Psychological Research
DOI 10.1007/s00426-017-0918-y

ORIGINAL ARTICLE

The exogenous and endogenous control of attentional focusing

Lisa N. Jefferies[1,2] · James T. Enns[3,4] · Vincent Di Lollo[5]

Received: 13 April 2017 / Accepted: 14 September 2017

Abstract Selective visual attention involves prioritizing both the location (orienting) and distribution (focusing) of processing. To date, much more research has examined attentional orienting than focusing. One of the most well-established findings is that orienting can be exogenous, as when a unique change in luminance draws attention to a spatial location (e.g., Theeuwes in Atten Percept Psychophys 51:599–606, 1992; Yantis and Jonides in J Exp Psychol Hum Percept Perform 10:601, 1984), and endogenous, as when a red distractor shape diverts attention when one is looking for a red target (e.g., Bacon and Egeth in Percept Psychophys 55:485–496, 1994; Folk et al. in J Exp Psychol Hum Percept Perform 18:1030, 1992). Here we ask whether attentional focusing—the broadening and contracting of prioritized processing—is influenced by the same two factors. Our methodology involved a dual-stream attentional blink task; participants monitored two spatially separated streams of items for two targets that could appear unpredictably either in the same stream or in opposite streams. The spatial distribution of attention was assessed by examining second-target accuracy in relation to inter-target lag and target location (same or opposite streams). In Experiment 1, we found that attentional contracting was more rapid when the targets differed in luminance from the distractor items. In Experiments 2 and 3, we found that the rate of attentional contracting was slower when there were task-relevant distractors in the stream opposite the first target. These results indicate that the rate of attentional focusing, like orienting, can be modulated by both exogenous and endogenous mechanisms.

✉ Lisa N. Jefferies
L.Jefferies@griffith.edu.au

1 School of Applied Psychology, Griffith University, Southport, QLD 4222, Australia

2 Menzies Health Institute Queensland, Brisbane, Australia

3 University of British Columbia, Vancouver, Canada

4 University of Western Australia, Perth, Australia

5 Simon Fraser University, Burnaby, Canada

Introduction

Focused visual attention allows us to selectively process relevant stimuli while filtering out irrelevant information, thus enabling the efficient perception of our visual world.

To keep track of changes in the environment, the focus of attention can be shifted rapidly from one object or location to another (*attentional orienting*; Posner, 1980; Posner & Cohen, 1984; Weichselgartner & Sperling, 1987), expanded or contracted to match the size of relevant objects (*attentional focusing*; e.g., Castiello & Umiltà, 1990; Eriksen & Yeh, 1985; Eriksen & St. James, 1986; Jefferies, Gmeindl, & Yantis, 2014), and may even be split into more than one focus (Bay & Wyble, 2014; Jefferies, Enns, & Di Lollo, 2014; McMains & Sommers, 2004).

Focusing and orienting are distinct, independent aspects of attentional control. The focus of attention can be shifted between objects or locations without changes in size, and it can be expanded or contracted without changing location (Maringelli & Umiltà, 1998). Orienting and focusing follow distinct time courses (e.g., Benso, Turatto, Mascetti, & Umiltà, 1998; Jefferies & Di Lollo, 2009; Weichselgartner & Sperling, 1987), can be triggered and measured independently from one another (Maringelli & Umiltà, 1998), and are affected differently by normal aging (Greenwood, Parasuraman, & Haxby, 1993; Jefferies, Roggeveen, Enns, Bennett, Sekuler, & Di Lollo, 2015), and by neurodevelopmental disorders (Facoetti, Lorusso, Paganoni, Cattaneo, Galli, & Mascetti, 2003; Ronconi, Gori, Ruffino, Molteni, & Facoetti, 2012).

From several decades of research, we have learned much about attentional orienting, its time course, and the stimulus attributes that trigger it. Two broad classes of factors are known to influence attentional orienting: exogenous factors and endogenous factors. Exogenous factors relate to the physical characteristics of the stimuli, including salience (e.g., spatial non-uniformities of primitive features such as luminance, shape, or motion; Egeth & Yantis, 1997; Remington, Johnston, & Yantis, 1992; Theeuwes, 1992; Yantis & Jonides, 1984). Endogenous factors relate to the relevance of the stimuli for the goals of the observer (Bacon & Egeth, 1994; Eimer & Kiss, 2008; Folk, Remington, & Johnson, 1992). These two classes of factors generally combine in determining the deployment of visual attention, allowing the observer to adapt to changing circumstances.

Although we clearly know a good deal about attentional orienting, we do not have a comparable understanding of attentional focusing and of the factors that influence both its incidence and rate of change. The principal objective of the present work was to examine whether the factors known to affect attentional orienting also affect attentional focusing. Specifically, we examined whether the physical characteristics (an exogenous factor) and the conceptual similarity between the stimuli (an endogenous factor) modulate the rate of attentional focusing.

Using Lag-1 sparing and Lag-1 deficit to track attentional focusing

Several studies have assessed the temporal dynamics of attentional focusing and have provided estimates of the rate at which the focus of attention can be expanded or contracted (e.g., Benso et al., 1998; Jefferies & Di Lollo, 2009). To track changes in the spatial extent of the attentional focus over time, we adopted the dual-stream attentional blink (AB) paradigm used by Jefferies and Di Lollo (2009).

In a typical AB paradigm, two sequential letter targets (T1, T2) are embedded in a stream of digit distractors presented in rapid serial visual presentation (RSVP). The observer's task is to identify the two targets. Two separate temporal factors need to be distinguished in the AB paradigm: inter-target lag (Lag) and stimulus-onset-asynchrony (SOA). SOA refers to the temporal separation between the onsets of successive frames in the RSVP streams. Typically, successive frames are separated by an SOA of about 100 ms. The term Lag refers to the frame at which T2 follows T1. Thus, at Lag 1, T2 is presented in the frame directly after T1; at Lag 3, T2 is presented three frames after T1 (i.e., with two intervening distractors); at Lag 9, T2 is presented nine frames after T1 (i.e., with 8 intervening distractors). As a rule, T1 is identified with a high degree of accuracy, but identification of T2 is impaired if it appears within about 700 ms of T1 (Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992). In a dual-stream AB paradigm such as that used by Jefferies and Di Lollo, two simultaneous RSVP streams are presented, one on either side of fixation. The two targets appear unpredictably in either the left or the right stream and in either the same stream as one another or in opposite streams (Fig. 1).

In the present work, we examine the time course of attentional focusing by means of the phenomenon known as *Lag-1 sparing* which occurs when T2 is presented directly after T1 in the ordinal position within the RSVP stream known as Lag 1. Generally, accuracy of T2 identification is lowest at short inter-target lags and increases as the lag is increased. An exception to this rule is the phenomenon of Lag-1 sparing in which T2 is identified with a high degree of accuracy when presented directly after T1 (Potter, Chun, Banks, & Muckenhoupt, 1998). A meta-analysis conducted by Visser, Bischof, and Di Lollo (1999) suggested that Lag-1 sparing occurs only when the two targets appear at the same spatial location. Further work has shown that Lag-1 sparing does occur when the targets appear in different spatial locations, but only if T2 falls within the focus of attention (Jefferies, Ghorashi, Kawahara, & Di Lollo, 2007; Shih, 2000). If T2 appears in an unattended location, Lag-1 *deficit* occurs instead of Lag-1 sparing (Breitmeyer, Ehrenstein, Pritchard, Hiscock, & Crisan, 1999; Visser et al., 1999). The magnitude of Lag-1 sparing and Lag-1 deficit is calculated as T2 accuracy at Lag 1 minus T2 accuracy at the lag at which T2 accuracy is lowest (e.g., Lag 3). A positive difference is referred to as Lag-1 sparing (see Fig. 2, panel b); a negative difference is called Lag-1 deficit (Fig. 2, panel c).

The Lag-1 sparing/Lag-1 deficit distinction has been used to examine whether the location of T2 falls within or outside the focus of attention. This, in turn, has been used to evaluate the spatiotemporal dynamics of focal attention (Jefferies & Di Lollo, 2009; Jefferies et al., 2014, 2015; Kawahara & Yamada, 2006; Lunau & Olivers, 2010; Yamada & Kawahara, 2007). In the present work, the Lag-1 sparing/Lag-1 deficit distinction was used to track the time course of attentional focusing.

Consider a dual-stream AB paradigm in which observers monitor two streams of digit distractors for two spatially unpredictable letter targets (as in Fig. 1). Because T1 can appear in either stream, the initial extent of the attentional focus needs to be set broadly so as to encompass both streams. Once T1 appears, however, the focus contracts rapidly and reflexively to the T1-stream, thereby

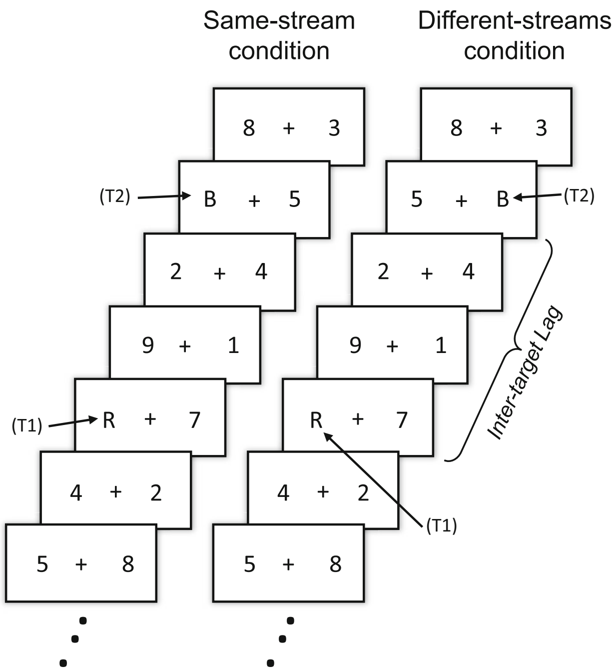

Fig. 1 Schematic representation of the sequence of events within a trial in Experiment 1. The first and the second targets (T1 and T2) could appear in either the left or the right stream and in either the same stream as one another (same-stream condition) or in opposite streams (different-streams conditions). Illustrated is a Lag-3 trial

withdrawing from the opposite stream[1]. This means that when T2 appears in the same location as T1, it falls in an attended location and Lag-1 sparing will always occur. If, on the other hand, T2 is presented in the opposite stream, whether or not it will fall within the focus of attention–and hence whether Lag-1 sparing or Lag-1 deficit will occur–depends on the time that has elapsed between the onsets of the two targets (SOA). If the SOA is short (as in the 53-ms SOA condition in Fig. 2), there will have been little time for the focus to contract, so T2 will fall within the initial broad focus of attention and Lag-1 sparing will result (Fig. 2, panel b). If, on the other hand, the SOA is long (as in the 133-ms SOA condition in Fig. 2), there will have been sufficient time for the focus to contract to the T1-stream. In this case, T2 will fall outside the focus of attention and Lag-1 deficit will occur (Fig. 2, panel c). By systematically varying the SOA and observing whether Lag-1 sparing or Lag-1 deficit occurs, it is possible to track changes in the breadth of focal attention over time. These temporal contingencies obviously apply only to the initial process of contracting to the T1-location. Given that observers are also required to report the T2 stimulus, which can appear unpredictably in either stream, we assume that having first contracted to the T1-location, the focus of attention will subsequently re-expand to encompass both streams, thus enhancing T2 identification at longer lags (e.g., Lag 9).

The pattern of Lag-1 sparing and Lag-1 deficit can be used to assess the *rate* at which the focus of attention contracts to the location of T1. If focusing occurs relatively quickly, attention will contract rapidly to the location of the T1-stream, the opposite stream will no longer be attended, and the transition from Lag-1 sparing to Lag-1 deficit will occur at relatively short SOAs (Fig. 3, left-hand panel). If, on the other hand, focusing occurs more slowly, then it will take longer for attention to contract to the T1-stream and to withdraw from the opposite stream. In that case, the transition from Lag-1 sparing to Lag-1 deficit will occur at a longer SOA (Fig. 3, right-hand panel).

In the present work, we employed the logic and methodology outlined above to examine whether the process of attentional focusing is modulated by both endogenous and exogenous factors. In Experiment 1, we asked whether the rate of attentional focusing is affected by the physical salience of the stimuli; in Experiments 2 and 3, we asked whether the process of contracting is modulated by the degree of conceptual similarity between the targets and the distractors.

Experiment 1

The objective of Experiment 1 was to determine whether the rate of attentional focusing is modulated by the physical salience of the stimuli. To that end, we used targets that were brighter—and hence more salient—than the distractors, and compared the results with those obtained by Jefferies and Di Lollo (2009) who used stimuli of uniform brightness in a paradigm that was otherwise identical to that of the present experiment. On the well-supported assumption that bright stimuli are processed more rapidly than dim stimuli (Di Lollo, Enns, Yantis, & Dechief, 2000; Hawkins, Shafto, & Richardson, 1988; Lit, Young, & Shaffer, 1971; Woodworth & Schlosberg, 1954), it is reasonable to expect that attention would be focused to the location of T1 more rapidly when it is bright than when it is dim. Based on the logic outlined above and illustrated in Fig. 3, we expected the transition from Lag-1 sparing to Lag-1 deficit to occur at shorter SOAs when the targets were brighter than the distractors (left-hand panel; present experiment) than when they were the same brightness as

[1] Several previous studies have provided evidence of such contracting of attention to the T1-stream (e.g., Jefferies et al., 2007, 2015; Jefferies & Di Lollo, 2009; Visser, Bischof, & Di Lollo, 1999). It is assumed that this contracting occurs primarily to optimize T1 identification accuracy. There is also evidence that T1 can be localized prior to being identified (Ghorashi, Jefferies, Kawahara, & Watanabe, 2008; Ghorashi, Enns, Klein, & Di Lollo, 2010), and that attention is deployed to the target's location even when the target's identity cannot be reported (Woodman & Luck, 2003).

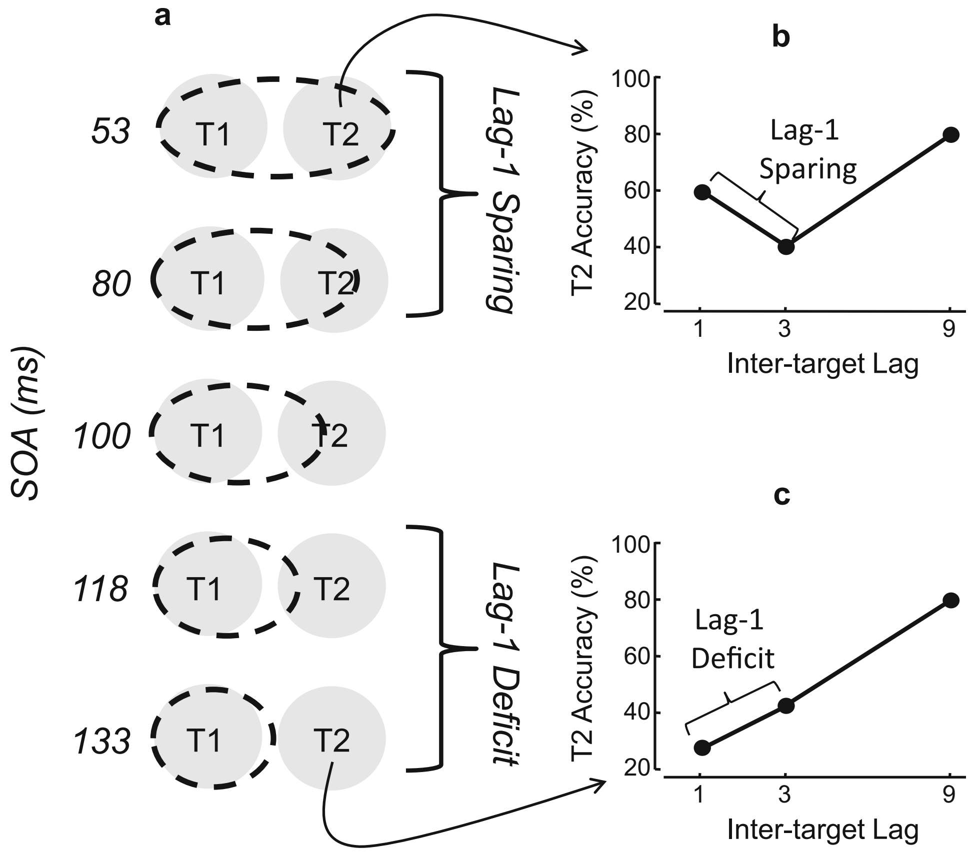

Fig. 2 Figure illustrates the hypothesized spatial extent of the focus of attention (segmented ovals) at Lag 1 at each of the five SOAs (panel **a**). The gray circles illustrate the locations of the two RSVP streams, labeled as T1 (T1-stream) and T2 (T2-stream). At the shortest SOA (53 ms), the attentional focus still mostly encompasses both streams because the process of contraction to the T1 stream has only just begun. As the SOA is increased, there is correspondingly more time for the attentional focus to contract to the T1 stream before the onset of T2. At short SOAs (e.g., 53 ms), both targets will fall within the focus of attention, and Lag-1 sparing will ensue (see **b**) whether the targets are presented in the same or in opposite streams. As the SOA is increased, the attentional focus progressive contracts to the T1-stream, resulting in a concomitant progressive withdrawal from the non-T1 stream. This reduces the probability of the two targets falling within the focus of attention when they are presented in opposite streams, thus decreasing the probability of Lag-1 sparing and increasing the probability of Lag-1 deficit (**c**)

the distractors (right-hand panel; as in Jefferies & Di Lollo, 2009).

Participants

Eighty-one undergraduate students at the University of British Columbia, Simon Fraser University, and Griffith University participated in the experiment for course credit. The participants were randomly allocated to one of five SOA conditions: 53, 80, 100, 118, and 133 ms. Five participants were eliminated due to having T1 accuracy lower than 55%: three in the 53 ms SOA condition, and two in the 80 ms condition. The final numbers of participants in each SOA group were 14, 14, 17, 16, and 15 in the 53, 80, 100, 118, and 133 ms conditions, respectively.

All participants were naïve as to the purpose of the experiment and reported normal or corrected-to-normal vision. All experiments reported in this paper were reviewed and approved by the respective Human Research Ethics Committees of the University of British Columbia, Simon Fraser University, and Griffith University. Informed consent was obtained from all individual participants included in the study.

Apparatus and 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. The computer monitor was viewed from a distance of approximately 60 cm. A white fixation cross (0.25° × 0.25°) was displayed in the center of the screen throughout each trial. Two synchronized RSVP streams of white digits (0–9) were centered 1.75° to the left and right of fixation. The digits were

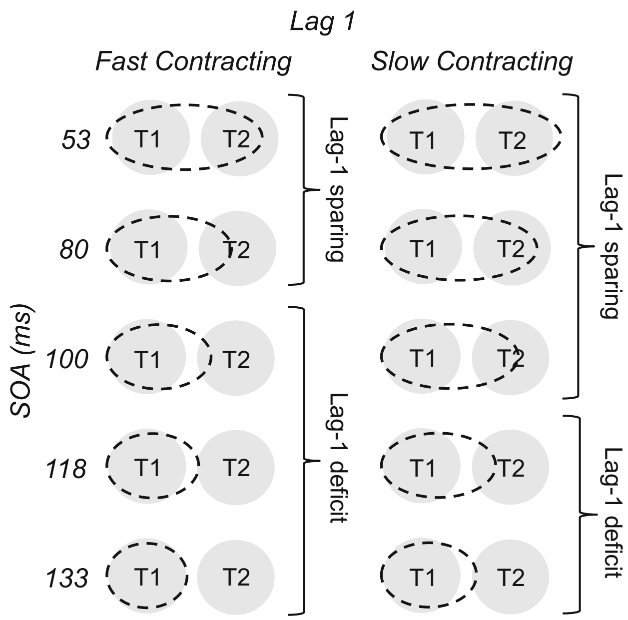

Fig. 3 Changes in the breadth of the attentional focus (segmented ovals) as it contracts to the location of the T1-stream. Illustrated are cases in which attention contracts rapidly (left panel) or slowly (right panel). Lag-1 sparing transitions to Lag-1 deficit at shorter SOAs when contraction is rapid than when it is slow

presented randomly with the restriction that the same digit could not be presented in the two streams simultaneously and that the same digit could not be presented back-to-back in either stream. The targets were capital letters (excluding the letters I, O, Q, Z) subtending approximately 0.9° vertically. The luminance of the distractor items was 60 cd/m^2 and that of the targets was 90 cd/m^2. The luminance of the black background was 2.3 cd/m^2.

Procedure

Observers pressed the space bar to initiate each trial. A trial began with the presentation of the two RSVP streams; items in the streams appeared approximately every 53, 80, 100, 118, or 133 ms, depending on the SOA condition. Both streams contained 8–14 leading distractor items prior to the onset of T1. Two non-identical letter targets were inserted in the RSVP sequence. The two targets appeared in the same stream (both in the left stream or both in the right stream) on a random half of the trials and in opposite streams (T1 in the left stream and T2 in the right stream or vice versa) on the remaining trials. Each target was followed by a digit mask, except in those Lag-1 trials in which T1 and T2 appeared in the same stream. In this case, T1 was masked by T2. The observer's task was to report the identities of the two target letters by pressing the appropriate keys on the keyboard at the end of each trial. The order of responses was irrelevant.

T2 followed T1 at a random inter-target lag of 1, 3, or 9. At Lag 1, T2 was presented in the RSVP position directly after T1; at Lag 3, two distractors intervened between the two targets; at Lag 9, there were eight intervening distractors. Lag-9 trials are of little theoretical interest to the present work since Lag-1 sparing is defined by the difference in T2 identification accuracy between Lags 1 and 3. Lag 9 was included primarily to maintain the temporal unpredictability of the targets. It is also worth noting that our primary interest was in the different-streams condition, because only that condition allows an assessment of the temporal dynamics of attentional focusing, as illustrated in Fig. 2.

The time interval that elapsed from the onset of T1 to the onset of T2 at each lag depended on the SOA condition. The T1–T2 interval at Lags 1, 3, and 9 was 53, 159, and 477 for the 53-ms condition; 80, 240, and 720 for the 80-ms condition; 100, 300, and 900 for the 100-ms SOA condition; 118, 354, and 1062 for the 118-ms condition; and 133, 399, and 1197 for the 133-ms condition. The SOA between successive items in the RSVP stream consisted of approximately two-thirds stimulus duration and one-third blank inter-stimulus interval (ISI). The precise ratio of stimulus duration to blank ISI was constrained by the refresh rate of the display monitor and were as follows: 26.5:26.5 (53 ms SOA), 45:35 (80 ms SOA), 70:30 (100 ms SOA), 71:47 (118 ms SOA), and 80:53 (133 ms SOA). The procedure of having an approximately fixed ratio between the stimulus duration and blank ISI has been used by Jefferies and Di Lollo (2009; see also Jefferies et al., 2015) who compared this ratio procedure to one in which the stimulus exposure duration was kept constant and the duration of the blank ISI was varied. The two procedures yielded comparable patterns of results.

Results and discussion

Only those trials in which T1 was identified correctly were included in the analysis. This procedure is commonly adopted in AB experiments on the grounds that, on trials in which T1 is identified incorrectly, the source of the error is unknown, and thus its effect on T2 processing cannot be estimated. Averaged across observers and lags, the percentages of correct responses for T1 were 51.3, 68.4, 83.5, 77.8, and 86.3% in the 53, 80, 100, 118, and 133 ms SOA conditions, respectively. Although T1 identification accuracy is not directly relevant to the goals of the present study, one clear trend in the results of T1 is worth brief comment. Specifically, T1 identification accuracy improves as the SOA increases. The pattern can be attributed to the effects of masking, the strength of which is inversely related to the period of time that elapses from the onset of a target to the onset of a trailing mask (i.e., the SOA; Breitmeyer et al., 1984). Thus, the effects of masking are strongest when the SOA is short (53 ms) and weakest when the SOA is long (133 ms), leading to worse T1 identification accuracy when the SOA is short.

Figure 4 illustrates the percentage of correct T2 responses as a function of Lag, Stream, and SOA. Those data were first analyzed in an omnibus 5 (SOA: 53, 80, 100, 118, 133) × 2 (Stream: Same, Different) × 3 (Lag: 1, 3, 9) Analysis of Variance (ANOVA). Stream and Lag were within-subjects factors; SOA was a between-subjects factor. The analysis revealed significant effects of Lag, $F(2,142) = 35.26$, $p < 0.001$, $\eta_p^2 = 0.396$, Stream, $F(1,71) = 35.26$, $p < 0.001$, $\eta_p^2 = 0.33$, and SOA, $F(4,71) = 26.09$, $p < 0.001$, $\eta_p^2 = 0.56$. There were significant interactions between Stream and SOA, $F(4,71) = 2.903$, $p = 0.028$, $\eta_p^2 = 0.141$, between Lag and Stream, $F(2,142) = 41.81$, $p < 0.001$, $\eta_p^2 = 0.37$, and between Lag and SOA, $F(8,142) = 2.38$, $p = 0.02$, $\eta_p^2 = 0.12$.

The principal objective of the present study was to examine whether the rate at which the focus of attention contracts is modulated by the physical salience of the stimuli. As outlined in "Introduction", this can be answered by examining the incidence and magnitude of Lag-1 sparing and Lag-1 deficit. If the focus of attention broadly encompasses both streams, T2 will fall within the attentional focus regardless of whether it is presented in the same stream as T1 or in the opposite stream. If, on the other hand, attention is narrowly focused on the T1-stream, then Lag-1 sparing will occur if T2 is presented within the attentional focus (i.e., in the same stream as T1) and Lag-1 deficit will occur if T2 is presented outside the attentional focus (i.e., in the stream opposite T1). The rate at which the focus of attention contracts to the T1-stream can be assessed by the SOA at which Lag-1 sparing transitions to Lag-1 deficit.

Before addressing the result of principal interest, we note two incidental results. First, with the exception of the 53-ms SOA condition, Lag-1 sparing is in evidence at every SOA in the Same-Stream condition. This is because the T1 location is always attended, whether the focus is broad or narrow (see Fig. 2). Thus, in the Same-Stream

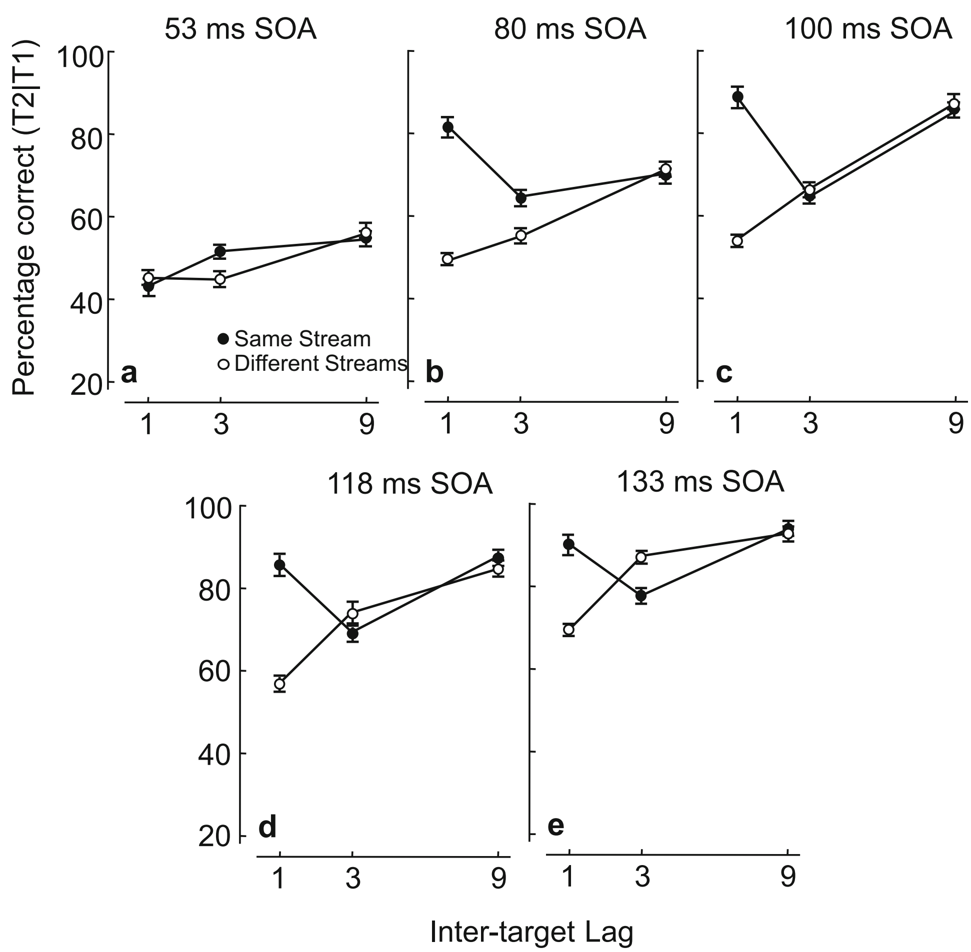

Fig. 4 Mean percentages of correct identifications of the second target in Experiment 1 with the data for each SOA plotted in separate panels. The open symbols represent data from the different-streams condition; the filled symbols represent data from the same-stream condition. Error bars illustrate the standard error of the mean

condition, T2 arrives at an attended location, and its processing is enhanced, giving rise to Lag-1 sparing. A second preliminary observation is that the overall level of the functions in Fig. 4 increases progressively as the SOA is increased. This is because, as the SOA is increased, the trailing mask after T2 is progressively delayed, causing the strength of masking to decrease and T2 accuracy to increase correspondingly in both conditions.

To determine whether the magnitude of Lag-1 sparing varied as a function of SOA, we performed a follow-up analysis in which only the data from Lags 1 and 3 in the Different-streams condition were analyzed. This 2 (Lags 1 and 3) × 5 (SOA: 53, 80, 100, 118, 133 ms) repeated-measures ANOVA revealed significant effect of Lag, $F(1,71) = 28.32$, $p < 0.001$, $\eta_p^2 = 0.29$, and SOA, $F(4,71) = 12.63$, $p < 0.001$, $\eta_p^2 = 0.42$. The interaction between Lag and SOA was also significant, $F(4,71) = 3.71$, $p = 0.008$, $\eta_p^2 = 0.173$, indicating that the magnitude of Lag-1 sparing changed as a function of SOA.

Coupled with the graphical evidence in Fig. 4, these statistical analyses strongly suggest that the focus of attention becomes progressively narrower as the SOA is increased. However, they do not address the primary objective of Experiment 1, which was to determine whether the breadth of the focus of attention decreases more rapidly when the targets are brighter than the distractors as compared to when they have the same luminance as the distractors. This can be determined by comparing the results of the Different-Stream condition in the present experiment, in which the targets were brighter than the distractors, with the corresponding results of Jefferies and Di Lollo (2009, Experiment 1) in which the targets and the distractors were displayed at a fixed luminance. If it is indeed the case that brighter targets lead to faster contracting of the attentional focus, Lag-1 sparing should transition to Lag-1 deficit at a shorter SOA in the present experiment than in the experiment of Jefferies and Di Lollo. This is because faster contraction of the attentional focus to the T1 location means that the location of T2 becomes unattended sooner (see Fig. 3) with consequent impairment of T2 processing, leading to an earlier transition from Lag-1 sparing to Lag-1 deficit.

These conjectures can be verified by comparing the present results with the corresponding results of Jefferies and Di Lollo (2009). To assess whether the transition from Lag-1 sparing to Lag-1 deficit occurred at a shorter SOA when the targets were brighter than the distractors (the present Experiment 1) as compared to when the targets were of equal luminance with the distractors (Jefferies & Di Lollo, 2009, Experiment 1) we performed a 2 (Experiment) × 2 (Lag: 1, 3) × 5 (SOA: 53, 80, 100, 118, 133) ANOVA. SOA and Experiment were between-subjects factors; Lag was a within-subjects factor. The analysis revealed significant main effects of Lag, $F(1,170) = 18.95$, $p < 0.001$, $\eta_p^2 = 0.10$; SOA, $F(1,170) = 103.72$, $p < 0.001$, $\eta_p^2 = 0.38$; and Experiment, $F(1,170) = 13.93$, $p < 0.001$, $\eta_p^2 = 0.08$. There were also significant interactions between Lag and SOA, $F(1,170) = 51.70$, $p < 0.001$, $\eta_p^2 = 0.23$; and between Lag and Experiment, $F(1,170) = 18.60$, $p < 0.001$, $\eta_p^2 = 0.10$. Finally, there was a significant Lag × SOA × Experiment interaction, $F(4,163) = 2.71$, $p = 0.032$, $\eta_p^2 = 0.064$. The significant three-way interaction suggests that the attentional focus contracted more rapidly when the targets were brighter than the distractors than when they were the same luminance as the distractors.

The principal objective of the present study was to determine whether the rate at which the focus of attention contracts is modulated by the physical salience of the stimuli as indexed by the SOA at which Lag-1 sparing transitions to Lag-1 deficit. The data in Fig. 4 do not provide a ready estimate of SOA at which the transition occurs. For that reason, the data in Fig. 4 have been replotted in Fig. 5 (panel a), which illustrates T2 accuracy at Lags 1, 3, and 9 separately as a function of SOA.

All functions in Fig. 5a exhibit progressive increment in accuracy of T2 identification across SOA. This corresponds to the progressive increment in overall level across the five panels in Fig. 4. The progressive increment in Fig. 5a is due in large part to decrement in masking strength with increasing SOA. Were masking the only determinant of T2 identification accuracy, then we would expect all three functions to exhibit similar improvements over SOAs. The fact that the improvement in the Lag-1 function is less pronounced strongly suggests the involvement of an additional factor. According to the model outlined in Fig. 2, that factor is the progressive withdrawal of attention from the T2 location as the focus of attention contracts to the T1-location. Thus, the improvement due to reduction in strength of masking is counteracted by the gradual impairment due to the withdrawal of attention.

In Fig. 5a, Lag-1 sparing occurs at SOAs at which the Lag-1 function (circular symbols) is above the Lag-3 function (square symbols). Conversely, Lag-1 deficit occurs at SOAs at which the Lag-3 function (square symbols) is above the Lag-1 function (circular symbols). The transition from Lag-1 sparing to Lag-1 deficit is given by the SOA at which the two functions cross. The vertical line in Fig. 5a shows the transition SOA to be approximately 64 ms. Figure 5b shows the corresponding data from Experiment 1 of Jefferies and Di Lollo (2009). The transition SOA indicated by the vertical line in Fig. 5b is approximately 103 ms. Clearly, the transition from Lag-1

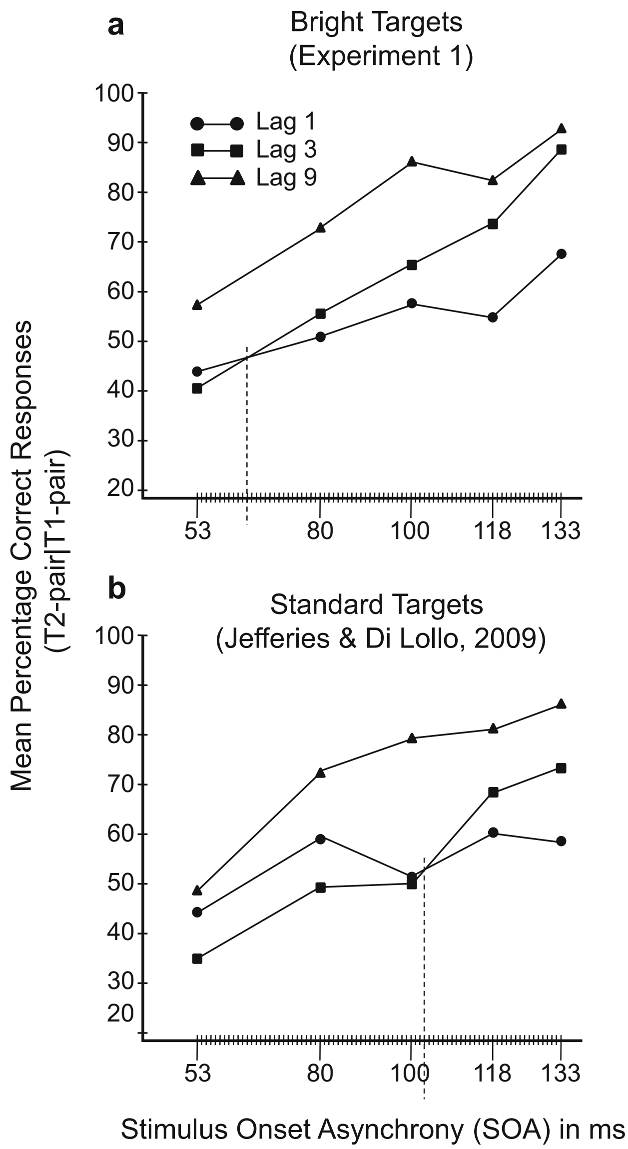

Fig. 5 The data in **a** were redrawn from the corresponding data in Fig. 4. The data in **b** were redrawn from the corresponding data in Jefferies and Di Lollo (2009, Experiment 1). The time of transition from Lag-1 sparing to Lag-1 deficit is indexed by the SOA at which the Lag-1 function crosses the Lag-3 function. The crossing occurs at an SOA of approximately 64 ms when the targets are bright (**a**) and at an SOA of approximately 103 ms when the targets are of the same luminance as the distractors (**b**)

sparing to Lag-1 deficit occurred at a shorter SOA when the targets were brighter than the distractors (present experiment) than when they were of the same luminance as the distractors (Jefferies & Di Lollo, 2009). This is consistent with the hypothesis outlined in the "Introduction" that the rate at which the focus of attention contracts is modulated by the brightness of the stimuli.

Experiment 2

In Experiment 1, we examined the effect of exogenous factors on how quickly the focus of attention can be contracted to the location of T1. This was done by manipulating an attribute of the target—its brightness—relative to the distractors. In so doing, we varied the degree to which the target captured attention while holding constant the degree to which the items in the stream opposite the target captured attention.

Although the concept of *attentional capture* is typically used in reference to the tendency of physically salient stimuli to capture attention (Jonides & Yantis, 1988; Yantis, 1993), it has also been shown that distractors that are in no way physically salient, but that share characteristics with the target, can also capture attention (e.g., *contingent capture*; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994). In Experiment 2, we examined the effect of *endogenous* factors on the rate at which the focus of attention is contracted. In practice, instead of manipulating an attribute of the target, we manipulated an attribute of the distractors—specifically, their capability to capture attention by virtue of their conceptual similarity with the target.

In the dual-stream attentional blink task used in Experiment 1, the targets were letters while the distractors were digits. In Experiment 2, we again employed letters as targets, but used two classes of distractors: (1) digits, which are closely related in features, meaning, and relative familiarity to letters and, hence, should strongly capture attention (e.g., Ghorashi, Zuvic, Visser, & Di Lollo, 2003; Jefferies & Di Lollo, 2015), and (2) random-dot patterns, which have low similarity to the targets, are not task relevant and, thus, should not capture attention (e.g., Visser, Bischof, & Di Lollo, 1999).

It goes without saying that random-dot patterns and digits differ with respect to some low-level features, such as edges and contours. Thus, the two classes of stimuli are likely to differ not only endogenously, but also exogenously. For the present purpose, despite some low-level differences, the most prominent difference between the two classes of stimuli was endogenous: meaningless aggregates of dots versus meaningful alphanumerical characters.

As was the case in Experiment 1, the display consisted of two simultaneous RSVP streams, one on either side of fixation, and two letter targets. All items were of uniform brightness. In one stream, the distractors were digits; in the other, they were random-dot patterns whose configuration varied from frame to frame (see Fig. 6). T1 appeared unpredictably in either the random-dot or the digit stream; T2 appeared in either the same stream as T1 or in the opposite stream. There were two conditions: *High-Capture*

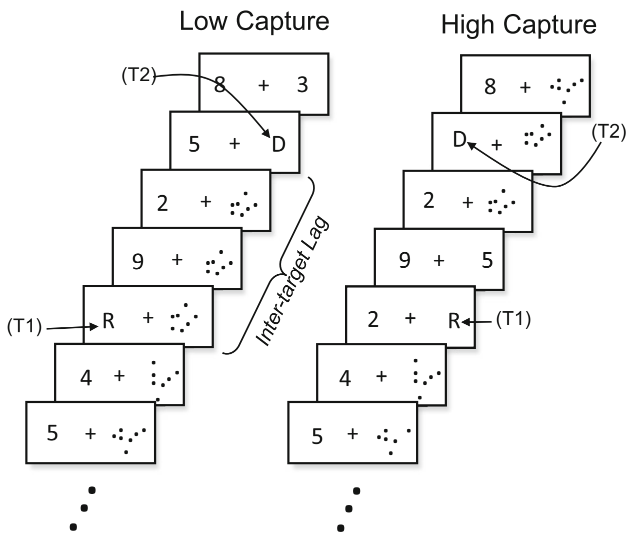

Fig. 6 Schematic representation of the sequence of events within a trial in the different-stream condition of Experiment 2. The first and the second targets (T1 and T2) could appear in either the digit or the random-dot stream and in either the same stream as one another (same-stream condition; not illustrated) or in opposite streams (different-streams conditions). Illustrated is a Lag-3 trial

and *Low-Capture*. These labels refer to the capability of the item opposite T1 to capture attention. In the High-Capture condition, the item opposite T1 was a digit which captured attention by virtue of its conceptual similarity with the target. Such capture would cause the time course of contracting the attentional focus to the T1-location to be relatively slow. In contrast, in the Low-Capture condition, the item opposite T1 was a random-dot pattern, which captured attention to a lesser degree because of its low conceptual similarity with the target. This would cause the time course of contracting attention to be relatively fast.

The juxtaposition of High-Capture and Low-Capture conditions leads to clear predictions regarding the transition from Lag-1 sparing to Lag-1 deficit. When the item opposite T1 is a digit (High-Capture condition), attention will linger for a relatively long time on that digit, thereby slowing the process of contracting attention to T1. If T2 is then presented in the stream opposite T1, it will fall within the still-broad attentional focus, and Lag-1 sparing will ensue. When the item opposite T1 is a random-dot pattern (Low-Capture condition), attention will withdraw rapidly from that location. If T2 is then presented in the stream opposite T1, it will fall outside the attentional focus, and Lag-1 deficit will ensue.

In the present work, we examined these notions with the same five SOAs as in Experiment 1. We expected that at the shorter SOAs the focus of attention would still encompass both streams at the time T2 is presented, thus leading to Lag-1 sparing in both the High- and Low-Capture conditions. The transition from Lag-1 sparing to Lag-1 deficit, however, should occur at a shorter SOA in the Low-Capture condition than in the High-Capture condition because the focus of attention would contract more rapidly in the former than in the latter (see Fig. 3). These temporal contingencies were tested in Experiment 2.

Method

Participants

78 undergraduate students from the University of British Columbia and Simon Fraser University participated in the experiment for course credit. Each group was tested in only a single SOA and, hence, there were a total of five groups: 14 participants in the 53-ms group, 14 participants in the 80-ms group, 17 participants in the 100-ms group, 17 in the 118-ms group, and 16 in the 133-ms group.

Stimuli and procedure

The stimuli and procedures in Experiment 2 were the same as in Experiment 1, with the following exceptions. First, whereas in Experiment 1 both RSVP streams contained digit distractors, in Experiment 2 one stream consisted of digits (0–9, measuring 0.9° vertically) while the other stream consisted of random-dot patterns. The random-dot patterns were created by randomly distributing ten 1-pixel dots into a square region of space 0.9° × 0.9°, with the restriction that the dots not overlap one another. The dots were randomly re-arranged on each new frame in the RSVP sequence. On a randomly intermixed half of the trials, the digit stream appeared to the left of fixation while the random-dot pattern stream appeared to the right; on the remaining trials, the presentation was reversed. Both targets independently appeared randomly in the digit stream on half the trials and in the random-dot stream on half of the trials. As such, the two targets appeared in the same stream on half of the trials and in opposite streams on the remaining trials. Second, unlike Experiment 1, all stimuli had the same luminance (90 cd/m^2). Finally, each target was followed by a digit mask regardless of whether the target appeared in the digit or the random-dot stream.

Results and discussion

The main finding of Experiment 2 was that the time course of attentional focusing (as indexed by the SOA at which Lag-1 sparing transitioned to Lag-1 deficit) was modulated by the nature of the item presented in the stream opposite T1. Attentional focusing occurred more rapidly when item opposite T1 was a random-dot pattern (Low-Capture condition) then when that item was a digit (High-Capture condition).

As in Experiment 1, only those trials in which T1 was identified correctly were included for analysis. Averaged across observers, lags, and stream (same or different), the percentages of correct responses for T1 in the Low-Capture condition were 59.2, 81.2, 84, 79.9, and 89.4% for the 53, 80, 100, 118, and 133 ms SOA conditions, respectively. The corresponding percentages for the High-Capture condition were 41.2, 56.0, 59.9, 55.4, and 81.0%. In general, T1 accuracy was higher in the Low-Capture condition. This is perhaps unsurprising if one considers that identification of T1 involves some competition with the item in the opposite stream. The strength of competition will vary with the conceptual similarity between the two items. In the High-Capture condition, competition would be strong because both items are alphanumeric characters; in the Low-Capture condition, competition would be weaker because of the low conceptual similarity between the two items, leading to higher T1 accuracy.

As was the case in Experiment 1, the trials of interest are those in which the two targets appeared in different streams because only the data from that condition allow inferences to be made regarding the spatial extent of focal attention. Figure 7 illustrates the percentage of correct T2 responses in the Different-streams condition as a function of Lag and condition (High-Capture, Low-Capture), separately for each SOA.

The important statistical comparisons in the present experiment are homologous to those in Experiment 1. Notably, the results of interest are the incidence and magnitude of Lag-1 sparing and Lag-1 deficit in relation to the High-Capture and Low-Capture conditions at each SOA. To examine changes in Lag-1 sparing and Lag-1 deficit, the data were analyzed in a 2 (Lag: 1, 3) × 2 (High-Capture, Low-Capture) × 5 (SOA: 53, 80, 100, 118, and 133 ms) mixed ANOVA, with SOA as the between-subjects factor. The analysis revealed significant effects of High/Low-Capture, $F(1,73) = 17.65$, $p < 0.001$, $\eta_p^2 = 0.195$, and SOA, $F(4,73) = 10.20$, $p < 0.001$, $\eta_p^2 = 0.359$. There were also significant interactions between High/Low-Capture and SOA, $F(4,73) = 5.13$, $p = 0.001$, $\eta_p^2 = 0.219$; Lag and SOA, $F(4,73) = 12.84$, $p < 0.001$, $\eta_p^2 = 0.413$; and High/Low-Capture and Lag, $F(1,73) = 13.24$, $p = 0.001$, $\eta_p^2 = 0.154$. Finally, the three-way interaction between High/Low-Capture, Lag, and SOA was significant, $F(4,73) = 2.78$, $p = 0.032$, $\eta_p^2 = 0.133$. This three-way interaction indicates that the transition from Lag-1 sparing to Lag-1 deficit as a function of SOA was modulated by the nature of the item presented in the stream opposite T1.

As we did in Experiment 1, the data in Fig. 7 were replotted in Fig. 8 to highlight the SOA at which Lag-1 sparing transitioned to Lag-1 deficit in the Low-Capture (panel a) and the High-Capture (panel b) conditions. The transition SOA was approximately 89 ms in the Low-Capture condition and approximately 123 ms in the High-Capture condition. This is consistent with the hypothesis that the rate at which the focus of attention contracts is modulated by the capability of the item opposite T1 to capture attention due to its conceptual similarity to the target—an endogenous factor.

A role for temporal integration?

An additional theoretical interpretation to be considered is that the Lag-1 sparing effect in the present experiments is caused by temporal integration of T1 and T2 (Hommel & Akyürek, 2005)[2]. On this account, the onset of T1 opens an attentional gate that closes sluggishly, allowing the next item in the RSVP stream to pass through the gate and thus gaining access to attentional resources. Lag-1 sparing ensues when the trailing item is T2. Enhanced identification of T2 at Lag 1 (Lag-1 sparing), however, comes at a cost. As noted by Hommel and Akyürek (2005, page 1415, and elsewhere), integration of T1 and T2 into a single attentional episode "… eliminates information about the targets' temporal order." The idea that temporal-order information is lost at Lag 1 is buttressed by the experimental evidence. For example, in Hommel and Akyürek's Experiment 1 (Fig. 2, p. 1421), T2 identification accuracy at Lag 1 was between 80 and 90% when the responses were scored irrespective of report order. In contrast, T2 identification accuracy fell to just above the 50% chance level when response order was taken into account. On the basis of these and similar results, Hommel and Akyürek (2005) concluded that Lag-1 sparing arises from the temporal integration of T1 and T2 into a single attentional episode.

It is worth asking, therefore, whether the present results may have arisen from a similar process of temporal integration rather than from our preferred interpretation of a change in attentional focus. On this option, the present finding that the magnitude of Lag-1 sparing is maximal at the shortest SOA and diminishes progressively at longer SOAs is said to arise from the temporal integration of T1 and T2—with attendant enhancement in T2 accuracy—at Lag 1 but not, or less so, at longer lags. We believe that

[2] We thank Elkan Akyürek (personal communication, June 2017) for suggesting temporal integration as a principle on which to explain the present results.

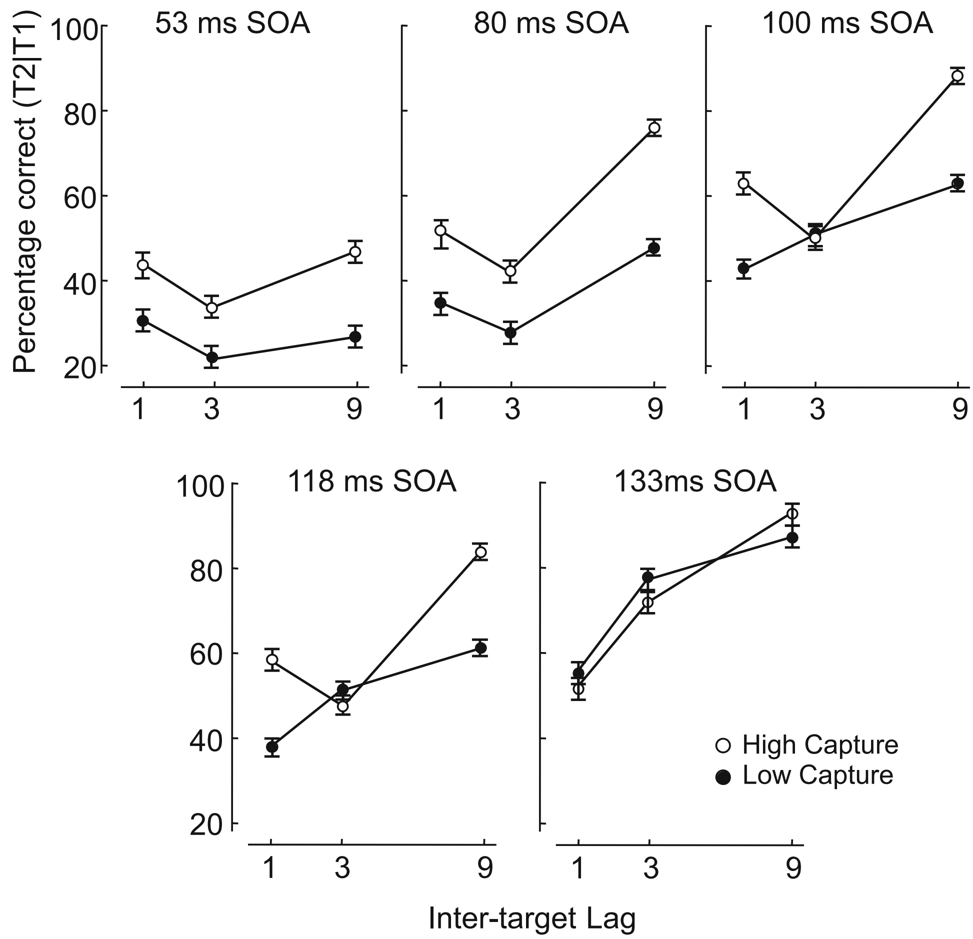

Fig. 7 Mean percentages of correct identifications of the second target in the different-stream condition of Experiment 2 with the data from each SOA plotted in separate panels. The open symbols represent data from the High-Capture condition; the filled symbols represent data from the Low-Capture condition. Error bars illustrate the standard error of the mean

temporal integration is not a suitable account of the present results for a number of reasons.

Perhaps the most telling reason is that the Lag-1 sparing in the present work was obtained with T1 and T2 displayed in separate spatial locations. To account for such Lag-1 sparing in terms of temporal integration, it would have to be assumed that integration of T1 and T2 is not only temporal but also spatial, namely, that it can occur across spatial locations. According to a temporal integration account, "… we may witness an interaction of time and space on temporal integration rates of the two targets. Integration across spatial locations is harder to accomplish than within a single location, but it is not impossible (cf. the classic dot-array tasks)" (as suggested by Akyürek, personal communication, June 2017). We agree that temporal integration occurs across spatial locations. However, this does not mean that the stimuli are also integrated *spatially* so as to be perceived as superimposed.

The classic dot-array task is a case in point. In that task, a 5 × 5 matrix of dots is presented with one dot missing at a random location. Observers name the location of the missing dot. To study temporal integration, the matrix is displayed in two brief frames of 12 dots each, separated by a blank inter-stimulus interval (ISI). At brief ISIs, observers see an integrated matrix with one missing dot whose location is easily identified. Integration breaks down at longer ISIs. The important point is that the integration is *temporal*, not *spatial*. To illustrate, suppose that the first frame in the display sequence consisted of the two leftmost columns of the matrix and the second frame consisted of the three rightmost columns. At short ISIs, the two frames would be seen as an integrated matrix with one dot missing, not as a unitary display of the three right-hand columns superimposed on the two left-hand columns. Yet this is what should be expected if integration were to occur in space as well as time.

A second reason for rejecting temporal integration as a suitable account for the present results is that it requires unsupported ad hoc assumptions even when T1 and T1 are presented within a single RSVP stream. Consider, for example, a study by Akyürek et al. (2012, especially Experiment 3A). In that experiment, an AB paradigm was designed in such a way that if the targets were temporally integrated, the percept would be meaningful. The targets could be /, \, or X so that the observer could report either two targets (/or \) or one target (X). The results showed

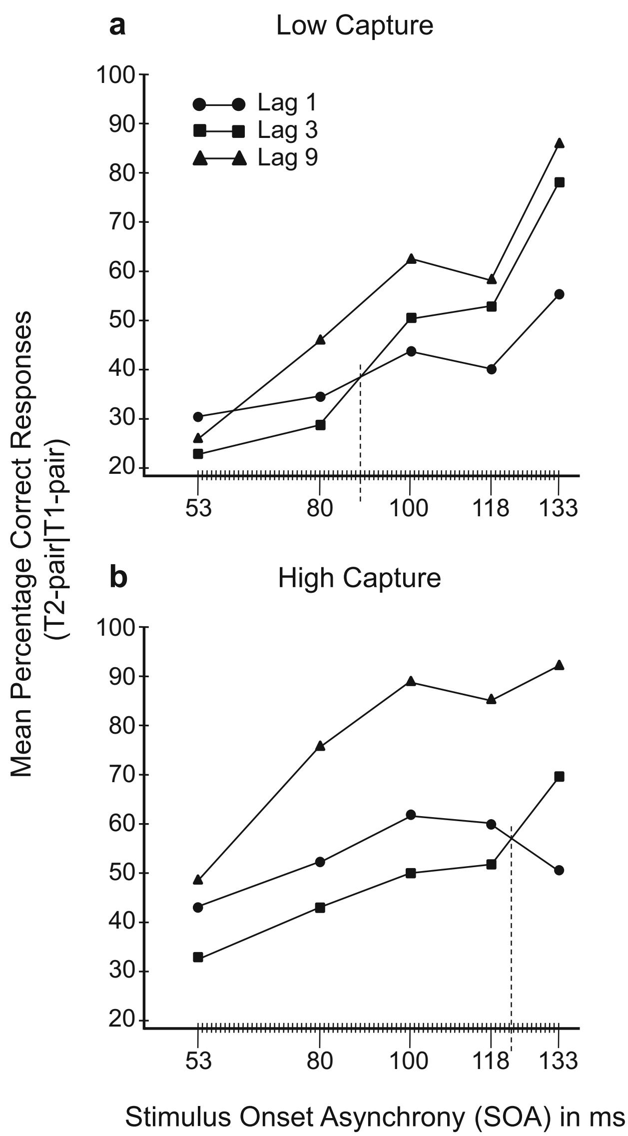

Fig. 8 The data in **a**, **b** were redrawn from the corresponding data in Fig. 7. The time of transition from Lag-1 sparing to Lag-1 deficit is indexed by the SOA at which the Lag-1 function crosses the Lag-3 function. The crossing occurs at an SOA of approximately 89 ms in the Low-Capture condition (**a**) and at an SOA of approximately 123 ms in the High-Capture condition (**b**)

that, when the stimuli were/and \, and the inter-target lag was short, the two line segments were seen as superimposed on one another, and observers reported seeing an X. This outcome creates a problem for interpretation. Suppose that T1 and T2 were the letters "A" and "R" at Lag 1 in a conventional AB study. As was the case for the two line segments, temporal integration would lead to the superimposition of the two letters. But this would result in an unintelligible combination of lines and curves akin to camouflage masking, and would most likely lead to an incorrect response. In fact, no such superimposition/camouflage masking occurs in conventional AB experiments. In the classic experiments of Chun and Potter (1995), T1 and T2 were not seen as superimposed on one another, and were identified with a high degree of accuracy, as evidenced by the phenomenon of Lag-1 sparing.

So, why were T1 and T2 temporally integrated into a unitary percept in Akyürek et al.'s (2012) line-segment experiment but not in conventional AB experiments such as that of Chun and Potter (1995)? Akyürek et al. (2012) attempted to account for this apparent inconsistency by suggesting that T1 and T2 are initially integrated and superimposed on one another, but end up being segregated, as follows: "… a more "unstable," but nonetheless still singular percept emerges, which is also indicated by the detection of some "flicker" in the stimulus stream. This percept may allow the perceptual system to perform a post hoc disentanglement of the stimuli (presumably at a later stage of processing). Nonetheless, the consequences of their integration can still be observed in the irreparable loss of order information that resulted" (page 1461). As presently stated, this account lacks empirical support and is, therefore, ad hoc. Besides, it does not explain why T1 and T2 are not disentangled at a later stage of processing when they are line segments.

Pursuing the ideas of "integration" and "disentanglement" as they apply to dual-stream displays, suppose that T1 is presented in one stream and T2 in the opposite stream. The onset of T1 would open an attentional gate, leading to the integration of four items: T1, the item following T1, the item preceding T2 (i.e., the item opposite T1), and T2. If, as noted above, those four items become integrated into a "singular percept", the process of disentanglement would have to be even more complicated than when T1 and T2 are presented in a single stream. And the ad hoc nature of an integration account would be in evidence even more clearly.

Based on these considerations, it is hard to see how temporal integration can provide a credible theoretical basis on which to explain the present results. To become a plausible account of the results obtained in our study—and, generally, in the AB literature—the conditions that cause a singular percept to become unstable—and hence available for disentanglement—need to be specified and examined. Similarly, the role of flicker in the process of disentanglement needs to be made explicit.

A third factor that needs to be considered is the maintenance of temporal order information. As noted above, integration of T1 and T2 into a single attentional episode is said to be achieved at the cost of information about temporal order. According to the temporal integration account, order errors can be taken as a proxy for integration and may provide an indication of whether integration across streams varies with the SOA manipulation.

The order of responses was not recorded in Experiments 1 and 2, but it was recorded in Experiment 3, which was a follow-up experiment. That experiment comprised a total of 3058 Lag-1 trials (at which most order reversals are predicted to occur), 400 of which exhibited T1–T2 order reversals. This amounts to 13.08% of the trials, which falls far short of the level expected on the basis of temporal integration (i.e., approximately 50%, see above). Of those trials, 152 (4.94%) occurred in the Different-Stream condition, and 248 (8.1%) in the Same-Stream condition.

This pattern of results strongly suggests that temporal integration—as indexed by order reversals—was not a major determinant of the Lag-1 sparing obtained in our experiments. We should emphasize that in Experiment 3 (and also in Experiments 1 and 2), observers were explicitly told that the order in which they typed the target letters did not matter, thus rendering any analysis of order information less informative as a proxy for integration.

The claim that order reversals can be used as a proxy for integration is itself questionable. It is commonly believed that the probability of order reversals is maximal at Lag 1, and drops rapidly as the inter-target lag is increased. As noted above, this loss of temporal information at Lag 1 has been interpreted as the cost of the higher accuracy usually obtained at Lag 1 (Hommel & Akyürek, 2005). That interpretation, however, is complicated by a confounding. As the inter-target lag is increased, the temporal separation between the two targets increases correspondingly, making the targets more temporally distinct from one another. The improved perception of temporal order at lags beyond Lag 1 would then be attributable to increased ease of temporal discriminability rather than to improved ability to maintain temporal order. To avoid this confounding, it is necessary to keep the temporal discriminability of the two targets constant across all lags. This was achieved by Spalek et al. (2012) who used three targets: T1, T2, and T3. The temporal separation between T2 and T3 was kept constant by always presenting T3 directly after T2. The temporal separation between T1 and T2 was varied so as to present the T2–T3 pair at different lags relative to T1. By this means, the perception of temporal order between T2 and T3 could be studied throughout the period of the AB, with temporal discriminability between the two targets held constant. The main finding was that T2–T3 order reversals were maximal not at Lag 1 but at Lag 2, at which identification accuracy was lowest. To wit, as the inter-target lag was increased from Lag 1 (at which integration was supposedly high) to Lag 2 (at which it was supposedly low), identification accuracy decreased but order reversals increased. This decoupling of identification accuracy from order reversals is inconsistent with the idea that order reversals can be used as a proxy for integration.

Additional reasons for questioning a temporal-integration account come from the results of Experiment 2, where it would have to be assumed that temporal integration is governed by the *conceptual* similarity of the targets. Such an assumption would be entirely ad hoc, as there is no evidence in the literature to support it. Taken together, the arguments convince us that temporal integration is not a viable alternative account of the present findings.

Returning to Experiment 2

One salient aspect of the results illustrated in Fig. 7 is that accuracy of T2 identification is generally higher when the items in the RSVP stream preceding T2 are digits (open symbols) than when they are patterns of random dots (filled symbols). This result can be explained with reference to the finding that the processing of a letter target is delayed when it is preceded by a string of digits but not when it is preceded by a blank screen (Visser et al., 1999). A string of random-dot patterns is equivalent to a blank screen as a source of delay (Jefferies et al., 2007; Kawahara & Yamada, 2006). It must be noted, in this respect, that a target's representation remains vulnerable to masking by a trailing stimulus until it has been consolidated into working memory. The important issue for the present purpose is that when T2 is preceded by a string of digits, its consolidation is delayed, thus leaving the target's representation vulnerable to masking. When T2 is preceded by a stream of random-dot patterns, on the other hand, consolidation is more likely to have been completed by the time the mask arrives. This makes the T2 representation more vulnerable to masking when T2 is preceded by a string of digits than when it is preceded by a string of random-dot patterns. The effect of type of item in the leading stream is mostly in evidence at the shorter SOAs, consistent with the idea that consolidation of T2 was completed within about 100 ms.

One question not answered in Experiment 2 regards the assumptions underlying the time at which the focus of attention begins to contract to the location of T1. We have assumed that the trigger for the contracting process is provided by the onset of T1. The tacit assumption was that the RSVP items preceding T1 (i.e., the leading distractors) played no role in determining the rate at which the focus of attention was contracted. This tacit assumption, however, might be questioned. It is possible, for example, that observers developed a predisposition to attend to the digit stream from the very outset of the RSVP sequence. This is because they were set to look for letter targets and, being part of the greater alphanumeric character set, digits also attracted attention. This bias would result in a readiness to respond to T1 when it was presented in the digit stream (Low-Capture condition). This supposition is supported by the finding that T1 was identified more accurately when it was presented in the digit stream than in the random-dot stream. This possibility is examined in Experiment 3.

Experiment 3

In Experiment 3, both RSVP streams contained digit distractors prior to the onset of T1. The intent was to prevent the early development of a selective bias towards the digit stream as might have been the case in Experiment 2. In Experiment 3, therefore, the items preceding T1 were always digits, thus restricting the attentional capture manipulation to the T1 frame. Specifically, on half of the trials, the item that appeared simultaneously with T1 but in the opposite stream was a digit (High-Capture condition), while on the remaining trials the item opposite T1 was a random-dot pattern (Low-Capture condition; see Fig. 9). When the item opposite T1 was a digit, the process of contracting the focus of attention to T1 should be relatively slow; when the item opposite T1 was a random-dot pattern, the contracting process should be relatively rapid. Thus, the transition from Lag-1 sparing to Lag-1 deficit would occur at a shorter SOA when the item opposite T1 was a random-dot pattern than when it was a digit.

Participants

23 undergraduate students from the University of British Columbia participated in the experiment for course credit. Four participants were eliminated due to having T1 accuracy lower than 55%, leaving a total of 19 participants in the analysis.

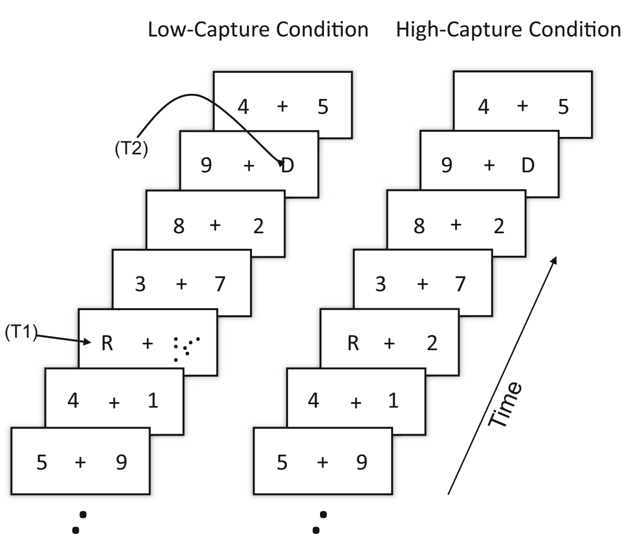

Fig. 9 Schematic representation of the sequence of events within a trial in Experiment 3. The critical difference in this experiment is that both leading streams contain digit distractors and the attentional pull manipulation is implemented only in the T1-frame

Procedure

The procedure of Experiment 3 was identical to that in Experiment 2 with two exceptions. First, whereas in Experiment 2 there was one stream of digit distractors and one stream of random-dot patterns, in Experiment 3, both RSVP streams contained digit distractors. On a random half of the trials, the digit presented simultaneously with T1 in the opposite stream was replaced with a random-dot pattern (Low-Capture condition); on the remaining trials, the digit was not replaced (High-Capture condition). To be clear, the T1-frame was identical in Experiments 2 and 3.

The second difference was that only a single SOA (118 ms) was tested in this experiment. The reason for this is simply that we expected to find the same pattern of results as in Experiment 2, and this could be confirmed adequately with only a single SOA. The 118 ms SOA was chosen because it was at this SOA that the largest difference between the High- and Low-Capture slow conditions occurred in Experiment 2.

Results and discussion

As in Experiment 2, only those trials in which T1 was identified correctly were included for analysis. The average T1 accuracy was 80% in the Low-Capture condition and 79% in the High-Capture condition. As in the previous experiments, only the results for the Different-streams condition are illustrated as only those data allow inferences to be made regarding the spatial extent of the focus of attention. The results of Experiment 3 are illustrated by the solid-line black functions in Fig. 10.

The important statistical comparisons in the present experiment are homologous to those in Experiments 1 and 2; namely the incidence and magnitude of Lag-1 sparing and Lag-1 deficit in the High- and Low-Capture conditions. The data from Experiment 3 were analyzed in a 2 (Condition: High- and Low-Capture) × 2 (Lag: 1, 3) within-subject ANOVA. The analysis revealed a significant Lag × Condition interaction $F(1,19) = 13.48$, $p = 0.002$, $\eta_p^2 = 0.154$. The main effects of Condition and Lag were not significant, both $F < 1$. Coupled with the graphical evidence in Fig. 10, the significant interaction indicates that Lag-1 sparing occurred in the High-Capture condition and Lag-1 deficit occurred in the Low-Capture condition.

To determine whether the difference between the High-Capture and the Low-Capture conditions is comparable in Experiments 2 and 3, we plotted the data for Experiment 2 (gray symbols, segmented lines) along with those of Experiment 3 in Fig. 10. It is immediately clear that, but for a difference in overall level, the pattern of results in

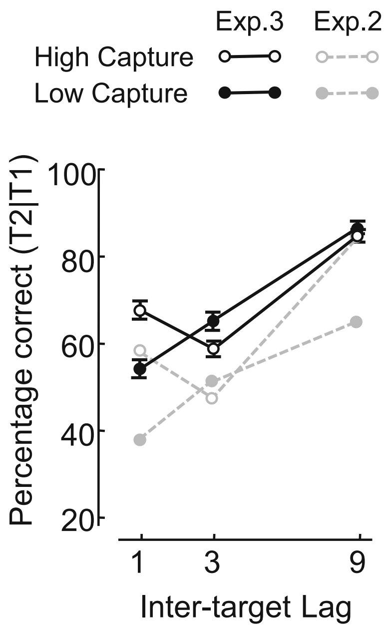

Fig. 10 Mean percentages of correct identifications of the second target in Experiment 3 as a function of Lag. The open symbols represent data from the High-Capture condition; the filled symbols represent data from the Low-Capture. The corresponding data from Experiment 2 have been plotted in gray to facilitate comparison. Error bars illustrate the standard error of the mean

Experiment 3 is virtually identical to that in the 118-ms SOA condition in Experiment 2. Notably, Lag-1 sparing occurred in the High-Capture condition and Lag-1 deficit occurred in the Low-Capture condition in both experiments. Importantly, these findings are inconsistent with the hypothesis that the relatively rapid contraction in the High-Capture condition seen in Experiment 2 arose because attention was biased towards the digit stream from the outset of each trial.

General discussion

It has been known for some time that two broad classes of factors—exogenous and endogenous—influence attentional orienting. The principal objective of the present work was to assess whether the same two classes of factors also affect the rate at which the spatial extent of the focus of attention changes over time. To this end, we adopted the methodology of Jefferies and Di Lollo (2009), consisting of a dual-stream Attentional Blink paradigm. On critical trials, T1 appeared in one stream followed by T2 in the opposite stream. Jefferies and Di Lollo found that upon the presentation of T1, the focus of attention contracted reflexively to the T1-stream, thus leaving the T2-stream unattended. Lag-1 sparing occurred when the focus of attention broadly encompassed both streams so that T2 fell within the focus of attention (see Fig. 2). In contrast, Lag-1 deficit occurred when the focus of attention had contracted to the T1-stream, leaving the T2-stream unattended. By systematically varying the SOA between successive items in the stream, we manipulated the amount of time available for the focus of attention to contract. The SOA at which Lag-1 sparing transitioned to Lag-1 deficit provided an estimate of the rate at which the focus of attention contracted (see Fig. 3).

In Experiment 1, we examined the effect of stimulus brightness, an exogenous factor, and found that the focus of attention contracted more rapidly when the targets were bright. In Experiment 2, we examined the effect of an endogenous factor, conceptual similarity between targets and distractors, and found that conceptual similarity also modulated the rate at which the attentional focus contracts. The focus of attention contracted more rapidly when the conceptual similarity between the targets and the distractors was low. Experiment 3 tested and dismissed an alternative account of the results of Experiment 2.

Models of attentional shifting

Contraction and expansion of the focus of attention have been modeled in the present work as a single focus that expands and contracts in an analog fashion in response to task demands. An alternative approach is that proposed by Posner and colleagues in which shifting the focus of attention comprises three distinct stages: disengaging from an initial location, moving to a new location, and then engaging at the new location (Posner & Petersen, 1990; Posner, Petersen, Fox, & Raichle, 1988; Posner, Sheese, Odludas, & Tang, 2006; Posner, Snyder, & Davidson, 1980). Posner et al.'s scheme was intended to account for shifts of attention between two discrete locations. As such, it cannot be applied readily to the processes of contraction and expansion hypothesized in the present work.

In the context of our paradigm, the idea that a narrow focus of attention moves from one location to another would imply that attention could never be allocated simultaneously to both streams. In this case, Lag-1 sparing should occur only in either the Same-stream condition or in the Different-streams condition—never both, which is inconsistent with the present results. An alternative would be a focus of attention that is set broadly so as to encompass both streams. According to Posner's model, this would require that the attentional focus be disengaged from both streams before moving to and engaging on the T1-stream. While the attentional focus is disengaged, neither stream would be attended, resulting in Lag-1 deficit in both the Same-stream and the Different-streams conditions, which is again inconsistent with our findings. Clearly, interpretation of the present results in terms of Posner et al.'s model is problematic. Posner, however, also acknowledged an alternative modus operandi of the attentional system in which, rather than moving discretely between two spatial locations, the attentional spotlight can be expanded or contracted so as to encompass larger or smaller regions of space (e.g., Eriksen & Yeh, 1985; Posner & Petersen, 1990). This alternative is consistent with the present theoretical approach and can easily account for the present findings.

The focus of attention: unitary or divided?

We have interpreted the results of the present experiments in terms of a unitary attentional focus that contracts and expands. There is growing evidence, however, that separate and independent attentional foci can be deployed simultaneously to discrete locations in space and even to objects presented sequentially in different locations (e.g., Awh & Pashler, 2000; Bay & Wyble, 2014; Eimer & Grubert, 2014; Jefferies et al., 2014; Jefferies & Witt, 2017; Kawahara & Yamada, 2006; Müller, Malinowski, Gruber, & Hillyard, 2003; Yamada & Kawahara, 2007). We now consider whether the present results can be explained also by two discrete foci.

In the single-focus account, as illustrated in Fig. 2, the focus of attention begins by being set broadly so as to encompass both streams. Upon the presentation of T1, the focus contracts to the T1-stream, withdrawing from the T2-stream. This results in Lag-1 sparing at short SOAs and Lag-1 deficit at long SOAs. On a dual-focus account, the two foci are initially deployed one to each stream. Upon the presentation of T1, the focus on the T2-stream is gradually turned off, leaving only the T1-stream attended. As in the single-focus account, this would result in Lag-1 sparing at short SOAs and Lag-1 deficit at long SOAs.

Jefferies and Di Lollo (2009) tested such a dual-focus account by varying the spatial separation between the streams. According to the single-focus account, as the separation is reduced, it should take less time for the focus of attention to contract to the T1-stream and then re-expand to encompass the opposite stream (see Fig. 11). This would result in reduced Lag-1 deficit at the longer SOAs. In contrast, according to the dual-focus account, since the two foci are assumed to be independent of one another, spatial separation should not affect the speed at which the focus on the T2-stream is turned off. Jefferies and Di Lollo found at an SOA of 133 ms, there was Lag-1 deficit when the streams were far apart, but Lag-1 sparing when the streams were close together. This finding is consistent with the single-focus account, but not with the dual-focus account.

The inability of the dual-focus model to account for the present results, however, does not mean that the model is invalid under all circumstances. In fact, it is known that

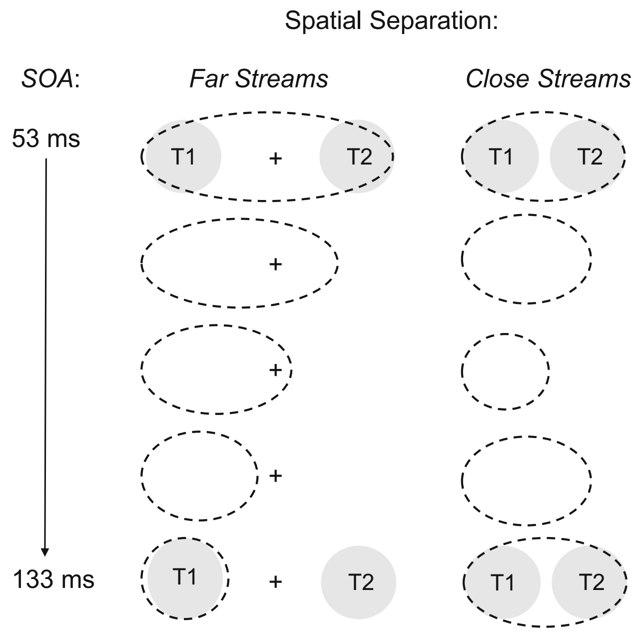

Fig. 11 Schematic illustration of the progressive changes in the spatial extent of the focus of attention (segmented ovals) as a joint function of SOA and inter-stream spatial separation. At an SOA of 133 ms, Lag-1 deficit is expected in the Far-Streams condition, but Lag-1 sparing is expected in the Close-Streams condition. See text for a detailed description

attention can be deployed to several locations concurrently (e.g., Awh & Pashler, 2000; Bay & Wyble, 2014; Jefferies et al., 2014; Jefferies & Witt, 2017; Kawahara & Yamada, 2006; Müller et al., 2003; Yamada & Kawahara, 2007). The evidence for 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; Jans, Peters, & De Weerd, 2010; Jonides, 1983; LaBerge, 1983). Overall, the evidence seems to be consistent with the idea that whether a unitary or a divided focus is employed depends on task demands, the objective being to optimize performance. This view has been buttressed by Jefferies et al. (2014), who found that whether observers employed a unitary or a divided focus depended on task demands, even when the displays were physically identical.

In summary, the present work shows that the rate at which the focus of attention is contracted can be influenced by both exogenous factors (e.g., physical salience) and endogenous factors (e.g., the conceptual similarity between targets and distractors). Future research might examine whether internal factors such as mood, aging, or even circadian rhythms influence the rate at which focal attention expands and contracts as each of these has implications for the efficient functioning of attention in our day-to-day lives.

Acknowledgements This research was supported by Discovery Grants from the Natural Sciences and Engineering Research Council of Canada to V. Di Lollo and J. T. Enns.

Compliance with ethical standards

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.

References

Akyürek, E. G., Eshuis, S. A., Nieuwenstein, M. R., Saija, J. D., Başkent, D., & Hommel, B. (2012). Temporal target integration underlies performance at lag 1 in the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *38*, 1448.

Awh, E., & Pashler, H. (2000). Evidence for split attentional foci. *Journal of Experimental Psychology: Human Perception and Performance, 26*(2), 834–846.

Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics, 55,* 485–496.

Barriopedro, M. I., & Botella, J. (1998). New evidence for the zoom lens model using the RSVP technique. *Perception & Psychophysics, 60,* 1406–1414.

Bay, M., & Wyble, B. (2014). The benefit of attention is not diminished when distributed over two simultaneous cues. *Attention, Perception, & Psychophysics, 76,* 1287–1297.

Benso, F., Turatto, M., Mascetti, G. G., & Umiltà, C. (1998). The time course of attentional focusing. *European Journal of Cognitive Psychology, 10,* 378–388.

Breitmeyer, B. G., Ehrenstein, A., Pritchard, K., Hiscock, M., & Crisan, J. (1999). The roles of location specificity and masking mechanisms in the attentional blink. *Attention, Perception, & Psychophysics, 61,* 798–809.

Breitmeyer, B. G., Hoar, W. S., Randall, D. J., & Conte, F. P. (1984). *Visual masking: An integrative approach*. Oxford: Clarendon Press.

Castiello, U., & Umiltà, C. (1990). Size of the attentional focus and efficiency of processing. *Acta Psychologica, 73,* 195–209.

Chun, M. M., & Potter, M. C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 109–127.

Di Lollo, V., Enns, J. T., Yantis, S., & Dechief, L. G. (2000). Response latencies to the onset and offset of visual stimuli. *Attention, Perception, & Psychophysics, 62,* 218–225.

Egeth, H. (1977). Attention and preattention. *Psychology of Learning and Motivation, 11,* 277–320.

Egeth, H. E., & Yantis, S. (1997). Visual attention: Control, representation, and time course. *Annual Review of Psychology, 48,* 269–297.

Eimer, M., & Grubert, A. (2014). Spatial attention can be allocated rapidly and in parallel to new visual objects. *Current Biology, 24,* 193–198.

Eimer, M., & Kiss, M. (2008). Involuntary attentional capture is determined by task set: Evidence from event-related brain potentials. *Journal of Cognitive Neuroscience, 20,* 1423–1433.

Eriksen, C. W., & St. James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics, 42,* 225–240.

Eriksen, C. W., & Yeh, Y-y. (1985). Allocation of attention in the visual field. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 583–597.

Facoetti, A., Lorusso, M. L., Paganoni, P., Cattaneo, C., Galli, R., & Mascetti, G. G. (2003). The time course of attentional focusing in dyslexic and normally reading children. *Brain and Cognition, 53,* 181–184.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 1030.

Folk, C. L., Remington, R. W., & Wright, J. H. (1994). The structure of attentional control: contingent attentional capture by apparent motion, abrupt onset, and color. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 317.

Ghorashi, S., Enns, J. T., Klein, R. M., & Di Lollo, V. (2010). Spatial selection and target identification are separable processes in visual search. *Journal of Vision, 10*(3), 7.

Ghorashi, S. M. S., Jefferies, L. N., Kawahara, J.-I., & Watanabe, K. (2008). Does attention accompany the conscious awareness of both location and identity of an object. *Psyche, 14,* 1–13.

Ghorashi, S. M., Zuvic, S. M., Visser, T. A., & Di Lollo, V. (2003). Focal distraction: spatial shifts of attentional focus are not required for contingent capture. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 78.

Greenwood, P. M., Parasuraman, P., & Haxby, J. V. (1993). Changes in visuospatial attention over the adult lifespan. *Neuropsychologia, 31,* 471–485.

Hawkins, H. L., Shafto, M. G., & Richardson, K. (1988). Effects of target luminance and cue validity on the latency of visual detection. *Perception & Psychophysics, 44*(5), 484–492.

Hommel, B., & Akyürek, E. G. (2005). Lag-1 sparing in the attentional blink: Benefits and costs of integrating two events into a single episode. *The Quarterly Journal of Experimental Psychology Section A, 58,* 1415–1433.

Jans, B., Peters, J. C., & De Weerd, P. (2010). Visual spatial attention to multiple locations at once: The jury is still out. *Psychological Review, 117,* 637–684.

Jefferies, L. N., & Di Lollo, V. (2009). Linear changes in the spatial extent of the focus of attention across time. *Journal of Experimental Psychology: Human Perception and Performance, 35,* 1020–1031.

Jefferies, L. N., & Di Lollo, V. (2015). When can spatial attention be deployed in the form of an annulus? *Attention, Perception, & Psychophysics, 77,* 413–422.

Jefferies, L. N., Enns, J. T., & Di Lollo, V. (2014a). The flexible focus: Whether spatial attention is unitary or divided depends on observer goals. *Journal of Experimental Psychology: Human Perception and Performance, 40,* 465.

Jefferies, L. N., Ghorashi, S., Kawahara, J-i, & Di Lollo, V. (2007). Ignorance is bliss: The role of observer expectation in dynamic spatial tuning of the attentional focus. *Perception & Psychophysics, 69,* 1162–1174.

Jefferies, L. N., Gmeindl, L., & Yantis, S. (2014b). Attending to illusory differences in object size. *Attention, Perception, & Psychophysics, 76,* 1393–1402.

Jefferies, L.N., & Witt, J.B. First unitary, then divided: The temporal dynamics of dividing attention **(under review).**

Jefferies, L. N., Roggeveen, A. B., Enns, J. T., Bennett, P. J., Sekuler, A. B., & Di Lollo, V. (2015). On the time course of attentional focusing in older adults. *Psychological Research, 79,* 28–41.

Jonides, J. (1983). Further toward a model of the mind's eye's movement. *Bulletin of the Psychonomic Society*, *21*(4), 247–250.

Jonides, J., & Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception & Psychophysics*, *43*, 346–354.

Kawahara, J. I., & Yamada, Y. (2006). Two noncontiguous locations can be attended concurrently: Evidence from the attentional blink. *Psychonomic Bulletin & Review, 13,* 594–599.

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

Lit, A., Young, R. H., & Shaffer, M. (1971). Simple time reaction as a function of luminance for various wavelengths. *Attention, Perception, & Psychophysics, 10*(6), 397–399.

Lunau, R., & Olivers, C. N. (2010). The attentional blink and lag 1 sparing are nonspatial. *Attention, Perception & Psychophysics, 72,* 317–325.

Maringelli, F., & Umiltà, C. (1998). The control of the attentional focus. *European Journal of Cognitive Psychology, 10,* 225–246.

McMains, S. A., & Somers, D. C. (2004). Multiple spotlights of attentional selection in human visual cortex. *Neuron, 42,* 677–686.

Müller, M. M., Malinowski, P., Gruber, T., & Hillyard, S. A. (2003). Sustained division of the attentional spotlight. *Nature, 424,* 309–312.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32,* 3–25.

Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. *Attention and Performance X: Control of Language Processes, 32,* 531–556.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience, 13*(1), 25–42.

Posner, M. I., Petersen, S. E., Fox, P. T., & Raichle, M. E. (1988). Localization of cognitive operations in the human brain. *Science, 240*(4859), 1627.

Posner, M. I., Sheese, B. E., Odludaş, Y., & Tang, Y. (2006). Analyzing and shaping human attentional networks. *Neural Networks, 19,* 1422–1429.

Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General, 109,* 160.

Potter, M. C., Chun, M. M., Banks, B. S., & Muckenhoupt, M. (1998). Two attentional deficits in serial target search: The visual attentional blink and an amodal task-switch deficit. *Journal of Experimental Psychology. Learning, Memory, and Cognition, 24,* 979–992.

Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance, 18,* 849–860.

Remington, R. W., Johnston, J. C., & Yantis, S. (1992). Involuntary attentional capture by abrupt onsets. *Attention, Perception, & Psychophysics, 51,* 279–290.

Ronconi, L., Gori, S., Ruffino, M., Molteni, M., & Facoetti, A. (2012). Zoom-out attentional impairment in children with autism spectrum disorder. *Cortex, 49,* 1–9.

Shih, S. I. (2000). Recall of two visual targets embedded in RSVP streams of distractors depends on their temporal and spatial relationship. *Perception & Psychophysics, 62,* 1348–1355.

Spalek, T. M., Lagroix, H. E., Yanko, M. R., & Di Lollo, V. (2012). Perception of temporal order is impaired during the time course of the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance*, *38*, 402.

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Attention, Perception, & Psychophysics, 51,* 599–606.

Visser, T. A. W., Bischof, W. F., & Di Lollo, V. (1999a). Attentional switching in spatial and non-spatial domains: evidence from the attentional blink. *Psychological Bulletin, 125,* 458–469.

Visser, T. A., Zuvic, S. M., Bischof, W. F., & Di Lollo, V. (1999b). The attentional blink with targets in different spatial locations. *Psychonomic Bulletin & Review, 6,* 432–436.

Weichselgartner, E., & Sperling, G. (1987). Dynamics of automatic and controlled visual attention. *Science, 238,* 778–781.

Woodman, G. F., & Luck, S. J. (2003). Serial deployment of attention during visual search. *Journal of Experimental Psychology: Human Perception and Performance, 29*(1), 121.

Woodworth, R. S., & Schlosberg, H. (1954). *Experimental Psychology*. New Delhi: Oxford & IBH.

Yamada, Y., & Kawahara, J. I. (2007). Dividing attention between two different categories and locations in rapid serial visual presentations. *Perception & Psychophysics, 69,* 1218–1229.

Yantis, S. (1993). Stimulus-driven attentional capture and attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 676–681.

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance, 10,* 601.