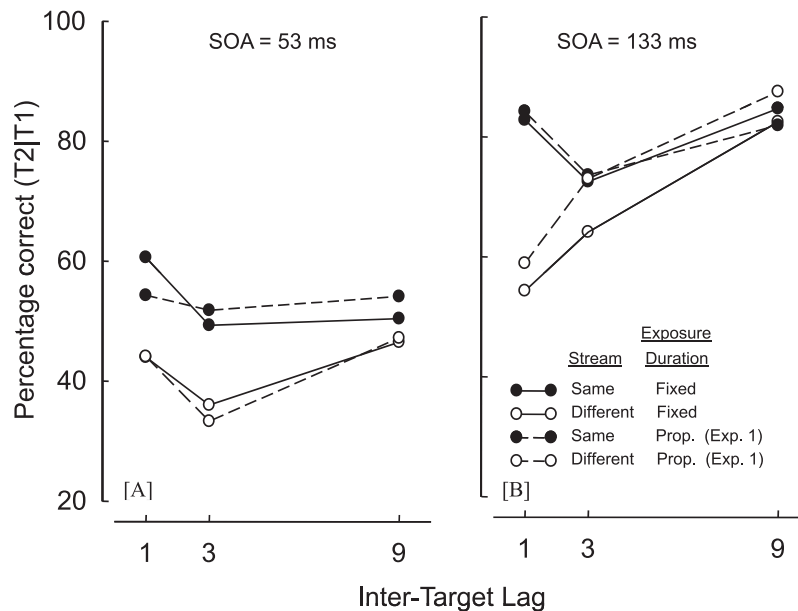


Figure 9. Mean percentages of correct identifications of the second target in Experiment (Exp.) 1, in which the exposure duration was proportional (Prop.) (dashed lines), and in Experiment 3, in which the exposure duration was fixed (solid lines). Panel A shows the results with a 53-ms stimulus-onset asynchrony (SOA); panel B shows the results with a 133-ms SOA.

the RSVP stream is too short for the focus to have narrowed on the location of the first target. In this case, the second target falls within the focus of attention, and Lag-1 sparing ensues. At long SOAs, on the other hand, there is sufficient time for the focus to narrow fully onto the location of the first target, leaving the second target outside focal attention and therefore effectively unattended. In this case, a Lag-1 deficit ensues, rather than Lag-1 sparing. The outcomes of both experiments confirmed these expectations.

While confirming the relationship between the spatial extent of the focus of attention and Lag-1 sparing (illustrated in Figures 1 and 4), the data in Figure 7 do not permit the rate of change in the extent of the focus of attention to be expressed in spatiotemporal units such as degrees of visual angle/millisecond. What can be inferred from Figure 7, however, is that the extent of the focus of attention varied linearly as a function of time in the manner illustrated in the first column of Figure 1.

Spatial Dynamics of the Focus of Attention: Analog or Quantal?

The continuous, smooth changes in the width of the attentional focus illustrated in Figures 1 and 7 are consistent with the view that changes in the spatial deployment of attention over time follow an analog course. This contrasts with the view expressed by Weichselgartner and Sperling (1987) and by Sperling and Weichselgartner (1995) that the spatial deployment of attention over time follows a quantal course.

These contrasting views pose an obvious question: is attention re-deployed in an analog or in a quantal manner? The present study and that of Weichselgartner and Sperling (1987) lead to ostensibly inconsistent answers. This inconsistency, however, is easily resolved by considering the task differences between the two studies. The observers in Weichselgartner and Sperling's (1987) study were required to redeploy the focus of attention between two discrete spatial locations. In contrast, in the present experiments the observers were required to monitor both spatial locations concurrently.

Given these task differences, the optimal strategy in Weichselgartner and Sperling's (1987) study was to redeploy the focus of attention discretely from one location to the other. In contrast, in the present research the optimal strategy was to maintain a wide focus of attention (and, if anything, resist the reflexive narrowing of the attentional focus to the location of the first target) throughout a trial. We are led by this line of argument to the following conclusion: whether the focus of attention is modulated in an analog or quantal manner depends on the task at hand. If the task involves a discrete switch of locations, attention is redeployed in a quantal manner. If the task requires the maintenance of a wide attentional setting, any shrinking or expanding of the focus of attention is accomplished in an analog manner.

The Focus of Attention: Unitary or Divided?

There is evidence in the attention literature that separate and independent foci can be deployed simultaneously to discrete locations in space (Awh & Pashler, 2000; Kawahara & Yamada, 2006; Müller, Malinowski, Gruber, & Hillyard, 2003). The results of Experiment 1 can be explained equally well by a single focus of

attention that expands or contracts (see Figure 1) or by two discrete foci, each centered on one RSVP stream.

We have seen how the results of Experiment 1 can be explained in terms of a unitary attentional focus that shrinks and expands. To interpret those results in terms of two discrete foci, it must be assumed that the two foci draw on a single resource pool. The reasoning is as follows. At the outset of a trial, attention is deployed to two separate foci, one at each RSVP stream. Upon detection of the first target, the resources allocated to the stream opposite that of the first target, are gradually redeployed to the stream containing the first target to enhance first-target identification. At short SOAs, the reallocation of resources has only just begun. Thus, if the second target appears in the stream opposite the first, sufficient attentional resources remain at that location to process the second target, resulting in Lag-1 sparing. At longer SOAs, the transfer of attentional resources to the first-target stream will have been completed, leaving few or no resources for the second target if it appears in the stream opposite the first. This would result in Lag-1 deficit. Thus, the results of Experiment 1 can be explained in terms of two discrete foci.

Such a dual-focus account could be mediated by at least two mechanisms. One is that the two foci draw upon a single pool of resources. A single-resource assumption is indicated because, if each focus were to draw upon its own independent resource pool, Lag-1 sparing should always occur, even when the two targets are presented in opposite streams, because the resources initially deployed to the stream which does not contain the first target would remain unchanged. A second possibility is an inhibitory or strategic mechanism of attentional control that would act concurrently on the two foci even if their respective resource pools were independent.

The single- and the dual-focus models, however, make different predictions regarding the effect of reducing the spatial separation between the two RSVP streams. According to the single-focus model, as the separation between the two streams is reduced, it should take less time for the focus of attention to shrink to the location of the first target and to re-expand to the location of the second (see Figure 8). This would result in reduced Lag-1 deficit at the longer SOAs. In contrast, according to the dual-focus model, the shifting of resources from one focus to the other should be independent of spatial separation. Thus, the magnitudes of Lag-1 sparing and Lag-1 deficit should be invariant with spatial separation. The results of Experiment 2 show that at an SOA of 133 ms, the magnitude of Lag-1 deficit was reduced relative to that obtained at the corresponding SOA in Experiment 1. In fact, at an SOA of 133 ms, the Lag-1 deficit seen in Experiment 1 changed to Lag-1 sparing in Experiment 2. This finding is consistent with predictions from the single-focus model, but not with predictions from the dual-focus model.

The inability of the dual-focus model to account for the overall pattern of results, however, does not mean that the model is invalid under all circumstances. The evidence supporting the claim that attention can be deployed to several spatial locations concurrently and independently is substantial and convincing (e.g., Awh & Pashler, 2000; Kawahara & Yamada, 2006; Müller, Malinowski, Gruber, & Hillyard, 2003; Yamada & Kawahara, 2007). The evidence in favor of a single focus of attention that expands and contracts is equally believable (e.g., Barriopedro & Botella, 1998; Egeth, 1977; Eriksen & St. James, 1986; Eriksen & Yeh, 1985;

Jonides, 1983; LaBerge, 1983, 1995). It seems likely, therefore, that both the single-focus and the multiple-independent-foci modes of attentional deployment are valid. Whether one or the other is employed in any given instance depends on the specific demands of the task at hand, the objective being to optimize performance. That this is in fact the case, has been demonstrated in a study by Jefferies and Di Lollo (2008) in which whether observers employed a single unitary focus or two separate foci depended on task demands.

To summarize, the present study employed the well-established phenomenon of Lag-1 sparing to examine the spatiotemporal modulations of attention. Systematic variation of the interval between successive items in an RSVP stream revealed that the spatial extent of the focus of attention varies linearly over time.

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Thank you. Once a claim is received and resolved, delivery of replacement issues routinely takes 4–6 weeks.

(TO BE FILLED OUT BY APA STAFF)

DATE RECEIVED: _____	DATE OF ACTION: _____
ACTION TAKEN: _____	INV. NO. & DATE: _____
STAFF NAME: _____	LABEL NO. & DATE: _____

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PLEASE DO NOT REMOVE. A PHOTOCOPY MAY BE USED.