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First unitary, then divided: The temporal dynamics of dividing attention

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Abstract

Whether focused visual attention can be divided has been the topic of much investigation, and there is a compelling body of evidence showing that, at least under certain conditions, attention can be divided and deployed as two independent foci. Three experiments were conducted to examine whether attention can be deployed in divided form from the outset, or whether it is first deployed as a unitary focus before being divided. To test this, we adapted the methodology of Jefferies, Enns, and Di Lollo (2014), who used a dual-stream Attentional Blink paradigm and two letter-pair targets. One aspect of the AB, Lag-1 sparing, has been shown to occur only if the second target-pair appears within the focus of attention. By presenting the second target-pair at various spatial locations and assessing the magnitude of Lag-1 sparing, we probed the spatial distribution of attention. By systematically manipulating the stimulus-onset-asynchrony between the targets, we also tracked changes to the spatial distribution of attention over time. The results showed that even under conditions which encourage the division of attention, the attentional focus is first deployed in unitary form before being divided. It is then maintained in divided form only briefly before settling on a single location.

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First unitary, then divided: The temporal dynamics of dividing attention

In order to optimise the selection of relevant information from a rich visual world, the focus of attention can be flexibly changed in several ways: it can, for example, be shifted from one object or location to another (*attentional orienting*; LaBerge, 1995; Posner, 1980; Weichselgartner & Sperling, 1987) or it can be expanded or contracted in spatial extent to encompass larger or smaller objects (*attentional focusing*; Benso, Turatto, Mascetti, & Umiltà, 1998; Castiello & Umiltà, 1990; Eriksen & Yeh, 1985; Huang, Xue, Wang, & Chen, 2016; Jefferies, Gmeindl, & Yantis, 2014). It has been intensely debated whether the focus of attention can also be divided and deployed independently to spatially separated objects or locations. Although the evidence initially suggested that the focus of attention was exclusively unitary (e.g., Barriopedro & Botella, 1998; Heinze et al., 1994; Jonides, 1983; LaBerge, 1983; LaBerge & Brown, 1989; Posner, Snyder, & Davidson, 1980; see also Jans, Peters, & De Weerd, 2010), there is a growing consensus based on both behavioural and neuroimaging studies that the focus of attention can be divided, at least under certain circumstances (e.g., Awh & Pashler, 2000; Bichot, Cave, & Pashler, 1999; Cave, Bush, & Taylor, 2010; Dubois, Hamker, & VanRullen, 2009; Godijn & Theeuwes, 2003; Jefferies, Enns, & Di Lollo, 2014; Kawahara & Yamada, 2007; Kramer & Hahn, 1995; McMains & Somers, 2004, 2005; Müller, Malinowski, Gruber, & Hillyard, 2003).

The majority of studies investigating divided attention examine the distribution of attention at a single point in time – in essence, they provide a snapshot of the distribution of attention (e.g., Awh & Pashler, 2000; Bay & Wyble, 2014; Jefferies, Enns, & Di Lollo, 2014; Kramer & Hahn, 1995; McMains & Somers, 2004, 2005). The spatial distribution of attention, however, changes over time (Egeth & Yantis, 1997; Müller & Rabbitt, 1989; Posner, 1980; Weichselgartner & Sperling, 1987), allowing us to respond flexibly and optimally to our visual environment. We cannot, therefore, gain a complete understanding of how attention functions by testing a single point in time. The present study examines a key question about how divided attention may change over time. Specifically, it has been suggested that it is more effortful to deploy a divided focus of attention than a unitary one (e.g., Cave, Bush, & Taylor, 2010). If so, observers may deploy attention first as a unitary focus before gradually dividing attention; the present study tests this possibility.

A variety of paradigms have been used to assess whether attention is unitary or divided. One recent study was able to show both unitary and divided attention within a single paradigm (Jefferies, Enns, & Di Lollo, 2014). Specifically, it was found that observers flexibly deployed either a unitary or a divided attentional focus in response to physically identical visual displays, depending on their knowledge and expectation regarding where targets would appear. The present study will adapt that paradigm to examine the time course of dividing attention.

In their study, Jefferies, Enns, and Di Lollo (2014) employed two well-established measures of attention – the Attentional Blink and Lag-1 sparing – to assess whether attention was unitary or divided. In a typical attentional blink (AB) paradigm, observers are presented with a rapid stream of distractors (e.g., digits) in which are embedded two targets (e.g., letters). While observers can generally identify the first target (T1) quite accurately, identification of the second target (T2) depends critically on the number of items that intervene between the two targets (i.e., the inter-target lag). At short lags, identification accuracy of T2 is impaired; at lags beyond about 500-700 ms, the impairment disappears (Raymond, Shapiro, & Arnell, 1992). This lag-dependent T2-impairment is the hallmark of the AB (Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992).

Paradoxically, the AB is often much reduced when T2 is presented directly after T1 at the ordinal position known as Lag 1. This pattern of results is known as *Lag-1 sparing* (Potter, Chun, Banks, & Muckenhoupt, 1998). Lag-1 sparing is calculated as the difference in T2 identification accuracy at Lag 1 and at the lowest following lag (Visser, Bischof, & Di Lollo, 1999; see Figure 1). It was originally thought that Lag-1 sparing occured only when T2 appears in the same location as T1 (i.e., in the same RSVP stream; Visser, Bischof, & Di Lollo, 1999; Visser, Zuvic, Bischof, & Di Lollo, 1999). Subsequent research showed, however, that Lag-1 sparing can also occur when T1 and T2 appear in different spatial locations, but only if T2 falls within the focus of attention (Jefferies, Ghorashi, Kawahara, & Di Lollo, 2007; Shih, 2000). One can, therefore, probe the spatial distribution of attention by systematically manipulating the location at which T2 is presented and assessing whether or not Lag-1 sparing occurs (e.g., Jefferies & Di Lollo, 2009, 2015; Jefferies, Enns, & Di Lollo, 2014, 2017; Jefferies, Roggeveen, Enns, Bennett, Sekuler, & Di Lollo, 2015; Kawahara & Yamada, 2006; Lunau & Olivers, 2010; Yamada & Kawahara, 2007).

In developing a paradigm to allow the assessment of unitary and divided attention, Jefferies, Enns, and Di Lollo (2014) employed a dual-stream AB paradigm, with two concurrent RSVP streams of digit distractors – one displayed to the left and the other displayed to the right of fixation. The first target consisted of two simultaneously-presented letters (the T1-pair). On a random half of the trials, the two letters were the same as one another; on the remaining trials, the two letters were different from one another. The second target also consisted of two simultaneously-presented letters (the T2-pair), but those letters always differed from one another. At the end of each trial, participants made three responses, indicating first whether the letters in the T1-pair were the same as one another or different from one another, and then identifying each of the two letters in the T2-pair.

The key manipulation in Jefferies, Enns, and Di Lollo's (2014) study was the participants' expectation about where the targets would appear, and thus where attention should be allocated to optimize task performance. This was accomplished by manipulating the location of the T1-pair. For one group of observers – the Unpredictable group – the location of the letters in the T1-pair was unpredictable from one trial to the next. That is, on a randomly-intermixed half of the trials, the T1-letters appeared such that one letter appeared in each RSVP stream (the *In-Stream* condition). On the remaining trials, the letters appeared in the blank region between the streams (the *Between-Streams* condition). Jefferies, Enns, and Di Lollo reasoned that in order to optimize identification accuracy of the T1-pair, participants in the Unpredictable condition would deploy a broad, unitary focus of attention that encompassed both RSVP streams as well as the region between the streams. For a second group of observers – the Predictable group – the T1-pair letters always appeared in the RSVP streams (i.e., the In-Stream condition). It was hypothesized that presenting the T1-pair consistently In-Stream would cause the observers to divide attention and deploy one focus to each stream. For both groups, the T2-pair appeared randomly either within the streams or between the streams so that the distribution of attention could be assessed.

Jefferies, Enns, and Di Lollo (2014) predicted that Lag-1 sparing would occur to the T2-pair when it appeared at the In-Stream location in both the Predictable and the Unpredictable conditions because the RSVP stream locations are attended regardless of whether the focus of attention is unitary or divided (see Figure 1). The trials of critical interest, therefore, were those in which the T2-pair was presented between the streams. If Lag-1 sparing occurred in the Between-Streams condition, this would indicate that the region between the streams was attended, consistent with a unitary focus of attention. If, on the other hand, Lag-1 sparing did not occur, this would indicate that the region between the streams was unattended and that the focus of attention was divided (see Figure 1).

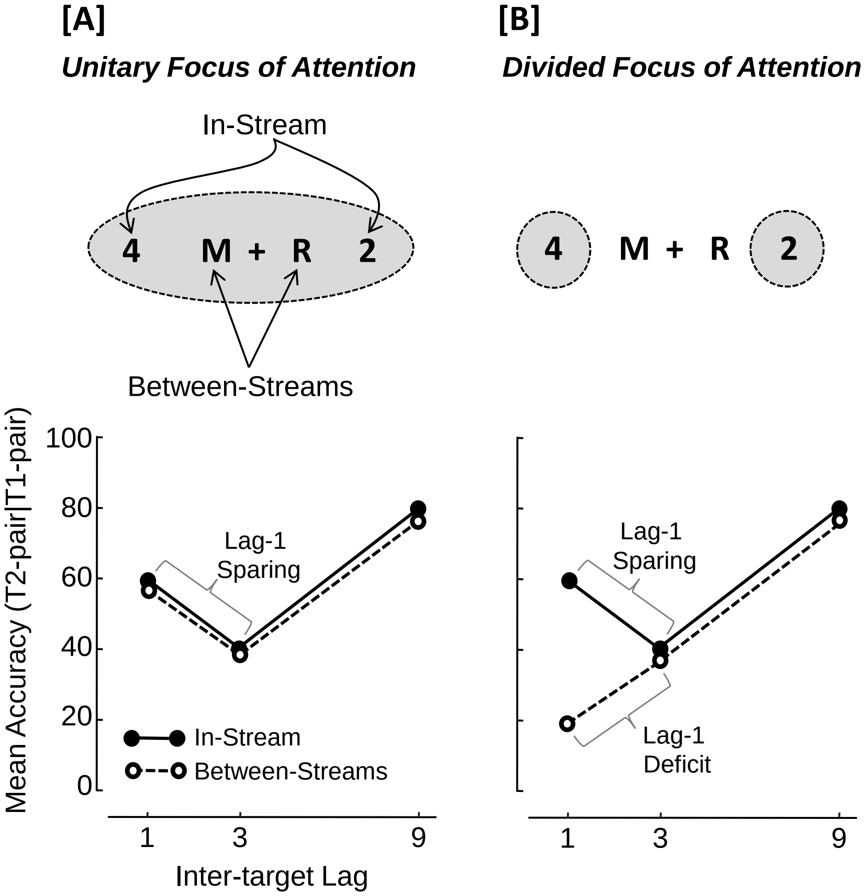

***Figure 1**. Schematic illustration the hypothesized distribution of attention (grey circular regions) and expected pattern of Lag-1 sparing and Lag-1 deficit when the focus of attention is unitary (Panel A) or divided (Panel B). Illustrated is the case in which the T2-pair (the letters M and R) is presented in the Between-Streams location. In the experiment, the T2-pair appeared unpredictably but with equal frequency in the In-Stream and the Between-Streams locations. Example data from trials in which the T2-pair appeared either In-Stream or Between-Streams is illustrated in the graphs.*

As expected, Jefferies, Enns, and Di Lollo (2014), found that Lag-1 sparing occurred when the T2-pair appeared In-Stream in both the Unpredictable and the Predictable conditions. When the T2-pair was presented Between-Streams, however, Lag-1 sparing occurred in the Unpredictable condition but not in the Predictable condition. This outcome is consistent with the region between the streams being attended (a unitary focus) in the Unpredictable condition and unattended (a divided focus) in the Predictable condition.

The goal of the present study was to examine the early time course of the deployment of attention in order to determine whether the focus of attention can be deployed in divided form from the outset, or whether the focus of attention is first deployed in unitary form and subsequently divided. To answer this, we employed the methodology of the Predictable condition of Jefferies, Enns, and Di Lollo (2014), in which observers deployed a divided focus of attention. In Experiment 1 we first provided a more spatially-refined test of the distribution of attention, confirming that attention is indeed deployed as a divided focus and not in the form of an annulus or a ring. Experiment 2 then assessed the distribution of attention after 70, 84, 98, 112, and 126 milliseconds. Experiment 3 examined task difficulty and hemifield effects in the distribution of attention.

Experiment 1

One limitation of the paradigm used by Jefferies, Enns, and Di Lollo (2014) was that the T2 letters were presented only along the horizontal midline of the display. It is possible, therefore, that the focus of attention, rather than being divided, was deployed in the form of a ring or annulus which encompassed the left- and right-hand RSVP streams, but excluded the central region (see Jans, Peters, & De Weerd, 2010; also Egly & Homa, 1984; Eimer, 1999, 2000; Juola, Bouwhuis, Cooper, & Warren, 1991). It has been shown that the deployment of attention in the form of an annulus depends critically on the sustained presentation of an appropriate structural framework such as a ring or other appropriate framework to which attention can be deployed (Jefferies & Di Lollo, 2015, 2017; Eimer, 1999, 2000; Juola, Bouwhuis, Cooper, & Warner, 1991). Previous research has shown that an RSVP stream of digit distractors can provide just such a framework (Jefferies, Ghorashi, Kawahara, & Di Lollo, 2007; Ghorashi, Jefferies, Kawahara, & Wantanabe, 2008), and it is therefore possible that the two RSVP streams in the paradigm of Jefferies, Enns, and Di Lollo could have provided a partial structural framework sufficient to allow attention to be deployed in the form of an annulus. Experiment 1 is therefore designed to determine whether attention is deployed in the form of an annulus in the present paradigm. To this end, the spatial distribution of attention was probed more precisely by presenting the T2-pair along a vertical as well as a horizontal axis (see Figures 2 and 3A).

Method

Observers

Twenty-five undergraduate students (mean age = 21.28 years, SD=5.06; 19 females; 22 right-handed) at Griffith University participated in the experiment for course credit. An a priori power analysis was conducted using G*Power (Faul & Erdfelder, 1998) based on the effect size for the interaction between Lag and T2-pair location obtained by Jefferies, Enns, and Di Lollo (2014). The analysis revealed that a minimum total sample of 18 participants would be needed in order for an effect of that size to be detected with 90% probability with alpha set to .05."

All participants were naïve as to the purpose of the experiment and reported normal or corrected-to-normal vision. Ethical approval for this experiment was granted by the Griffith University Human Research Ethics Committee.

Stimuli

All stimuli were presented on a BenQ XL2430T computer monitor running at 144 Hz powered by a Dell computer with a Windows operating system. Stimulus presentation was controlled by a custom Matlab script using libraries provided by the Psyctoolbox 3 software (Brainard, 1997; Pelli, 1997; Kleiner et al, 2007). Stimuli were viewed from a distance of approximately 60 cm. The background of the display was light grey, and a black fixation cross (0.25° × 0.25°) was displayed in the center of the screen at the beginning of each trial. Observers initiated each trial by pressing the spacebar. After a delay of 500 – 800 ms, two synchronized rapid serial visual presentation (RSVP) streams of digits (subtending 0.9° vertically) were presented 1.75° to the left and to the right (center-to-center) of fixation. The digits were selected randomly from the set 0-9 with the restriction that the same digit could not be presented successively, and that the same digit could not be presented simultaneously in both streams.

The targets were pairs of letters selected randomly from the English alphabet, excluding the letters I, O, Q, Z, (which are visually similar to the digits 0, 1, and 2), and the letters S and D (which were used to respond to the T1-pair). The first target pair (T1-pair) was presented such that one letter appeared in the left-hand stream and the other letter in the right-hand stream. On a random half of the trials, the two letters were the same as one another; on the remaining trials, the two letters were different from one another.

Unlike the letters in the T1-pair, the letters in the second-target pair (T2-pair) were always different from one another. The same letters were never presented in both the T1- and T2-pairs. The T2-pair letters appeared randomly but with equal probability at one of four locations. In the *In-Stream* condition, the T2-pair appeared such that one letter was in the left-hand RSVP stream and the other letter was in the right-hand RSVP stream (Figure 2A). In the *Horizontal-Inner* condition, one letter of the T2-pair was presented in the blank region between the left-hand stream and fixation and the other letter was presented in the blank region between the right-hand stream and fixation (Figure 2B). In the *Vertical-Outer* condition (Figure 2D), the letters in the T2-pair were presented 1.75° from fixation, but along a vertical axis (i.e., the same eccentricity as in the In-Stream condition, but along a vertical axis). Lastly, in the *Vertical-Inner* condition (Figure 2C), the letters in the T2-pair were presented above and below fixation in the regions between the Vertical-Outer locations and fixation.

Both letters of each target pair were masked. The T1-pair was masked either by the T2-pair (in the In-Stream condition at Lag 1) or by the following digit in the RSVP stream (in all other conditions). When the T2-pair appeared In-Stream, it was masked by the following digit in the RSVP stream; when the T2-pair appeared at the Horizontal-Inner, Vertical-Outer, or Vertical-Inner locations, the T2-pair was masked by a pair of digits (drawn randomly from the set 0-9) presented at same locations as the letters in the T2-pair. The RSVP stream continued during the presentation of the T2 mask. Each letter and digit and was displayed for 98 ms before being replaced by the items in the following frame.

Procedure

Each trial began with the presentation of the fixation cross, followed by a 500-ms delay. The two streams of distractor digits then appeared, one to the left and one to the right of fixation. After a random 8 to 14 leading digits, the T1-pair was presented with one letter in each stream. The T2-pair followed the T1-pair at one of three lags: 1 (98 ms), 3 (294 ms), or 9 (882 ms), presented randomly but with equal frequency throughout the experiment. The T2-pair location was chosen randomly on each trial, with the restriction that each of the four possible locations – In-Stream, Horizontal-Inner, Vertical-Inner, and Vertical-Outer – was chosen an equal number of times. Participants were instructed that the T1-pair would always appear at the In-Stream location whereas the T2-pair would appear unpredictably at any of the four locations.

At the end of each trial, participants made three responses. They first indicated whether the letters in the T1-pair were the same as one another or different from one another by pressing the ‘S’ key or the ‘D’ key on the keyboard. They then identified the two letters in the T2-pair by pressing the corresponding keys on the keyboard, in either order.

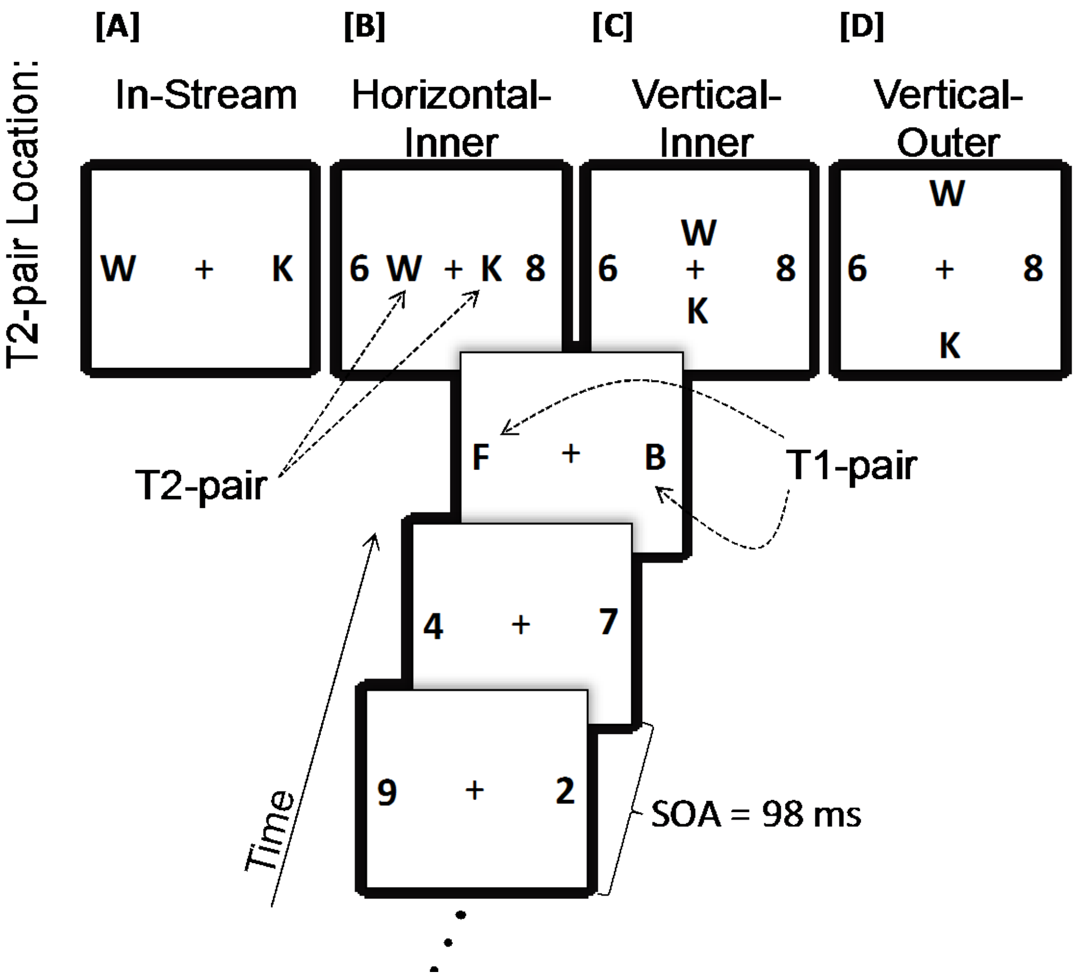

Figure 2. *The display sequence in Experiment 1 with the four possible T2-pair locations. Illustrated is a trial in which the letters in the T1-pair are different from one another (F and B) and the letters of the T2-pair are W and K. The T2-pair was always masked by a pair of digits, which appeared in the same location as the T2-pair in the following frame (not illustrated).*

Results

Only trials in which the response to the T1-pair was correct were included for analysis. This technique is commonly adopted in AB studies on the view that, if the T1-pair is identified incorrectly, the source of any further error is unknown and thus its effects on T2 processing cannot be estimated. T1-pair response accuracy averaged across Lag and T2-pair location was 71.6%.

The two responses to the letters in the T2-pair were averaged to calculate a single T2-pair accuracy score, following the procedures of Kawahara and Yamada (2007) and Jefferies, Enns, and Di Lollo (2014). Figure 3B illustrates the percentage of correct T2-pair responses as a function of T2-pair location and inter-target lag. If attention was deployed as a divided focus in Experiment 1, one would expect Lag-1 sparing to occur when the T2-pair was presented at the In-Stream location and not when it was presented at the Horizontal-Inner, Vertical-Outer, or Vertical-Inner locations. If, on the other hand, attention was deployed in the form of an annulus, one would expect Lag-1 sparing to occur both when the T2-pair was presented at the In-Stream location and when it was presented at the Vertical-Outer location. No Lag-1 sparing would be expected when the T2-pair was presented at either the Horizontal-Inner or Vertical-Inner location (see Figure 3A).

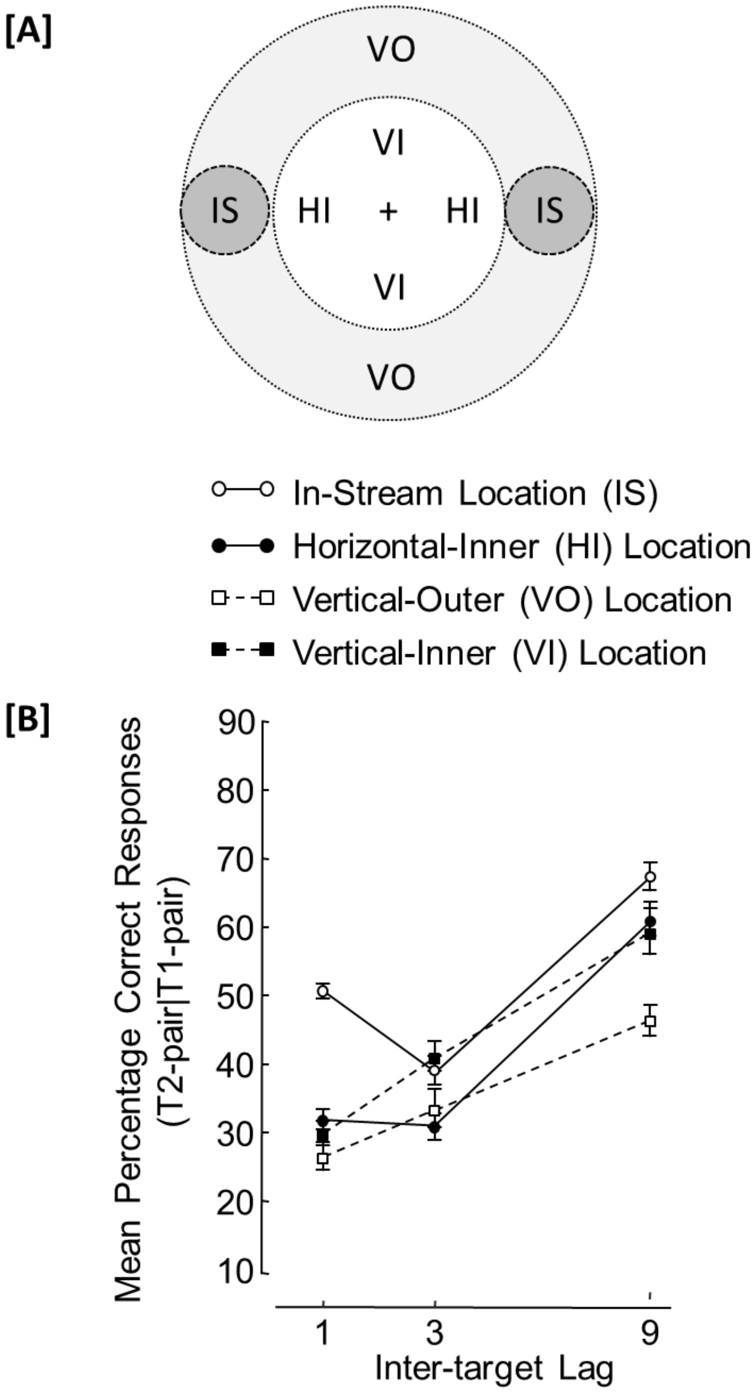

Figure 3. *Panel A: Two alternative distributions of attention: a divided focus of attention (darker grey circular regions) or an annular distribution (lighter grey ring-shaped regions). Panel B: Mean percentage of correct responses to T2 in Experiment 1. Lag-1 sparing occurs only in the In-Stream location, indicating that the focus of attention is divided (darker grey circles in Panel A). Error bars indicate standard error of the mean.*

The data illustrated in Figure 3B were first analyzed in an overall 4 (T2-Location: In-Stream, Horizontal-Inner, Vertical-Inner, Vertical-Outer) × 3 (Lag: 1, 3, 9) repeated-measures ANOVA. The analysis revealed significant main effects of T2-Location, *F*(3,72) =

15.03, $p < .001$, $\eta_p^2 = .385$, and Lag, $F(2,48) = 53.15$, $p < .001$, $\eta_p^2 = .689$, and a significant interaction between T2-Location and Lag, $F(6,144) = 10.89$, $p < .001$, $\eta_p^2 = .312$.

Since the spatial distribution of attention is indexed by the presence or absence of Lag-1 sparing, which is assessed by comparing relative accuracy at Lags 1 and 3, Lag 9 is of no particular theoretical interest to the present study. It was included only to decrease the temporal predictability of the T2-pair and to confirm that an AB is present. Therefore, to test whether Lag-1 sparing occurred at each T2-Location, separate Bonferroni-corrected *t*-tests (corrected *p*-values are reported) were performed on the data at Lags 1 and 3 at each T2-Location. The outcomes showed that accuracy was significantly higher at Lag 1 than at Lag 3 (i.e., Lag-1 sparing occurred) for the In-Stream condition [$t(24) = 2.77$, $p = .04$], but that accuracy did not differ between Lags 1 and 3 (i.e., Lag-1 sparing did not occur) at the Horizontal-Inner, Vertical-Inner, or Vertical-Outer locations, $t(24) = 1.047$, $p = 1.0$; $t(24) = 2.08$, $p = .192$; and $t(24) = 2.43$, $p = .092$, respectively. This outcome confirms the graphical evidence in Figure 3B that Lag-1 sparing occurred only in the In-Stream location. Since Lag-1 sparing occurs only when T2 falls within the focus of attention, the above pattern of results is consistent with observers deploying a divided focus of attention, with one focus centred on each RSVP stream (see Figure 3A).

Is attention deployed equally to both letters in the T2-pair?

Before concluding that the focus of attention is divided, it should first be confirmed that attention is deployed equally to both letters in the T2-pair. In Experiment 1, participants were required to identify both letters in the T2-pair, and, taking the same approach as Kawahara and Yamada (2007) and Jefferies, Enns, and Di Lollo (2014), we averaged across the two responses to create a single measure of response accuracy to the T2-pair. Averaging, however, could potentially obscure the fact that only one of the targets was reported correctly. If that were the case, it would suggest that the focus of attention is deployed as a single narrow focus centred on just one stream rather than as a divided focus of attention with one focus deployed to each stream. This alternative can be tested by considering whether Lag-1 sparing occurs for each of the letters in the T2-pair separately. Figure 4 illustrates the percentage of correct responses to each letter in the T2-pair separately for each T2-Location.

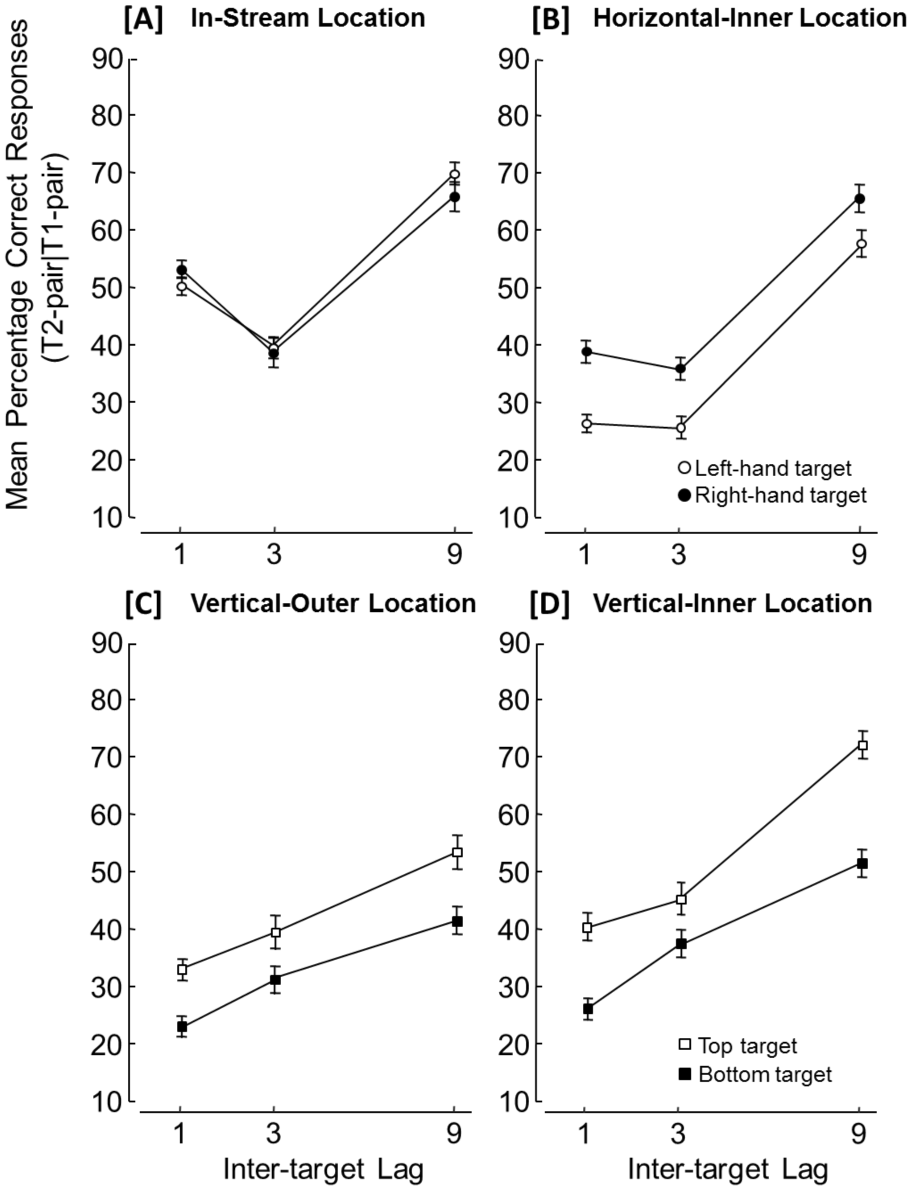

Figure 4. *Mean percentage of correct responses to each letter in the T2-pair as function of Lag and T2-pair Location. Panels A and B illustrate the In-Stream and Horizontal-Inner locations, and the graphs show identification accuracy to targets presented to the left of fixation (open circular symbols) and to the right of fixation (filled circular symbols). Panels C and D illustrate the Vertical-Outer and Vertical-Inner locations, and thus show identification accuracy to targets presented above fixation (open square symbols) and below-fixation (filled square symbols). Error bars indicate standard error of the mean.*

The key question is whether Lag-1 sparing occurs equally to both targets in the T2-pair. Since Lag-1 sparing is defined as the difference in T2 identification accuracy between Lags 1 and 3 (Visser, Bischof, & Di Lollo, 1999), only the data for Lags 1 and 3 were included for analysis. The data were analyzed in a 4 (T2-pair Location) × 2 (Target Side) × 2

(Lag: 1, 3) repeated-measures ANOVA. The analysis revealed a significant main effect of T2-pair Location, $F(3,72) = 12.20$, $p < .001$, $\eta_p^2 = .337$. The main effects of Target Side and Lag were not significant ($F(1,24) = 1.07$, $p = .312$, $\eta_p^2 = .043$; and $F<1$, respectively). There were significant interactions between T2-pair Location and Target Side, $F(3,72) = 14.13$, $p < .001$, $\eta_p^2 = .371$; and between T2-pair Location and Lag, $F(3,72) = 12.32$, $p < .001$, $\eta_p^2 = .339$. The Target Side × Lag interaction was not significant, $F<1$. Critically, the three-way interaction between T2-pair Location, Target Side, and Lag was not significant, $F<1$, indicating that the magnitude of Lag-1 sparing was comparable for both letters in the T2-pair at each location. This outcome is consistent with the expectation that attention was not biased towards one target over the other – both targets were processed equally, as would be expected if the focus of attention is divided.

It is clear from an examination of Panels A-D that although Lag-1 sparing did not vary as a function of Target Side, overall accuracy did vary quite markedly as a function of Target Side among the four T2-pair Locations. In the In-Stream location, performance was comparable for the left and the right targets; in the Horizontal-Inner location, overall identification accuracy was better for the right target than for the left target; and in the Vertical-Outer and Vertical-Inner locations, overall identification accuracy was better for the top target than for the bottom target. These differences are buttressed by the significant interaction between T2-pair Location and Target Side in the analysis reported above. This issue will be considered further in the General Discussion. One comment, however, must be made at this point. Although there are clear overall differences in identifying targets appearing at different locations, these accuracy differences are evident at all lags and do not interact with either the Attentional Blink or with Lag-1 sparing. The differences in accuracy, therefore, do not index differences in the deployment of attention, but rather in the ability of the observer to detect briefly-displayed letters presented in the left versus the right hemifield and above versus below fixation.

Why not consider only accuracy at Lag 1?

One might ask why we do not simply compare T2-pair identification accuracy at Lag 1 in the various experimental conditions rather than focusing on Lag-1 sparing/deficit. As outlined in the Introduction, Lag-1 sparing has been shown to occur only when T2 falls within the spatial extent of the focus of attention. As such, it provides an ideal tool for probing the distribution of attention (e.g., Bay & Wyble, 2014; Jefferies & Di Lollo, 2009; Jefferies, Enns, & Di Lollo, 2014; Jefferies, Ghorashi, Kawahara, & Di Lollo, 2007; Kawahara & Yamada, 2007; Lunau & Olivers, 2010; Yamada & Kawahara, 2006). The fundamental reason to consider Lag-1 sparing rather than simple Lag-1 accuracy, however, is that identification accuracy at Lag 1 may be influenced by more than one factor, making it difficult to interpret. Consider, for example, the data illustrated in Figure 3. Unless one takes into account the fact that T2-pair accuracy at Lag 3 is almost identical at all T2-Locations, the greater accuracy at Lag 1 in the In-Stream condition could simply be attributable to differences in overall task difficulty between the conditions. Also consider the results illustrated in Figure 4B. If one were to consider only identification accuracy at Lag 1, one would conclude that attention is deployed to the right-hand target and not to the left-hand target. If one considers Lag 3, however, one realizes that there is an overall difference in accuracy between the two conditions which occurs independently from the allocation of attention and which makes the foregoing conclusion inappropriate. This overall level difference can be partialled out by compared accuracy at Lag 1 and Lag 3 (i.e., by considering Lag-1 sparing). For this reason, we assessed Lag-1 sparing to probe the distribution of attention and to determine whether focal attention was unitary or divided.

In summary, the purpose of Experiment 1 was to test the possibility that attention, rather than being divided, was deployed in the form of an annulus in the paradigm of Jefferies, Enns, and Di Lollo (2007). The results show clearly that this was not the case and that attention was divided, with separate attentional foci being deployed to each stream.

Experiment 2

In Experiment 2, we turn to the question of whether attention is deployed in divided form immediately upon deployment or whether it is first deployed in unitary form and then gradually divided. To this end, we assessed changes to the spatial distribution of attention by systematically varying the stimulus-onset asynchrony (SOA) between successive items in the RSVP sequence. This manipulates the amount of time that passes between the presentation of the T1-pair and the T2-pair, providing sequential “snapshots” of the spatial distribution of attention after 70, 84, 98, 112, and 126 milliseconds.

The primary factor of interest is whether the incidence and magnitude of Lag-1 sparing at each T2-pair location changes as the SOA is increased. As in Experiment 1, the location of key interest will be the Horizontal-Inner location. If the focus of attention is initially deployed in unitary form and then gradually divided over time, Lag-1 sparing should occur at the Horizontal-Inner location at the shortest SOAs (indicating a unitary attentional focus) and Lag-1 deficit should occur at the longer SOAs (indicating a divided attentional focus). The finding that Lag-1 deficit occurs at the Horizontal-Inner location at all SOAs, on the other hand, would be consistent with a focus of attention that is deployed in divided form from the outset.

Observers

Thirty-one undergraduate students at Griffith University participated in the experiment for course credit. Four participants were excluded due to near-chance levels of T1-pair accuracy (< 55%), leaving a total of twenty-seven participants (mean age=23.26 years, SD=6.79; 19 females; 23 right-handed). An a priori power analysis was conducted using G*Power (Faul & Erdfelder, 1998) based on the effect size of the interaction between Lag and SOA obtained by Jefferies and Di Lollo (2009). The analysis revealed that a minimum total sample of 22 participants would be needed in order for an effect of that size to be detected with 90% probability with alpha set to .05.

All participants were naïve as to the purpose of the experiment and reported normal or corrected-to-normal vision. Ethical approval for this experiment was granted by the Griffith University Human Research Ethics Committee.

Stimuli and Procedures

The stimuli and procedures for Experiment 2 were identical to those of Experiment 1 with two exceptions. First, whereas Experiment 1 consisted of a single SOA of 98 ms, Experiment 2 included five SOAs: 70, 84, 98, 112, and 126 ms. SOAs were randomly intermixed, but occurred with equal frequency. In order to reduce the overall number of trials and to make it possible to include SOA as a within-subject variable, one T2 location was removed from Experiment 2. The In-Stream and Horizontal-Inner conditions are particularly important for assessing whether attention is unitary or divided, so those locations were retained. On the other hand, identification accuracy was virtually indistinguishable in the Vertical-Outer and the Vertical-Inner conditions, and those locations are less critical for determining whether the attentional focus is unitary or divided. Thus, the Vertical-Inner condition was removed from Experiment 2. The remaining three T2-pair locations were presented randomly but with equal frequency.

Results

Average T1-pair response accuracy was 62%, 63%, 69%, 80%, and 81% when the SOA was 70, 84, 98, 112, and 116 ms, respectively. As in Experiment 1, the two responses to the T2-pair were averaged to calculate a single T2 score, and only trials in which the response to the T1-pair was correct were included for analysis. Figure 5 illustrates the percentage of correct T2-pair responses as a function of SOA and Lag, separately for each T2-Location. The key result in the present study is whether the incidence of Lag-1 sparing changes as a function of SOA – the key comparison, therefore, is between identification accuracy at Lags 1 and 3 as a function of SOA. To facilitate this comparison, SOA has been graphed on the x-axis and Lag is illustrated as separate lines. This mode of graphing means that each vertical column of three data points depicts one attentional blink observed over three lags. If accuracy at Lag 1 (black circular symbols) is higher than accuracy at Lag 3 (white circular symbols), Lag-1 sparing has occurred; if accuracy at Lag 3 is higher than accuracy at Lag 1, then Lag-1 deficit has occurred.

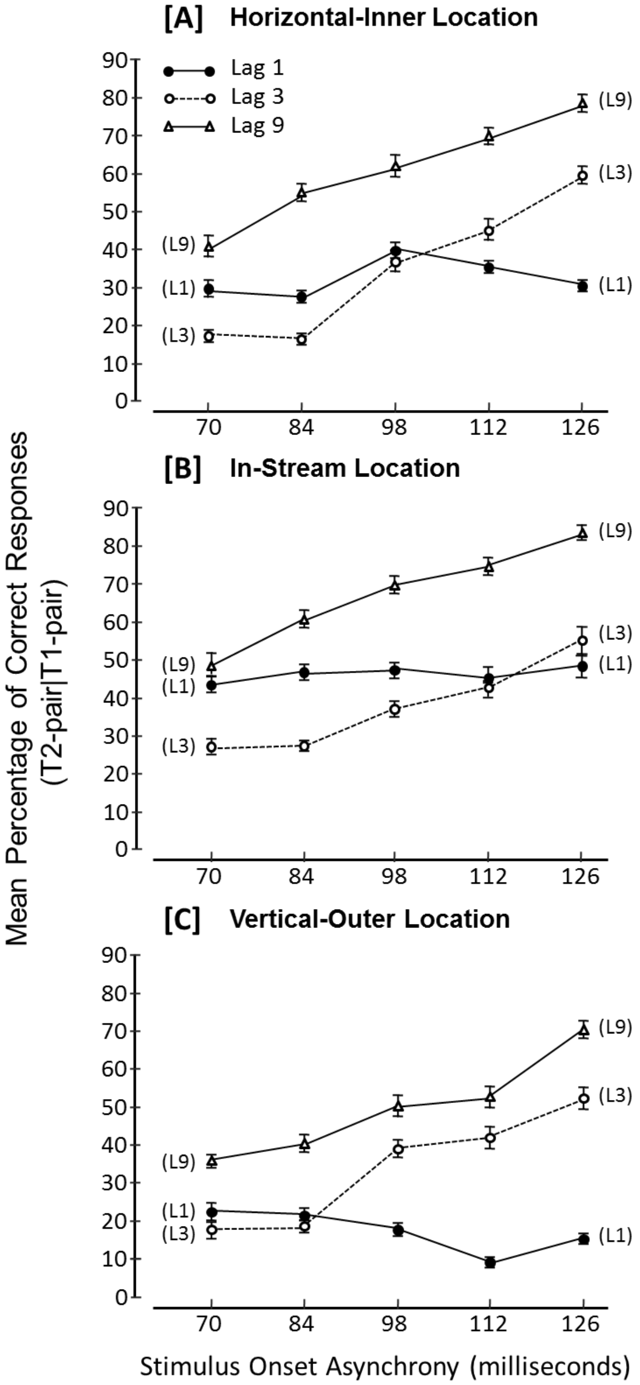

Figure 5. *Results of Experiment 2. The graphs illustrate the mean percentage of correct responses to the T2-pair as a function of SOA, separately for each T2-pair Location. Panel A illustrates the results from the Horizontal-Inner condition, Panel B illustrates the results from the In-Stream condition, and Panel C illustrates the results from the Vertical-Outer condition. The open triangular symbols illustrate the data from Lag 9, the open circular symbols illustrate the data from Lag 3, and the filled circular symbols illustrate the data from Lag 1. Each vertical column of three data points thus depicts one attentional blink observed over three lags. The functions for Lags 1, 3, and 9 have been marked as L1, L3, and L9. Error bars indicate the standard error of the mean.*

The data were first analyzed in an overall 5 (SOA: 70, 84, 98, 112, and 126 ms) × 3 (Lag: 1, 3, 9) × 3 (T2-Location: In-Stream, Horizontal-Inner, Vertical-Outer) repeated-measures ANOVA. The analysis revealed significant main effects of T2-Location, $F(2,53) = 29.77$, $p < .001$, $\eta_p^2 = .534$; SOA, $F(4,104) = 103.72$, $p < .001$, $\eta_p^2 = .800$; and Lag, $F(2,52) = 87.29$, $p < .001$, $\eta_p^2 = .770$. There were also significant two-way interactions between T2-Location and SOA, $F(8,208) = 2.40$, $p = .017$, $\eta_p^2 = .085$; SOA and Lag, $F(8,208) = 31.19$, $p < .001$, $\eta_p^2 = .545$; and T2-Location and Lag, $F(4,104) = 19.99$, $p < .001$, $\eta_p^2 = .435$. Lastly, the three-way interaction between T2-Location, SOA, and Lag was significant, $F(16,416) = 2.06$, $p = .009$, $\eta_p^2 = .073$.

Lag-1 sparing as a function of SOA

The primary objective of Experiment 2 was to determine whether attention can be divided immediately upon deployment, or whether attention is initially deployed in a unitary form and then gradually divided. Critical to answering this question is an examination of Lag-1 sparing as a function of SOA. Lag-1 sparing occurs whenever T2 is presented within an attended region (Jefferies, Ghorashi, Kawahara, & Di Lollo, 2007). If, therefore, attention can be deployed in unitary form at the outset, Lag-1 sparing should be evident at the In-Stream location at all SOAs and should not occur at the Horizontal-Inner or the Vertical-Outer conditions at any SOA. If, on the other hand, the focus of attention is initially unitary and divides gradually over time, a very different pattern of results should emerge. At the shorter SOAs, Lag-1 sparing should occur at all locations, indicating that attention is deployed broadly in unitary form. As the SOA is increased and the focus of attention is divided, Lag-1 sparing should cease to occur at the Horizontal-Inner and Vertical-Outer locations and should be present only at the In-Stream location. The critical consideration in Experiment 2, therefore, is Lag-1 sparing as a function of SOA at the three T2-Locations.

Horizontal-Inner Location. The data from the Horizontal-Inner condition were analysed in a 2 (Lag: 1, 3) × 5 (SOA: 70, 84, 98, 112, and 126) repeated-measures ANOVA. The analysis revealed a significant main effect of SOA, $F(4,104) = 34.15$, $p < .001$, $\eta_p^2 = .568$. The main effect of Lag was not significant, $F < 1$. Critically, there was a significant Lag × SOA interaction, $F(4,104) = 18.82$, $p < .001$, $\eta_p^2 = .420$, confirming the graphical evidence in Figure 5A that T2-pair identification accuracy was higher at Lag 1 (filled circular symbols) than at Lag 3 (open circular symbols) when the SOA was short; the opposite was true when SOA was long. In other words, Lag-1 sparing occurred when the SOA was short and Lag-1 deficit occurred when the SOA was long. Bonferroni-corrected *t*-tests (corrected *p*-

values are reported) comparing accuracy at Lag 1 and at Lag 3 confirmed that significant Lag-1 sparing occurred when the SOA was 70 ms [$t(26) = 3.36$, $p = .01$] and 84 ms [$t(26) = 3.35$, $p = .015$], that neither Lag-1 sparing nor Lag-1 deficit occurred at the 98-ms or 112-ms SOA conditions [$t(26) = .53$, $p = 1.0$; $t(26) = 2.03$, $p = .053$, respectively]. Significant Lag-1 deficit occurred at 126 ms [$t(26) = 7.31$, $p < .005$]. These outcomes indicate that the region between the streams was attended at short SOAs and unattended at longer SOAs, indicating that the focus of attention is initially unitary and divides over time.

In-Stream Location. Since the In-Stream location should be attended regardless of whether the focus of attention is unitary or divided, Lag-1 sparing is expected to occur in this condition at all SOAs. The data, however, are only partially consistent with this expectation: Lag-1 sparing occurs at the shorter SOAs, but is absent at the longer SOAs (Figure 5B). To confirm this, a 2 (Lag: 1, 3) × 5 (SOA: 70, 84, 98, 112, 126) repeated-measures ANOVA was conducted on the data from the In-Stream condition. The analysis revealed significant main effects of Lag, $F(1,26) = 10.69$, $p = .003$, $\eta_p^2 = .291$, and SOA, $F(4,104) = 13.39$, $p < .001$, $\eta_p^2 = .340$. A significant Lag × SOA interaction, $F(4,104) = 7.32$, $p < .001$, $\eta_p^2 = .220$, confirms the graphical evidence in Figure 5B that Lag-1 sparing is present only at the shorter SOAs. Bonferroni-corrected *t*-tests showed significant Lag-1 sparing at the 70-ms [$t(26) = 3.71$, $p = .005$] and 84-ms [$t(26) = 4.91$, $p < .005$] SOA conditions. No Lag-1 sparing was evident at the 98-ms [$t(26) = 2.29$, $p = .15$], 112-ms [$t(26) = .565$, $p = .577$], or 126-ms [$t(26) = 1.05$, $p = .303$] SOA conditions. At first glance, the lack of significant Lag-1 sparing at the longer SOAs is unexpected because since the stream locations should be attended regardless of whether the attentional focus is unitary or divided, the stream locations should be attended. We will return to this result later in the discussion of Experiment 2 and in Experiment 3, and will show that Lag-1 sparing does occur at the In-Stream locations at the longer SOAs – in fact, these unexpected results will provide an important insight into how the focus of attention changes over time.

Vertical-Outer Location. The data from the Vertical-Outer condition (Figure 5C) were analysed in a 2 (Lag: 1, 3) × 5 (SOA: 70, 84, 98, 112, and 126) repeated-measures ANOVA, which revealed significant main effects of Lag, $F(1,26) = 28.04$, $p < .001$, $\eta_p^2 = .519$, and SOA, $F(4,104) = 13.80$, $p < .001$, $\eta_p^2 = .347$. There was also a significant Lag × SOA interaction, $F(4,104) = 24.75$, $p < .001$, $\eta_p^2 = .488$. Bonferroni-corrected *t*-tests showed that Lag-1 sparing was absent at the 70 ms [$t(26) = 1.76$, $p = .46$] and 84 ms [$t(26) = 1.38$, $p = .89$] SOAs and that significant Lag-1 deficit occurred at SOAs of 98 ms [$t(26) = 3.83$, $p = .005$], 112 ms [$t(26) = 5.88$, $p < .005$], and 126 ms [$t(26) = 6.91$, $p < .005$]. Since Lag-1 sparing was absent at every SOA, we can conclude that the focus of attention never encompassed the Vertical-Outer location.

In summary, the overall pattern of results suggests that attention is initially deployed as a unitary focus that gradually divides over time. The lack of Lag-1 sparing to the Vertical-Outer location indicates that attention does not broadly encompass all potential T2-pair locations, even at the outset; rather, it appears to be focused in an elliptical shape centered along the horizontal axis and encompassing the two RSVP streams and the regions between them.

It is worth noting that, in the 100-ms SOA condition, the results of Experiment 2 closely replicate those of Experiment 1. There is Lag-1 sparing in the In-Stream condition, Lag-1 deficit in the Vertical-Outer location, and approximately equal accuracy at Lags 1 and 3 in the Horizontal-Inner location. This last result makes sense in light of the overall finding of Experiment 2: the focus of attention is first deployed in unitary form before being gradually divided. The 100-ms SOA condition appears to be a transition point, between the two modes.

Changes to the distribution of attention over time

In examining the data illustrated in Figure 5, there is an overall upwards trend – a marked general improvement in the observers' ability to correctly identify the letters in the T2-pair as the SOA increases. This can perhaps be seen most clearly by considering performance at Lag 9 for each T2-Location (Figure 5, open triangular symbols in Panels A-C). In all cases, identification accuracy increases linearly as a function of SOA. This improvement is independent of the AB since it is apparent at Lag 9, which is outside the period of the AB. The increase in overall accuracy as a function of increasing SOA can be attributed to the effects of masking. It is known that the strength of masking increases as the temporal interval between the onset of a target and the onset of its trailing mask decreases (Breitmeyer, 1984; Breitmeyer & Öğmen, 2006). Thus, masking becomes progressively weaker as the SOA is increased from 70 ms to 126 ms, and performance becomes correspondingly more accurate.

By causing an SOA-dependent change in the overall level of performance, the effects of masking cloud the incidence of Lag-1 sparing and make it more difficult to see changes to the distribution of attention over time. To address this, we have presented the data in a way that partials out the overall differences in performance level that arise from the effects of masking. This was accomplished by calculating a single measure of the magnitude of Lag-1 sparing or Lag-1 deficit for each participant: subtracting the percentage of correct responses at Lag 3 from the percentage of correct responses at Lag 1. A positive value indicates Lag-1 sparing whereas a negative value indicates Lag-1 deficit. The magnitude scores for each participant were then averaged. The results from Experiment 2 expressed in terms of the magnitude of Lag-1 sparing or Lag-1 deficit are illustrated in Figure 6.

This alternative approach to the data has another advantage. There are often substantial individual differences in the magnitude of the attentional blink and of Lag-1 sparing. Those differences may be under-represented by considering only average identification accuracy at each lag. Calculating the magnitude of Lag-1 sparing for each participant allows those individual differences to be taken into account (see Colzato, Spapé, & Pannebakker, 2007).

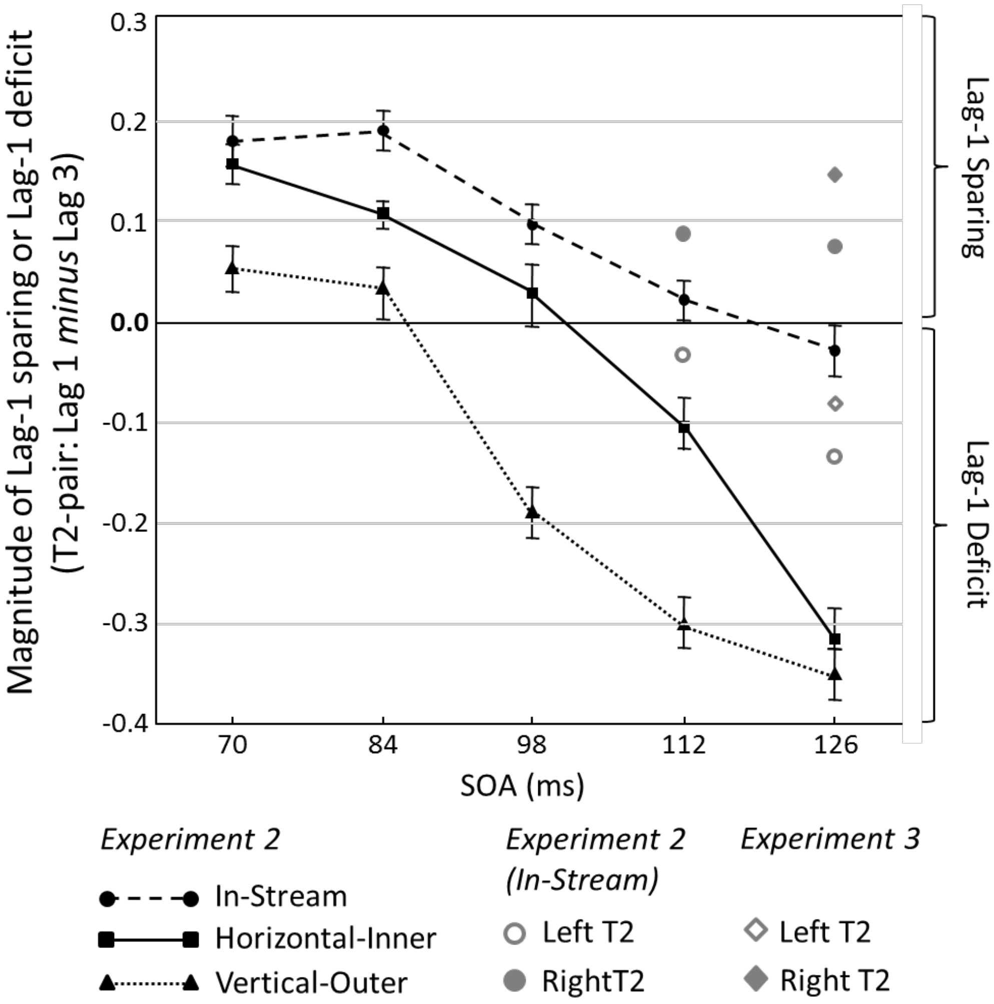

Figure 6. *Variation in the magnitude of Lag-1 sparing (positive values) and Lag-1 deficit (negative values) as a function of T2-Location and SOA. The filled square symbols illustrate the Horizontal-Inner location; the filled circular symbols illustrate the In-Stream location; the filled triangular symbols illustrate the Vertical-Outer location. The grey diamond symbols illustrate the Left (open symbol) and Right (filled symbol) targets in the T2-pair in the In-Stream condition of Experiment 2. Notably, Lag-1 sparing occurs at the longer SOAs for the Right T2, but not for the Left T2. The grey circular symbols illustrate the data from Experiment 3. The filled grey circle illustrates the data for the right T2 letter; the open grey circle illustrates the data for the left T2 letter. Lag-1 sparing occurs to the right target and Lag-1 sparing occurs to the left target.*

Consider first the data from the Horizontal-Inner condition (solid line, square symbols), in which the T2-pair appeared in the blank region between the streams. As discussed previously, this is the key condition to index whether attention is unitary or divided: if Lag-1 sparing occurs, this location is attended and the focus of attention must be unitary; if, on the other hand, Lag-1 deficit occurs, this location is unattended and the focus of attention must therefore be divided. Figure 6 shows that there is a linear change from Lag-1 sparing to Lag-1 deficit in the Horizontal-Inner condition. This pattern indicates that the focus of attention is unitary for at least 84 - 98 ms and then is gradually divided over the next 40+ milliseconds. The data from the In-Stream condition (segmented line, circular symbols) show that Lag-1 sparing occurs at the shorter SOAs, but not at the longer SOAs (although neither is there significant Lag-1 sparing).

As noted earlier, the lack of significant Lag-1 sparing at the longer SOAs in the In-Stream condition is unexpected and, at first glance, is inconsistent with previous research showing Lag-1 sparing at SOAs up to 133 ms when T2 is presented at an attended location (e.g., Jefferies & Di Lollo, 2009; Jefferies, Ghorashi, Kawahara, & Di Lollo, 2007; Jefferies, Roggeveen, Enns, Bennett, Sekuler, & Di Lollo, 2015). Although there are some differences in the methodology employed in the present experiment and those of previous studies – most notably, the use of a T2-pair, which required participants to process and remember two letters rather than one, and an intermixed SOA design rather than a blocked design – and although it is possible that these differences account for the lack of Lag-1 sparing, a more likely account is inspired by the findings of Dubois, Hamker, and VanRullen (2009).

In their study, Dubois, Hamker, and VanRullen showed that although attention can be divided, it can be maintained in a divided state only for about 100-150 ms before settling on a single object or location. This would suggest that at the longer SOAs, attention might no longer be divided with one focus deployed to each stream location. Rather, attention might be deployed as a single attentional focus centred on just one stream. In this case, Lag-1 sparing would occur to the target in the attended stream and Lag-1 deficit would occur to the target in the unattended stream. Averaging over the two responses would lead to roughly equivalent performance at Lags 1 and 3 – precisely the pattern of results observed at the longer SOAs in Experiment 2. This possibility can be examined by considering identification accuracy for the left and the right targets separately. Figure 7 illustrates the data for the In-Stream condition for the left-hand T2 letter (Panel A) and for the right-hand T2 letter (Panel B). Since the question of interest is whether Lag-1 sparing occurs to both targets, only the data for Lags 1 and 3 are illustrated

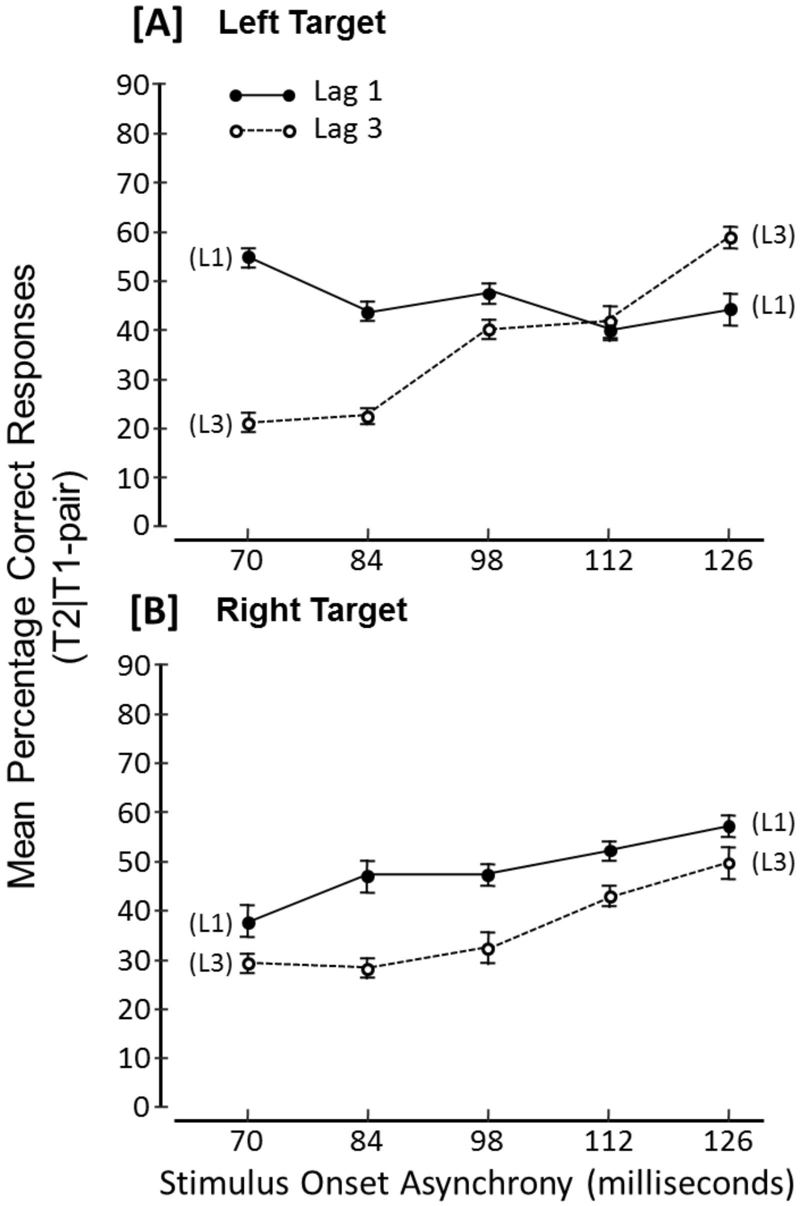

Figure 7. *T2 identification accuracy in the In-Stream condition of Experiment 2 as a function of SOA and Lag, separately for the T2 letter in the left-hand stream (Panel A) and the right-hand stream (Panel B). The filled circular symbols illustrate the data from Lag; the open circular symbols illustrate the data from Lag 3. The error bars represent standard error.*

Visual examination of the results shows that for the left-hand target, Lag-1 sparing occurs at the shorter SOAs, followed by Lag-1 deficit at the longer SOAs. For the right-hand target, Lag-1 sparing occurs at all SOAs. This was confirmed by performing two separate 5 (SOA: 70, 84, 98, 112, 126) × 2 (Lag: 1, 3) ANOVAs, one on the data from the left-hand target and the other on the data for the right-hand target. The analysis of the left-target data revealed significant main effects of Lag, $F(1,26) = 9.36$, $p = .005$, $\eta_p^2 = .265$, and SOA,

$F(4,104) = 5.40$, $p = .001$, $\eta_p^2 = .172$. Critically, the Lag × SOA interaction was significant, $F(4,104) = 14.66$, $p < .001$, $\eta_p^2 = .361$, confirming that while Lag-1 sparing occurred at the shorter SOAs, Lag-1 deficit occurred at the longer SOAs. Analysis of the right-target data revealed significant main effects of Lag, $F(1,26) = 5.71$, $p = .024$, $\eta_p^2 = .180$, and SOA, $F(4,104) = 9.39$, $p < .001$, $\eta_p^2 = .265$. Notably, there was no interaction between Lag and SOA, $F(4,104) = 1.29$, $p = .277$, $\eta_p^2 = .047$, indicating that performance at Lag 1 was better than performance at Lag 3 at all SOAs (i.e., Lag-1 sparing occurred at all SOAs). The results of the above analyses indicate that after about 100 ms, a divided focus of attention cannot be maintained, and a single focus of attention settles on the right-hand stream. The average Lag-1 sparing magnitude scores for the left T2 and the right T2 in the 112- and 126-ms SOA conditions have been superimposed on Figure 6 (grey diamond symbols), clearly showing that, at the longer SOAs, whereas Lag-1 sparing occurs for the right-T2, Lag-1 deficit occurs for the left T2.

Considered as a whole, the results of Experiment 2 indicate that even in a task that is optimally suited to a divided focus, attention is first deployed as a broad unitary focus for approximately 80 ms before being divided. The focus is then maintained in divided form for about 50 ms before a single unitary focus narrowly settles on the right side of the display.

Experiment 3

Although the results of the left/right analysis discussed above are consistent with a single attentional focus deployed to the right-hand stream at the longer SOAs, an alternative explanation must be considered. In the present experiments, T2 consisted of a pair of two letters presented simultaneously for no more than 126 ms before being masked. Observers are required to identify both letters. This is a considerably more difficult task than a typical AB task, in which observers are asked to identify only a single letter as T2. It is possible, therefore, that an inability to process and identify the two letters simultaneously encouraged observers to disengage attention from one of the streams in order to allow the accurate identification of at least one of the two targets. On this hypothesis, presenting a single letter as T2 should allow observers to continue to attend to both streams – that is, to continue to divide the focus of attention. This is tested in Experiment 3 by replicating Experiment 2, but including two T2 conditions – one in which a pair of letters is presented as T2 (*Dual-T2* condition) and one with a single letter as T2 (*Single-T2* condition). Since our primary interest is whether, at the longest SOA, the focus of attention settles on a single location rather than being divided between the two stream locations, we tested only an SOA of 126 ms.

Observers

Twenty-five undergraduate students (Mean age = 22.92 years, SD=6.83; 14 females; 22 right-handed) at Griffith University participated in the experiment for course credit; participants completed both the Single- and Dual-T2 conditions, in counterbalanced order of presentation. An a priori power analysis was conducted using G*Power (Faul & Erdfelder, 1998) based on the effect sizes obtained Experiment 1 of the current study. The analysis revealed that a minimum total sample of 20 participants would be needed in order for an effect of that size to be detected with 90% probability with alpha set to .05. All participants were naïve as to the purpose of the experiment and reported normal or corrected-to-normal vision. Ethical approval for this experiment was granted by the Griffith University Human Research Ethics Committee.

Stimuli and Procedures

The stimuli and procedures for the Dual-T2 condition were identical to those in 126 ms SOA condition of Experiment 2. The Single-T2 condition was identical to the Dual-T2 condition except that T2 consisted of only a single letter rather than a pair of letters. The single letter appeared randomly but with equal probability at one of 6 locations: In-Stream (Left), In-Stream (Right), Horizontal-Inner (Left), Horizontal-Inner (Right), Vertical-Outer (Top), and Vertical-Outer (Bottom).

Results

Average T1-pair response accuracy was 75.7% in the Single-T2 condition and 78.1% in the Dual-T2 condition. As in Experiments 1 and 2, only trials in which the response to the T1-pair was correct were included for analysis. The left-hand graphs in Figure 8 (Panel A) illustrate the results for the Single-T2 condition. The graphs illustrate the percentage of correct T2 responses as a function of Lag separately for each location at which the single T2 was presented. The right-hand graphs (Panel B) illustrate the results for the Dual-T2 condition, with the response to each of the letters in the T2-pair represented by a separate line. Visual inspection of the graphs indicates that Lag-1 sparing occurs to the right T2 in both the Single- and Dual-T2 conditions and that Lag-1 deficit occurs to T2 at all other locations.

The data were first analyzed in an overall 2 (Target Number: Single-T2, Dual-T2) × 6 (T2-Location: In-Stream (Left), In-Stream (Right), Horizontal-Inner (Left), Horizontal-Inner (Right), Vertical-Outer (Top), and Vertical-Outer (Bottom)) × 3 (Lag: 1, 3, 9) repeated-measures ANOVA. The analysis revealed significant main effects of T2-Location, $F(5, 120) = 2.67$, $p = .025$, $\eta_p^2 = .100$; Lag, $F(2,48) = 133.06$, $p < .001$, $\eta_p^2 = .847$; and Target Number, $F(1,24) = 17.91$, $p < .001$, $\eta_p^2 = .427$. There were also significant interactions between T2-

Location and Target Number, $F(5, 120) = 11.84$, $p < .001$, $\eta_p^2 = .330$; Lag and Target Number, $F(2,48) = 8.11$, $p < .001$, $\eta_p^2 = .253$; and T2-Location and Lag, $F(10, 240) = 10.60$, $p < .001$, $\eta_p^2 = .306$. Finally, the three-way interaction among T2-Location, Target Number, and Lag was significant, $F(10, 240) = 5.49$, $p < .001$, $\eta_p^2 = .186$.

The question of critical interest in Experiment 2 is whether Lag-1 sparing occurs in the In-Stream condition to T2 when it appears to the right, but not when it appears to the left, and whether this is the case in both the Single-T2 and the Dual-T2 conditions. This can tested most directly by means of a 2 (Lag: 1, 3) × 2 (Target Location: In-Stream (Left), In-Stream (Right)) × 2 (Target Number: Single-T2, Dual-T2) repeated measures ANOVA. Two outcomes are the key results. First, there was a significant interaction between Target Location and Lag, $F(1, 24)=18.88$, $p<.001$, $\eta_p^2=.440$, indicating that identification accuracy at Lag 1 was greater than accuracy at Lag 3 (i.e., Lag-1 sparing) for T2 on the right and accuracy at Lag 1 was worse than accuracy at Lag 3 (i.e., Lag-1 deficit) for T2 on the left. Critically, this did not vary as a function of the number of targets (i.e., Single-T2 versus Dual-T2), $F(1,24)=.10$, $p=.753$, $\eta_p^2=.004$. No other effects were significant.

The conclusion from Experiment 3 is quite clear: the failure to maintain a divided focus of attention in the present study does not arise from the requirement to process and identify two simultaneous letter targets since the same pattern of results is obtained when there is only a single letter target to identify and report. One salient aspect of the results of Experiment 3 is worth comment at this point. The overall level of T2 identification accuracy in the Single-T2 condition at Lags 3 and 9 is quite comparable regardless of where the target appears. In the Dual-T2 condition, however, there are clear accuracy differences as a function of T2 location, and quite marked left-right and top-bottom asymmetries are evident.

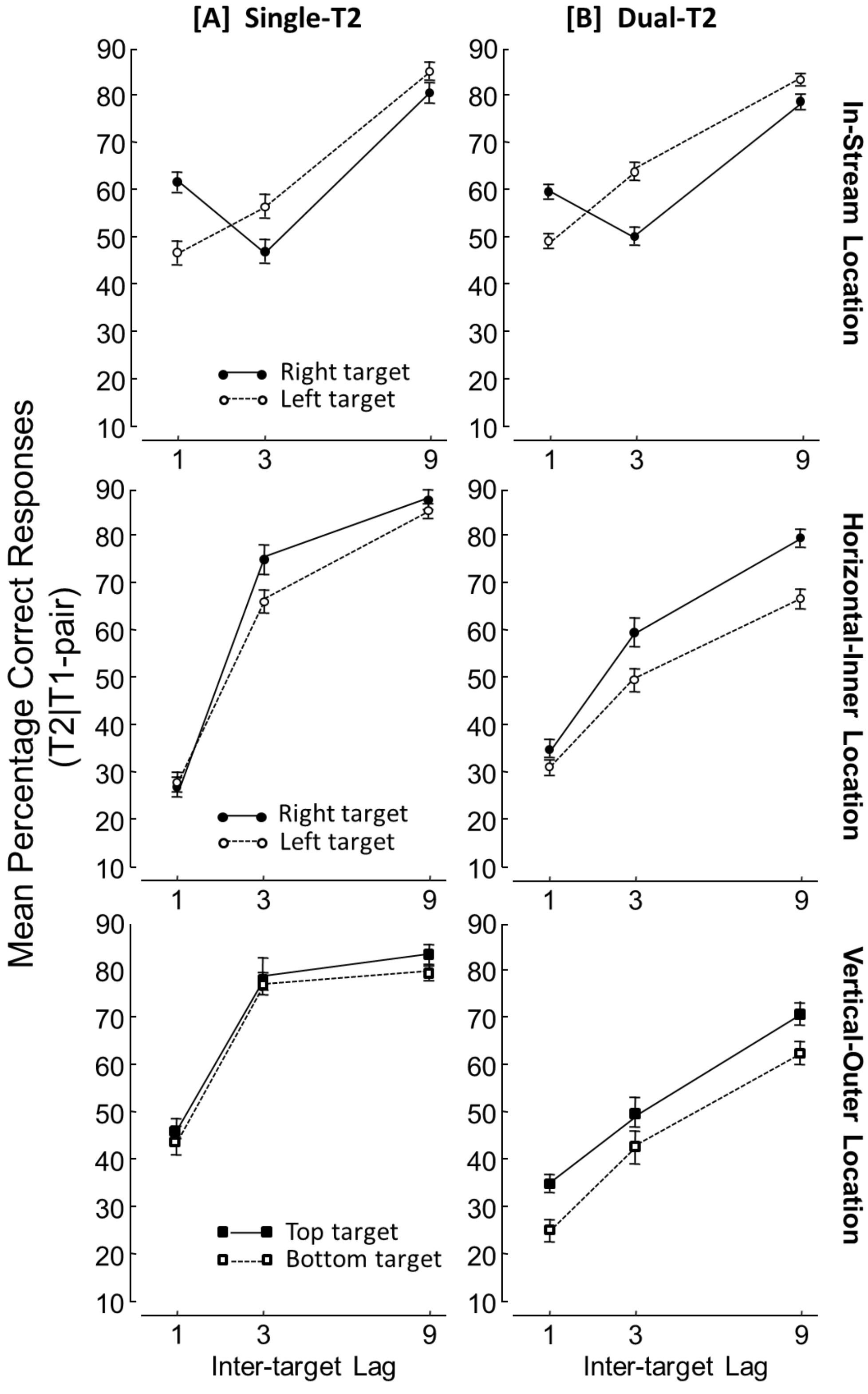

Figure 8. *The graphs illustrate the results of Experiment 3. In the Single-T2 condition, a single letter was presented as T2, and mean identification accuracy of that letter as a function of T2 location and Lag is illustrated in the Panel A graphs. In the Dual-T2 condition, a pair of T2 letters was shown, and accuracy for each of the two letters is illustrated with a separate line in the Panel B graphs. The error bars represent the standard error of the mean.*

It is important to draw a distinction in the present study between hemifield differences in the deployment of attention and hemifield differences in the accuracy of target identification. Hemifield differences in the deployment of attention are indexed by differences in the magnitude of Lag-1 sparing to targets presented in the right or the left hemifield. In contrast, visual field asymmetries in letter identification are best examined by considering performance at Lags 3 and 9. Accuracy at Lag 1 is not informative since Lag-1 sparing occurred in some conditions and not in others, which would occlude any overall level effects. Both types of asymmetries are considered below.

Visual field asymmetries in the deployment of attention. Consider the results of Experiment 3, which allowed an examination of hemifield differences. As can be seen in Figure 8. Lag-1 sparing occurred only to targets appearing in the right RSVP stream (top graphs of Panels A and B, filled circular symbols) – Lag-1 sparing did not occur to targets at any other locations. In other words, the attentional focus settled narrowly on the right-hand RSVP location, leaving all other locations unattended. This was the case regardless of whether a single T2 was presented or a pair of T2 letters was presented. It has been shown that the magnitude of Lag-1 sparing does not vary as a function of visual field (Jefferies, Ghorashi, Kawahara, & Di Lollo, 2007). The present results, therefore, cannot arise from asymmetries in the incidence of Lag-1 sparing, but rather must arise from asymmetries in the deployment of attention. The observed rightward bias in the distribution of attention is consistent with the findings of Kristjánsson and Sigurdardottir (2008) who, using a spatial cueing paradigm, found a greater attentional benefit to regions above and to the right of fixation relative to regions below and to the left of fixation. Notably, this bias occurred only when there were distractors present on the screen, as was the case in the present study.

Visual field asymmetries in letter identification accuracy. As outlined above, visual field asymmetries in letter identification accuracy are best examined by considering performance at Lags 3 and 9. Consider again the Single- and Dual-T2 conditions of Experiment 3. In the Single-T2 condition, T2 identification accuracy is almost identical regardless of whether T2 is presented on the left or on the right in both the In-Stream and Horizontal-Inner locations. Similarly, in the Vertical-Outer location, T2 identification accuracy is almost identical regardless of whether T2 appears above or below fixation. This was confirmed by performing three separate 2 (Lag: 3, 9) × 2 (Target Location: Left/Right or Top/Bottom) repeated measures ANOVAs for the In-Stream, Horizontal-Inner, and Vertical-Outer locations. The analyses showed a significant main effect of Lag in the In-Stream location, $F(1,24)=63.38$, $p<.001$, $\eta_p^2 = .725$; and the Horizontal-Inner Location, F

(1,24)=28.99, $p<.001$, $\eta_p^2 = .547$. The main effect of Lag was not significant in the Vertical-Outer Location, F (1,24)=.789, $p=.383$, $\eta_p^2 = .032$. Notably, neither the main effect of Target Location nor the Target × Lag interaction was significant at any Target Location. These outcomes indicate that when a single T2 is presented, it is identified equally well regardless of whether it appears to the left or the right or above or below fixation.

In the Dual-T2 condition, a very different pattern emerges. When there are two T2 letters to be identified and reported, observers are more accurate at reporting one target than the other. This was confirmed by performing separate 2 (Lag: 3, 9) × 2 (Target Location: Left/Right or Top/Bottom) repeated measures ANOVAs for the In-Stream, Horizontal-Inner, and Vertical-Outer locations. The analysis of the In-Stream condition revealed significant main effects of Lag, $F(1,24)=43.36$, $p<.001$, $\eta_p^2=.644$, and Target Location, $F(1,24)=7.51$, $p=.011$, $\eta_p^2=.238$, and the Lag × Location interaction effect was also significant, $F(1,24)=10.16$, $p<.004$, $\eta_p^2=.297$. The analysis of the Horizontal-Inner condition revealed similar results: significant main effects of Lag, $F(1,24) = 47.90$, $p < .001$, $\eta_p^2=.666$, and Target Location, $F(1,24) = 13.30$, $p < .001$, $\eta_p^2=.357$. The Lag × Location interaction effect was not significant, $F<1$. Finally, the analysis of the Vertical-Outer condition revealed a significant main effect of Lag, $F(1,24) = 66.13$, $p< .001$, $\eta_p^2=.734$. The main effect of Location (top, bottom) was marginally significant, $F(1,24) = 3.31$, $p = .072$, $\eta_p^2=.121$. The Lag × Location interaction effect was not significant, $F<1$. Considering the results of the Single- and Dual-T2 conditions of Experiment 3 it is clear that asymmetries in letter identification accuracy arise only when two targets are presented simultaneously – presumably, when there is competition for the resources necessary to process the letters.

Visual field asymmetries have been frequently reported in the literature when observers are required to select targets presented in dual-stream AB paradigms. The results typically show that identification accuracy is better when T2 appears in the left visual field (LVF) as compared to the right visual field (RVF; e.g., Holländer, Corballis, & Hamm, 2005; Scalf, Banich, Kramer, Narechania, & Simon, 2007; Śmigasiewicz, Shalgi, Hsieh, Möller, Jaffe, Chang, & Verleger, 2010; Śmigasiewicz & Möller, 2011; Verleger et al., 2009). Theoretical accounts of this finding have invoked the superior ability of the right cerebral hemisphere to compete for attentional resources. Thus, when T1 and T2 are presented in opposite visual hemifields, observers can more accurately identify T2 when it appears in the LVF and is processed by the right cerebral hemifield (e.g., Goodbourn & Holcombe, 2015). There is a trend towards this pattern in the In-Stream condition of Experiment 3; however, in the Horizontal-Inner location, T2 identification accuracy is significantly better when T2 appears in the RVF and thus processed by the left cerebral hemisphere. It should be noted, however, that the design of our study is quite different from that used in previous studies. Specifically, rather than using a single T1 and a single T2, the present study used a pair of T1 letters and a pair of T2 letters (except, of course, in the Single-T2 condition of Experiment 3). This means that T1 targets were presented simultaneously to both sides of the displays, thus activating the left and right cerebral hemispheres equally. This lack of imbalance in activating the left and right hemispheres may account for why the present results do not match those of the studies listed above. One might perhaps develop an alternative explanation that invokes reading behaviour since the targets are letters, since our observers were all English speakers, and since they were better at identifying T2 when it appears on the right. Such an explanation, however, is beyond the scope of the present study.

General Discussion

Recent research has shown that, at least under certain conditions, the focus of attention can be divided, and two or more foci can be deployed simultaneously and independently to separate objects or locations (e.g., Awh & Pashler, 2000; Bay & Wyble, 2014; Bichot, Cave, & Pashler, 1999; Cave, Bush, & Taylor, 2010; Dubois, Hamker, & VanRullen, 2009; Godijn & Theeuwes, 2003; Jefferies, Enns, & Di Lollo, 2014; Kawahara & Yamada, 2007; Kramer & Hahn, 1995; McMains & Somers, 2004, 2005; Müller, Malinowski, Gruber, & Hillyard, 2003). Although research has examined whether attention can be maintained in divided form (e.g., Dubois, Hamker, & VanRullen, 2009), the early time course of dividing attention is not yet known. If, as has been previously suggested, it is more effortful to deploy a divided rather than a unitary focus of attention, then a unitary focus may be the default mode and it may require time to divide the attentional focus. To answer this question, the present study examined the early time course of attentional deployment by probing the spatial distribution of attention at a series of time points between 70 and 126 ms. The results showed that, even under conditions that encouraged the deployment of a divided focus of attention, attention is first deployed as a unitary focus before being gradually divided. It is then maintained in divided form only briefly before settling on a single location.

In the present experiments, we employed a modified version of the dual-stream AB paradigm of Jefferies, Enns, and Di Lollo (2014). That is, we displayed two simultaneous RSVP streams of digit distractors, one to the left and one to the right of fixation. Two pairs of letter targets (T1-pair, T2-pair) were presented, separated by an inter-target lag. The T1-pair was always presented such that one letter appeared in each RSVP stream. By presenting the T2-pair unpredictably either in the RSVP streams, in the blank region between the streams along a horizontal axis, or above and below fixation along a vertical axis, we were able to assess whether the focus of attention was unitary or divided. By using Lag-1 sparing as an index of whether the location at which the T2-pair was presented was attended and systematically manipulating the SOA between the targets, we tracked changes to the spatial distribution of attention over the first 126 milliseconds.

The results showed that attention is initially deployed as a unitary focus, even under conditions which encourage divided attention (see Jefferies, Enns, & Di Lollo, 2014). A divided focus of attention is not in evidence until after about 85 ms. Consistent with previous research, our results also showed that the focus of attention is maintained in divided form only briefly before settling on a single location. The inferred distribution of attention at each SOA is illustrated in Figure 9.

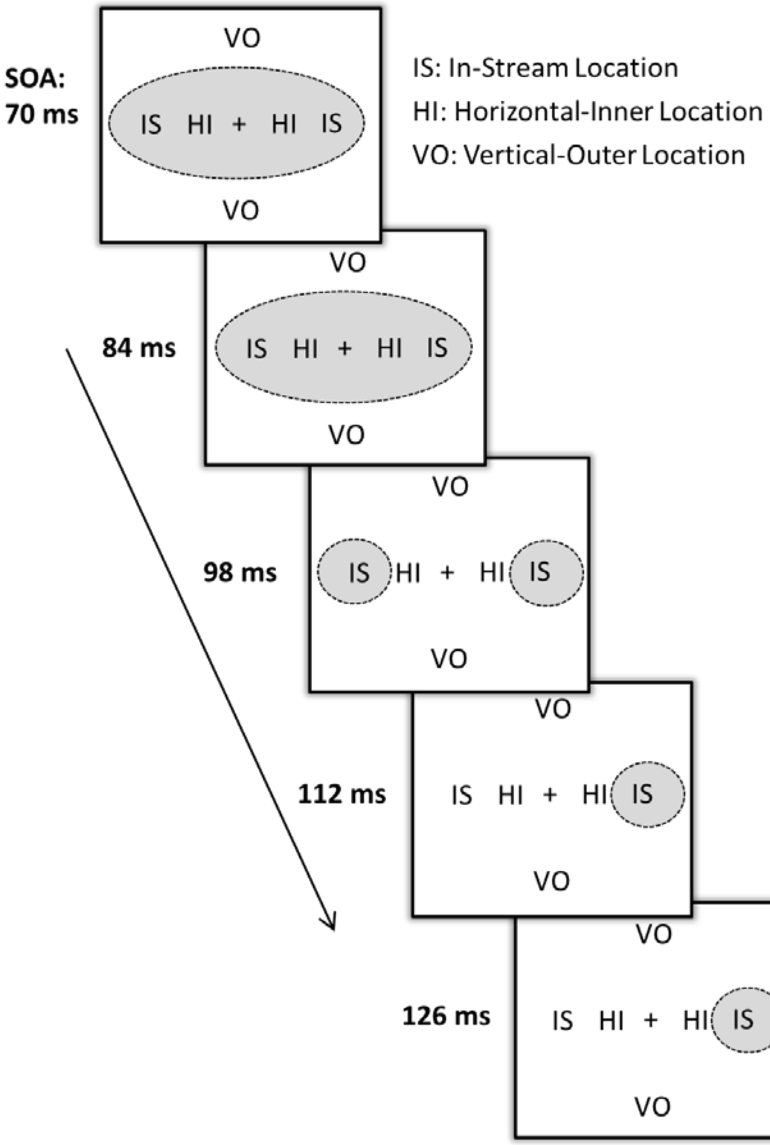

Figure 9. *Schematic illustration of the progressive changes to the distribution of spatial attention as a function of SOA and T2-pair location. The grey regions illustrate the hypothesized distribution of attention. See text for a detailed description.*

Although we presume that the sequence by which the focus of attention is initially deployed in unitary form and then gradually divided before settling on a single location is a general one, the exact timing of the transitions will almost certainly depend on the specific characteristics of the task and the stimuli. It has been shown, for example, that the rate at which observers can disengage from and narrow attention away from task-relevant information is much slower than the rate at which observers can disengage and shift away from task-irrelevant information (e.g., Jefferies, Enns, & Di Lollo, 2017; Visser, Bischof, & Di Lollo, 1999). Along the same lines, we assume that the change from unitary to divided attention will occur earlier or later depending on the specific displays being used as well as on the task requirements.

An elliptical focus of attention

Although the results of Experiment 2 showed that the focus of attention was initially unitary, it was not circular in shape and did not encompass all target locations. At the shortest SOAs, Lag-1 sparing occurred to the T2-pair when it was presented in the RSVP streams and when it was presented in the blank region between the streams (indicating a unitary attentional focus); Lag-1 sparing did not occur, however, to the T2-pair when it was presented above and below fixation, indicating an attentional focus that is more elliptical than circular. One element of the experimental design may have contributed to this elliptical shape. Specifically, two RSVP streams were presented on the screen throughout each trial, one to the left and one to the right of fixation. It is known that only under a very limited set of circumstances (e.g., Jefferies & Di Lollo, 2015; Jefferies & Di Lollo, in press; Visser, Bischof, & Di Lollo, 1999, 2004) can observers avoid attending to the continual onset transient signals arising from an RSVP stream. This is particularly the case when the items in the RSVP stream are similar to the targets (Visser, Bischof, & Di Lollo, 2004). In the present experiments, the distractors in the RSVP stream were digits and were thus from the same alphanumeric character set as the letter targets. As a consequence, the RSVP streams would have strongly captured attention. Since the RSVP streams were displayed along the horizontal axis and no RSVP streams were presented along the vertical axis, this may have contributed to attention being distributed to a region that is more elliptical than circular.

An account based on a rapidly-switching unitary focus or a serial-sampling process

In Experiment 1 and in the short- and mid-SOA conditions of Experiment 2, Lag-1 sparing occurred equally to both letters of the T2-pair when it was presented at the In-Stream location. Based on this, we concluded that attention was deployed equally to both letters of the T2-pair either because both letters fell within the ambit of a broad unitary attentional focus (at the short SOA conditions of Experiment 2) or because attention was divided and the foci were deployed one to each RSVP stream (in Experiment 1 and at the intermediate SOA condition of Experiment 2). The possibility must be considered, however, that Lag-1 sparing to both letters of the T2-pair arose not from both locations being simultaneously attended, but rather from either a narrow unitary focus being shifted rapidly between the T2 letters (see Jans, Peters, & De Weerd, 2010) or from a serial-sampling process (e.g., Fieblkorn, Saalman, & Kastner, 2013; Landau & Fries, 2012).

An account based on a rapidly-shifting narrow focus of attention seems unlikely in the present experiments for the straightforward reason that there is not sufficient time to process one letter, disengage and shift attention, and then engage on and process a second letter before the targets are masked. A 100-ms SOA has been proposed as the temporal limit between stimuli for ensuring that the focus of attention cannot switch from one location to another (Jans, Peters, & De Weerd, 2010), and the SOA in Experiment 1 meets this temporal limit. In Experiment 2, we also found Lag-1 sparing to both T2 letters when the SOA was only 70 ms. Further, it is the case that attentional shifts often take considerably more than 100 milliseconds, particularly in complex displays (see Cave, Bush, & Taylor, 2010). In a paradigm very similar to that used in the current study, for example, Weichselgartner and Sperling (1987) showed that it takes more than 200 ms to shift focused attention from one RSVP stream of letters to another.

A closely-related account stems from studies showing that attention sequentially samples objects or locations in a rhythmic fashion. This might allow observers to sequentially sample the two letters of the T2-pair rather than attending to both letters simultaneously. The results of a study by Fiebelkorn, Saalmann, and Kastner (2013) showed that the sampling of stimuli in different locations occurs at a rate of 4 Hz (i.e., one location sampled every 250 ms). The maximum exposure duration of the T2-pair in the present Experiment 1 was 98 ms while the maximum duration in Experiments 2 and 3 was 126 ms, both of which are considerably shorter than the 250 ms that would be required for both letters in the T2-pair to be sampled. Landau and Fries (2012) found evidence for a faster sampling rate of 8 Hz, meaning that a new location could be sampled every 125 ms. While this might enable observers to sample both T2 letters at the longest SOA in Experiment 2 (i.e., the 126 ms SOA condition), it cannot account for the findings at the shorter SOAs (e.g., 70 ms) that both letters in the T2-pair are reported accurately. In sum, the short exposure duration of the T2-pair in the present experiments, particularly when combined with the requirement to process simultaneous, spatially separated letter targets, seems sufficient to preclude a rapid-shifting or serial-sampling account of the present results.

Theoretical considerations

Several current models of selective attention include mechanisms to control the deployment of attention (such as winner-take-all and biased competition) that can, with the addition of a few parameters, account equally for both unitary and divided attention (e.g., Desimone & Duncan, 1995; Desimone, 1998; Hogendoorn, Carlson, Van Rullen, & Verstraten, 2010; Itti & Koch, 2000; Nebel, Wiese, Stude, Arminde, Greiff, Diener, &

Keidel, 2005; Standage, Trappenberg, & Klein, 2005; Zirnsak, Beuth, & Hamker, 2011). These same models, however, cannot readily account for the dynamic alternation between unitary and divided attention observed in the present study.

One mechanism capable of mediating the change between unitary and divided attention may be found in a model proposed by Standage, Trappenberg, and Klein (2005). In that model, a spatial saliency map – in which bottom-up and top-down signals are integrated by a winner-take-all mechanism – is combined with a continuous attractor neural network (Deco, Pollatos, & Zihl, 2002; Duncan & Humphreys, 2002; Koch & Ullman, 1985). Transient and sustained signals guide the winner-take-all mechanism and play a vital role in determining whether attention is deployed in unitary or divided form. Simulations showed that although transient signals to the saliency map result in the deployment of attention in a unitary mode, sustained signals instead lead to the deployment of divided attention. This distinction can account for the dynamic alternation between unitary and divided attention as follows. It can be assumed that the signals to the saliency map commence with the onset of the stimuli at the start of each trial (e.g., Bay & Wyble, 2014; Jefferies & Di Lollo, 2009; Wyble, Bowman, & Potter, 2009). These initially transient signals result in the deployment of a unitary focus. As the signals continue, they mediate the deployment of a divided focus of attention. Sustained signals, however, are difficult to maintain and susceptible to disruption (e.g., Di Lollo, Kawahara, Ghorashi, & Enns, 2005); once the sustained signals are disrupted, attention returns to unitary form.

Considering the interplay between transient and sustained signals in determining the dynamic alternation between unitary and divided attention, leads to a clear prediction: the more difficult it is to maintain sustained signals, the briefer the period of time for which attention will be divided. Thus, tasks with a high perceptual load or tasks that involve difficult target discrimination tasks should lead to attention being divided for a briefer period than less demanding tasks. Specific task demands, therefore, will likely play a vital role in determining the precise time course of dividing attention.

In summary, the present study employed the well-established phenomena of the Attentional Blink and Lag-1 sparing to examine the spatiotemporal changes to the distribution of attention. Systematic variation of the interval between successive RSVP stream items revealed that, even under conditions which encourage the deployment of divided attention, the focus of attention is initially deployed in a unitary form before being divided and subsequently settling as a narrow, unitary focus on a single location.

Compliance with Ethical Standards

Conflict of Interest: The authors declare that they have no conflict of interest.

Ethical approval: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent: Informed consent was obtained from all individual participants included in the study.

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