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**Implied reading direction
and prioritization of letter encoding**

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Abstract

Capacity limits hinder processing of multiple stimuli, contributing to poorer performance for identifying two briefly presented letters than for identifying a single letter. Higher accuracy is typically found for identifying the letter on the left, which has been attributed to a right-hemisphere dominance for selective attention. Here we use rapid serial visual presentation (RSVP) of letters in two locations at once. The letters to be identified are simultaneous and cued by rings. In a first experiment, we manipulated implied reading direction by rotating or mirror-reversing the letters to face to the left rather than to the right. The left-side performance advantage was eliminated. In a second experiment, letters were positioned above and below fixation, oriented such that they appeared to face downwards (90° clockwise rotation) or upwards (90° counter-clockwise rotation). Again consistent with an effect of implied reading direction, performance was better for the top position in the downwards condition, but not in the upwards condition. In both experiments, mixture modeling of participants' report errors revealed that attentional sampling from the two locations was approximately simultaneous, ruling out the theory that the letter on one side was processed first, followed by a shift of attention to sample the other letter. Thus, the orientation of the letters apparently controls not when the letters are sampled from the scene, but rather the dynamics of a subsequent process, such as tokenization or memory consolidation. Implied reading direction appears to determine the letter prioritized at a high-level processing bottleneck.

Keywords

Attention, reading, lateralization, rapid serial visual presentation

Prioritizing letters in the order of reading

To read English text, we move our eyes from left to right. Not every word is fixated, however, and it is likely that readers sometimes shift their attention in the direction of reading when the eyes are still. Indeed, this is an important element of the popular EZ-reader theory of reading (Reichle, Rayner, & Pollatsek, 2003). According to EZ-reader, only one word can be identified at a time, so attention or the eyes must shift before the next word can be identified. Other theories, however, posit simultaneous identification of multiple words (Engbert, Nuthmann, Richter, & Kliegl, 2005; Inhoff, Radach, & Eiter, 2006). Whether word identification is indeed limited to only one word at a time thus remains a contentious issue for theories of reading (Engbert et al., 2005; Reichle, Livergood, & Pollatsek, 2009). All theories agree that *early* visual processing of multiple words occurs simultaneously. The bottleneck process suggested by some theories reflects a later stage. Reichle et al. describe it as the identification stage, but its nature is not well understood. In addition to letters or words, processing of other types of objects is also thought to be constrained by a bottleneck. As Duncan highlighted in a 1980 review paper, performance identifying two spatially-disparate digits or letters and also other types of stimuli is much poorer than for identifying just one (Duncan, 1980).

The debate around the identification bottleneck posited by EZ-reader and the possible role of attentional shifts in guiding stimuli through it, one-by-one, has been based largely on naturalistic reading tasks, in particular eye-tracking studies of subjects reading entire sentences (e.g., the boundary paradigm, reviewed by Clifton et al., 2015) or longer passages of text. In such tasks, the locations of eye movements and their timing cannot be tightly controlled, making it difficult to probe task components such as shifts of attention.

It would be useful to identify tasks that do not involve uncontrolled eye movements, yet still reliably elicit prioritization of stimulus processing according to the direction of text flow. Such tasks might allow a closer investigation of attentional shifts related to reading and the relationship to multiple stages of processing. Some techniques from experimental psychology that are difficult to use in natural-reading tasks can reveal how different mental processing stages are coordinated in processing multiple items. One such technique, for

example, is Systems Factorial Technology, a response-time methodology that can distinguish between various serial and parallel processing architectures (Algom et al., 2015). Another, which we will use in the present experiments (and will explain further below), is mixture modeling of temporal errors (Goodbourn & Holcombe, 2015).

Simple tasks that reliably elicited processing in the direction of reading (left-to-right for English) might also benefit the study of attention more generally. Historically, visual-search tasks have been used to infer the role of attentional shifts in visual processing. But in visual-search tasks, the pattern of attentional shifts is not consistent and seems difficult or impossible to measure (e.g. Horowitz & Wolfe, 1998; Gilden et al., 2010).

A bias to perform better with stimuli in the left visual field has been consistently reported for a range of tasks. The overwhelming majority of the associated experiments used left-to-right readers as participants, and thus reading habit is a candidate explanation for the left bias. Yet typically, left biases are instead attributed to a difference between the cerebral hemispheres. Left biases can, however, be quite contingent on the task and stimulus, in a way that complicates hemispheric explanations. Boles (1990) compared performance in tasks where a stimulus was presented to only one side (left or right visual field) to performance in tasks where relevant stimuli were presented to both sides simultaneously. There was little-to-no performance difference between left and right stimuli in single-side conditions, but a large difference in both-sides conditions. Specifically, in both-sides conditions performance was markedly better for stimuli presented on the left than for those on the right. From this pattern of results—a left advantage, but restricted to both-sides conditions—Boles concluded that some form of interaction between the hemispheres must occur. One viable account is that the right hemisphere is especially important for selective attention, with selective attention needed when two stimuli are presented but not needed when only one is presented (Reuter-Lorenz et al., 1990; Kinsbourne, 1993; Scalf et al., 2007).

It likely is true that selective attention is more critical in two-stimulus conditions than in one-stimulus conditions, particularly if the two stimuli cannot be processed simultaneously. But rather than the left

Prioritizing letters in the order of reading advantage in two-stimulus conditions stemming from a right-hemisphere specialization for attention, it may instead reflect reading habits. Presented with two stimuli, participants may prioritize one; and, because of reading habits, it may be the left stimulus that is prioritized. If this could be established, such tasks might provide a window into understanding the link between reading direction, laboratory tasks, and the various stages of stimulus processing.

The possibility that reading direction contributes to the left-side advantage does not seem to have been investigated for tasks involving simultaneous presentation of one target on the left and a second target on the right. It has, however, been tested for some other tasks. One such task is line bisection, in which participants are asked to judge the middle of a horizontal line. Most line-bisection studies have been conducted with left-to-right readers and have found that participants tend to bisect the line slightly to the left of its true center, as if the right half is neglected or the left is prioritized. However, in three studies, Israelis with experience reading Hebrew from right to left were compared to native readers of French, and a substantial reduction or reversal in the left bias was found for the Israelis (Chokron & de Agostini, 1995; Chokron & Imbert, 1993; Rinaldi, Di Luca, Henik, & Girelli, 2014). A smaller study with a related *grayscale* task (Mattingley et al., 1994) did not find a significant difference between native English readers and readers whose main language was Hebrew, although a consistent trend is evident in the data (Nicholls & Roberts, 2002). A recent study with a larger sample of right-to-left readers found a significant right bias in the right-to-left readers (Friedrich & Elias, 2014). These findings question the usual interpretation of left biases in terms of an intrinsic right-hemisphere advantage (e.g. Thomas, Loetscher, & Nicholls, 2012; Nuthmann & Matthias, 2014).

Another way that reading order can be dissociated from visual hemifield is by varying the orientation of text. In a seemingly unappreciated study (it has relatively few citations), Hommel (1995) investigated whether letter identification was differentially impaired by distractors on the left or the right of a target. Using an Eriksen flanker task involving letter strings, Hommel found that distractors to the left caused the most interference for responding to a canonically oriented letter, but that

distractors to the right tended to interfere the most when the letter was presented in mirrored orientation. Hommel suggested that this was due to the difference in implied reading direction—mirrored letters appear to face to the left. These results occurred with single-string stimuli, which are perhaps analogous to a single word or object. In a final experiment, Hommel presented the letters of the string with sizeable gaps between them. The spatial asymmetry of the interference effect found for the previous experiments did not occur. Hommel concluded that the spatial asymmetry of flanker interference occurs only when the letters appeared grouped as if they formed a single word. The reading-direction effects reported in the previous paragraphs also came from tasks for which the stimulus was a single object (a line or a grayscale gradient). Thus, it remains unclear in precisely what situations reading-direction effects might be found for the identification of two separated objects.

The effect of reading direction on two-object identification performance was investigated by only one published study, as far as we are aware. Unfortunately, that study presented the two objects (letters) at different times. Only a small effect of participants' habitual reading direction was found (Smigasiewicz et al., 2010). Presenting the targets at different times may naturally have led to the first target occupying processing resources regardless of the side on which it appeared. Furthermore, as the authors of the study suggested, the reading process may not be engaged in selecting and identifying targets presented at different times. Presenting targets simultaneously may be more likely to engage a strategy of prioritizing stimuli in an order consistent with reading habits.

In a series of dual-stream RSVP (rapid serial visual presentation) experiments, Goodbourn and Holcombe (2015) included conditions requiring participants to identify two simultaneous letters that were widely separated. (Because we will frequently reference that paper, we will refer to it hereafter as G&H). For their task, G&H reported that accuracy was much lower for the cued letter on the right than for the cued letter on the left. But when participants were cued to identify only a single letter rather than two, accuracy was as high when the letter cued was presented on the right as when it was presented on the left. The requirement to identify a letter on both sides depressed accuracy on the right

Prioritizing letters in the order of reading specifically; accuracy on the left was unaffected. G&H called this phenomenon *pseudoextinction*; here, we will refer to it as the *second-target deficit*.

The *second-target deficit* might potentially be explained by right-hemisphere dominance rather than by processing related to reading order. However, G&H reported some additional results that suggest the hemispheric accounts are unsatisfactory. We will describe the full set of results from G&H, but first we give a detailed account of their method, as we will build on this method in the present experiments.

The right-side deficit with dual-stream RSVP

G&H used two RSVP streams of rapidly presented letters (Figure 1a). One of the streams was presented to the left of fixation and one was presented to the right of fixation. Each comprised an independent, random set of successively presented letters. In single-target conditions, a letter was cued in only one of the two streams. The participant's task was to report the cued letter (the target). In dual-target conditions, two white circles were presented simultaneously, one around each stream. The participant's task was to report the two letters cued by the circles.

Performance was quantified by *efficacy*, a measure of the proportion of trials in which participants either reported the letter cued by the circle, or reported a letter very close in time to the cue (see the *Analysis* section of the General Methods for details).

In half the trials, the response array required participants to report the letter from the right stream first, and in the other half of the trials it required them to report the letter from the left stream first. Regardless of the response order required, efficacy was markedly lower for the cued letter on the right than for the cued letter on the left. Relative to single-stream conditions, performance in the dual-stream condition was similar for the left stream, but worse for the right stream. That is, the requirement to report items from both streams selectively decreased the rate of successful reporting of the item in the right stream. The effect was large, with reporting accuracy decreasing twenty percentage points or more for letters on the right in the dual-target condition relative to the single-target condition.

The right-side deficit: reading order or hemispheric dominance?

The poorer performance on the right in the dual-stream conditions of G&H could be explained by right-hemisphere dominance in attentional processing (Heilman & van den Abell, 1980). However, right-hemisphere dominance does not explain the results found when the two streams were arrayed vertically, one directly above the other, rather than horizontally. A second-target deficit was found with the vertical array and was comparable in size to that of the horizontal array. With the vertical array, the upper stream mimicked the role of the left stream in the horizontal array. That is, the right-side deficit became a lower-side deficit: in the dual-target conditions, performance was much better for the upper stream than for the lower stream.

The large advantage of the upper position for dual-stream performance should feature in any general theory, as it is as large as the left position's advantage in the horizontal configuration. While it is difficult to explain with a hemispheric account, the advantage of the upper position is consistent with the reading-order theory, as participants may prioritize the stimuli in the order they would typically read text presented in marquee format—from top to bottom.

In other tasks, other researchers previously had found an advantage for targets presented in the upper visual field, and suggested that it reflects an attentional bias arising from a difference in cortical connectivity (Fecteau, Enns, & Kingstone, 2000) rather than reading habit. Specifically, it has been suggested that the upper visual field has stronger connections to the ventral stream in the brain, and the lower visual field stronger connections to the dorsal stream (Edwards & Badcock, 1993; Previc, 1996). A ventral-stream dominance theory could therefore explain the existence of an upper-target advantage specific to the dual-target conditions. However, it is difficult for this theory to explain the results of the diagonal conditions tested by G&H, which we will describe next.

In G&H's *main-diagonal* condition, one of the two streams was positioned above and to the left of fixation, while the other was positioned below and to the right of fixation. In the *anti-diagonal* condition, one stream was presented below and to the left of fixation, while the

Prioritizing letters in the order of reading other was positioned above and to the right of fixation. If the left advantage manifest in the horizontal arrangement and the upper advantage manifest in the vertical arrangement were caused by a right-hemisphere and ventral-stream advantage respectively, then one would expect both to affect performance in the diagonal conditions. In the main-diagonal condition, the top-left target would have the dual advantage of being processed by the right hemisphere and the ventral stream, while the bottom-right target would have the dual disadvantage of being processed by the left hemisphere and the dorsal stream. Here, the performance asymmetry ought to be even larger than in the horizontal and vertical arrangements. In the anti-diagonal condition, by contrast, the bottom-left target would have the advantage of being on the left but the disadvantage of being on the bottom, while the top-right target would have the advantage of being on the top but the disadvantage of being on the right. The difference in performance between the two targets should, therefore, be relatively small in the anti-diagonal condition, and relatively large in the main-diagonal condition.

Contrary to the prediction of the hemispheric and dorsal-ventral theories, the main-diagonal and anti-diagonal dual-stream conditions yielded very similar differences in efficacy between their two positions. Both conditions yielded a large left advantage, with the vertical arrangement having little to no effect. While this is difficult for the hemispheric and dorsal-ventral theories to explain, it is again consistent with prioritization based on reading order. Because the vast majority of English readers' experience is of reading left to right, it is plausible that participants' reading bias favors the left position approximately equally in the main-diagonal and anti-diagonal configurations.

In summary, G&H provided circumstantial evidence that implied reading order was the cause of the left (and upper) dominance. However, many previous results have been interpreted as reflecting right-hemisphere dominance rather than reading order. The predictions postulated for the hemispheric-dominance theory that were violated in the diagonal conditions of G&H's experiments were based on the assumption that the left-hemifield and upper-position dominance processes are independent. This assumption may be wrong, and instead an interaction between the hemispheric

imbalance and the process causing the upper visual field advantage may have resulted in the left position masking the upper advantage for both diagonals. Moreover, the suggestion that the upper position is prioritized by reading-related processes was post hoc. For the present paper, we devised more direct tests of the reading-order hypothesis, by changing the direction the letters were facing to manipulate implied reading order.

Simultaneous selection but prioritized processing

If the left stream is prioritized, as G&H suggested, then one might expect that people would tend to report letters from later in the stream on the right than on the left. In other words, a participant might first select an item from the left stream, and then select an item from the right stream. To assess this possibility, G&H applied a mixture-modeling technique to analyze the distribution of letters reported by participants. The analysis of serial-position errors was pioneered by Botella, Suero, & Barriopedro (2001). Vul, Nieuwenstein, & Kanwisher (2008) had the further insight to break down the serial-position error distribution into its temporal breadth (which we call *precision*), and the time on which it was centered relative to the target (which we call *latency*). G&H introduced a formal mixture-modeling analysis procedure to quantify latency and temporal precision, and take them into account when estimating *efficacy*—the proportion of trials on which processing and report of a letter from around the time of the cue was successful (see Figure 3; for details see the *Mixture Modeling* section of the *General Methods*, or G&H).

For the present experiments, we were particularly interested to know whether our manipulations of letter orientation would have any effect on efficacy and on latency. Rather than sampling letters from the two streams simultaneously in accord with the simultaneous cues, participants might not sample from one stream until they had first sampled from the other, resulting in a higher latency for the less-prioritized stream. That is, for left-to-right scripts the letter reported from the stream on the right would, on average, have been presented later relative to the cue than the letter reported from the stream on the left.

Mixture modeling, applied to the data of the G&H experiments, indicated that the streams were sampled

Prioritizing letters in the order of reading simultaneously rather than left-to-right. G&H therefore concluded that the apparent prioritization of the stream on the left (yielding higher overall accuracy for that stream) was not associated with earlier sampling from that stream. Rather, the left bias instead reflected a subsequent process, such as tokenization or memory consolidation. Such processes are thought to be capacity-limited. As a result, the selected letter on one side is not allocated all processing resources until processing of the other letter has been completed.

Not only did the G&H mixture-modeling results indicate that sampling from the streams is simultaneous rather than sequential, but also they suggested that sampling works in a somewhat surprising way. One might expect that the appearance of the cues would trigger sampling from the stream, resulting in the reported letters being either simultaneous with the cue or from some time after the cue—a positively skewed distribution of serial-position errors. Instead, the distribution of positions is symmetric, with many coming from before the time of the cue (Botella, Suero, & Barriopedro, 2001; G&H; Martini, 2013). Based on these findings, G&H theorized that even the letters presented before the cue activate orthographic representations, that the activation of these representations persists, and that subsequently the cue is bound to one of them (for a related model that anticipates some of these ideas, see Botella, Suero, & Barriopedro, 2001). Moreover, this process can occur in parallel, yielding independent and equivalent latencies for the two streams.

To explain the poorer efficacy for the right stream, G&H suggested that although the letter recognition and cue binding can occur in parallel for the two streams, a subsequent process has very limited capacity. This process, which may be tokenization or memory consolidation, prioritizes the left target. While the process is occupied by the left target, the representation of the right target decays. And by the time processing of the left target has completed, on many trials the representation of the right target has been lost.

In summary, G&H suggested that letters in the two RSVP streams activate representations of letters in the brain that persist for at least a few hundred milliseconds. Reporting the cued letters requires binding the appropriate activated letter representations to the cues, rather than the cues eliciting sampling from the scene. A

subsequent process is very capacity-limited. It prioritizes the letter in the left stream and sometimes does not finish until the representation of the letter cued on the right has decayed.

In the present experiments, we varied the implied reading order in an attempt to disrupt prioritization of the left stream. We assessed whether this affects the efficacy, the latency, or the temporal precision of selection. If, as G&H suggested, the prioritization affects only a second stage after temporal binding of the cue to a letter has already occurred, then only efficacy will be affected.

Manipulating implied reading order

English text is normally read from left to right, but presenting it in an unusual orientation can cue reading it in other directions. Mirror-reversed text, for example, encourages reading from right to left. Participants can read letters faster in the direction that they face than in other directions—Kolars and Perkins (1969) showed this with mirror-reversed letters and inverted letters, as well as canonically oriented letters. Wolff and Mewhort (1986) briefly presented a string of letters and asked participants to report as many as possible, in any order. The letters were most frequently reported from left to right when they were oriented normally, but when mirror-reversed they were frequently reported from right to left. Krueger (1976) asked participants to determine whether a target letter was present in a briefly presented string of four letters. For letters that were canonically oriented, participant responses were faster when the target was in one of the positions to the left. However, for mirror-reversed letters, participant responses were faster when the target was in one of the rightmost positions.

While the direction that letters face thus influences which letter or letters are prioritized for processing, it does not appear to affect the right visual-field advantage found when only a single letter is presented. Bryden (1966) compared accuracy identifying mirror-reversed letters to accuracy for canonically oriented letters. On each trial, a single letter was presented in the left or the right hemifield. Right visual-field presentation yielded higher accuracy, and this advantage was similar in magnitude for both the canonical and mirror-reversed letters, suggesting that it is likely due to an intrinsic (unrelated to reading direction) difference between

Prioritizing letters in the order of reading processing in the cerebral hemispheres. Here we will report evidence that such a hemispheric difference is not the reason for the left visual-field advantage observed in dual RSVP.

The present experiments

Both the hemispheric theory and the reading-order theory can predict the left dominance found for the canonically oriented letters used in the G&H experiments. To decouple the predictions of the two theories, here we varied the direction that the letters faced. Our first experiment was comprised of a canonical-orientation condition and a mirror-reversed condition. In both, one stream of letters was positioned to the left of fixation and the other stream was to the right of fixation. The canonical condition was identical to the main condition of G&H. In the mirror-reversed condition, all the letters in both streams were mirror-reversed. That is, each letter was flipped about its own vertical midline (Figure 1). The conditions were alternated in short blocks of 25 trials.

Figure 1. Schematic of the conditions used in our Experiment 1. (a) Canonical condition, in which letters are presented in their canonical orientation. The canonical condition is very similar to a condition tested by G&H. (b) Mirror-reversed condition, in which letters are reflected about their vertical axis.

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The participants were told that on each trial, two circles would simultaneously appear, one around each stream, and they were to report the cued letters. Practice trials familiarized the participants with the various orientations. There was no mention of reading order, and because the instructions were to identify simultaneous letters that were presented very briefly, if anything the task instructions and demands encouraged parallel processing.

Figure 2. Schematic of the conditions used in Experiment 2. *Canonical* condition: letters were presented in their canonical orientation and in a horizontal configuration. *Inverted* condition: letters were presented in a horizontal configuration, but each was rotated 180° about its center. *Downwards* condition: letters were presented in a vertical configuration with each rotated 90° clockwise about its center. *Upwards* condition: letters were presented in a vertical configuration with each rotated 90° counter-clockwise about its center.

In Experiment 2, to further investigate the possible effect of reading order, we added a vertical configuration. One stream was positioned above fixation and the other below, with all the letters either rotated by 90 degrees clockwise, so that they seemed to point downward and thus suggest a top-to-bottom reading order, or rotated by 90 degrees anticlockwise so that they suggested a bottom-to-top reading order.

We conjectured that the mirror-reversed letters (Experiment 1) or rotated letters (Experiment 2) would substantially reduce the tendency to prioritize the left target. But because English readers have a very strong default to read left to right, we suspected that the orientation of the letters could not fully reverse the asymmetry from a left advantage to a right advantage.

Mixture modeling

Overview of mixture modeling. Mixture modeling was performed to dissociate any changes in the latency or temporal precision of selection from changes in the efficacy of selection. When a participant reports the target letter correctly, she likely has succeeded in attending to the stream and the cueing ring, identified the letter in the ring, and consolidated it into short-term memory. When the participant fails to report the letter in the ring, any of various mental processes may be to blame, such as letter identification, attention, or memory consolidation. Mixture modeling decomposes the participant responses in a way that delivers some insight into which processes go wrong, and how often they do. G&H may have been the first to apply mixture modeling of responses to an RSVP task, and we adopted their technique here.

To understand the mixture-modeling analysis, first consider that because all the possible response options are presented on each trial, the letter that the participant reports always corresponds to a particular serial position in the stream. On some proportion of trials, however, participants fail to identify or remember a letter that was presented around the time of the ring, so they guess. These guesses form a pseudo-uniform distribution of serial position errors (see the *Details of mixture modeling* section below for explanation of why the distribution is pseudo-uniform rather than uniform). This guessing distribution contributes one component to the overall distribution of serial position errors.

In the histogram of serial position errors (Figure 3A), a hill of responses is present, centered near the time of the cue. The spread of the hill indicates that when participants do not report the target letter, often they report a letter that appeared one or a few items before or after the ring. Specifically, participant reports appear to be drawn from a roughly Gaussian distribution of serial positions (Goodbourn & Holcombe, 2015; Martini, 2013). This Gaussian distribution contributes the second component to the overall distribution of serial position errors. The mixture modeling estimates the proportion of trials corresponding to each component, and estimates the mean and standard deviation of the Gaussian component.

Importantly, the hill of cue-related responses is symmetrical. One might have expected that sampling

Prioritizing letters in the order of reading from the scene would not occur until the cue appeared, yielding a positively skewed distribution with responses drawn largely from serial positions after the cue. However, the data we observed in the present experiments, as in previous papers (Goodbourn & Holcombe, 2015; Cellini et al., 2015), is quite symmetrical. This symmetry property motivated the claim by G&H that rather than the cue triggering sampling from the scene, the task is done in a different way. Martini (2013) and G&H theorized that even before the cue is presented, the letters in the stream activate neural representations of those letters, which persist even as subsequent letters are presented. After the ring appears, it is bound to one of the persisting letter representations. But as this process is noisy, it yields a spread of serial position errors. In the Appendix, we statistically confirm that the empirical distributions are indeed symmetrical.

G&H referred to the mean of the Gaussian component distribution as the *latency* of selection. The latency is thus the time relative to the target at which the distribution of non-guessing responses is centered. The standard deviation of the Gaussian, an indicator of the temporal spread of non-guessing responses, is called the *precision*. Finally, the overall proportion of trials contributed by the Gaussian is termed the *efficacy*. Efficacy is the complement of the guessing rate. It is an estimate of the proportion of trials in which participants were successful in reporting a letter around the time of the target.

Figure 3. Example histogram of serial position error and model fit. (a) Each letter reported by a participant corresponds to a particular serial position error. The histogram shows an example distribution (the right stream responses of the inverted condition, averaged over participants), with the dashed line showing the best-fitting mixture model, whose components are shown in panel *b*. (b) Two component distributions together create the overall mixture distribution (dashed line). The area of the component Gaussian (cross-hatched) is the efficacy—the proportion of trials in which the participant did not guess. The pseudo-uniform (guessing) distribution is shown in light grey.

Details of mixture modeling. The range of serial position errors possible on a given trial depends on the serial position of the target in the stream. Very large negative serial position errors are only possible when the target appears late in the stream, whereas moderate negative errors are possible on any trial. Similarly, very large positive serial position errors are only possible when the target appears early in the stream. The pseudo-uniform distribution (and thus the uniform-Gaussian mixture distribution) is therefore tapered at the edges to account for the exact *a priori* possibility of extreme serial position errors.

A maximum-likelihood procedure was used to fit a model for each participant, in each condition, in each stream. Each fit was repeated 100 times with randomized starting values for each parameter. The best-fitting (highest likelihood) three-parameter model was then compared to a restricted, zero-parameter null

model made up of the pseudo-uniform (guessing) distribution alone. The latter model would provide a good fit if the participant guessed on every trial. We used a likelihood-ratio test to determine whether including a Gaussian distribution significantly ($p < .05$) improved the fit of the model. If it did, we used the estimates of efficacy, latency and precision from the three-parameter model. If not, we excluded the participant's data. This exclusion criterion was necessary because, first, a good fit by the guessing distribution alone suggested that the participant rarely or never responded to the cue in one of the streams and, second, it made estimation of latency and precision impossible (i.e. the mean and standard deviation of the Gaussian distribution were undefined).

Experiment 1: Mirror reversal

Methods

Design. A pilot experiment was conducted with a convenience sample of five graduate students and researchers. The results of this pilot were presented at a local conference. In this sample, the effect of letter orientation on efficacy difference between left and right was statistically significant (two-tailed, $p = .024$; effect size, Cohen's $d_z = 1.58$). A power analysis based on these numbers suggests that only six participants would be needed to achieve 95% power. However, a full experiment would sample from the department's undergraduate course-credit participant pool, and we expected that the effect size might be smaller in this less-experienced and less-motivated population. Therefore, we decided to aim for a couple dozen participants and stop after a couple weeks of recruiting, reasoning that this should provide more than sufficient power to detect the effects of interest.

Participants. From the sample of participants ($N = 22$; 11 female; age range 18–25 years, median = 19 years) that resulted from the sampling plan, six participants were excluded from analysis because efficacy in one or both streams was indistinguishable from zero, as described in the *Details of mixture modeling* section above.

Based on their Revised Edinburgh Handedness Inventory scores, all participants were right-handed. Note that G&H found that the pattern of left biases of

Prioritizing letters in the order of reading their left-handed participants was the same as that of their right-handed participants.

Apparatus. Visual stimuli were generated using Matlab R2012b with Psychtoolbox-3 (Brainard, 1997; Pelli, 1997; Kleiner et al., 2007) on a MacBook Pro and displayed on a Mitsubishi DiamondView touchscreen LCD monitor with a resolution of 1024 x 768 pixels and nominal refresh rate of 60 Hz (Experiment 1) or 56 Hz (Experiment 2).

Participants were seated in a dark room with their head supported on a chinrest to maintain a 57cm viewing distance to the monitor. They responded using a mouse placed to their right-hand side. Participants wore headphones that delivered an auditory tone to mark the beginning of each trial.

Stimuli and procedure. Stimuli were white uppercase letters (a maximum of 3.0° tall and wide), presented against a black background. The letters appeared in Sloan font (Committee on Vision, 1980; Pelli, Robson, & Wilkins, 1988), in which all letters share the same horizontal and vertical subtense, meaning that their dimensions did not change when rotated. A white fixation circle (0.25°) was located at the center of the screen. Letter streams were centered 6.0° to the left and right of fixation (horizontal configuration). Each stream consisted of a serial presentation of 24 different randomly ordered letters (C and V were excluded to reduce confusability among letters). Each letter in each stream was presented for 50 ms followed by a 33 ms blank interval (12 items.s^{-1}).

An auditory tone and two white rings (each of 5.0° subtense, 0.1° thickness, and 250 ms duration) at the locations of the streams informed the participant that the streams were about to commence. The first item appeared 1.0 s later. Target letters appeared simultaneously in both streams. Their serial position, between the 7th and 18th inclusive, was randomly chosen on each trial. Each target letter was surrounded by a cue, a white ring subtending 5.0° and 0.1° thick. The target letter and cue were presented for the same duration as a distractor letter.

Five hundred milliseconds after offset of the final items, a response screen appeared, comprising 24-letter vertical arrays (excluding C and V, and in alphabetical order from top to bottom) on the left and right side of the screen. One array was active at a time, with the inactive

array rendered in gray. Participants used the mouse to select the target letter from the active array, at which point the selected letter appeared at the corresponding stream location. Participants were free to reselect until they confirmed their answer (with an additional mouse click), after which the second array became active. On half of trials, the array that was active first was the left array, and on the other half of trials it was the right array.

Participants completed eight blocks, four in each of two sessions. Each session contained two blocks wherein every letter was presented in its canonical orientation, and two blocks wherein all the letters—including those in the response arrays—were mirror-reversed (completed in ABBA order, counterbalanced across sessions and participants). Each block contained 25 trials. Thus, participants completed 100 trials in the canonical condition and 100 in the mirror-reversed condition. At the beginning of the first session participants completed 24 practice trials with letters in the canonical orientation and 24 practice trials with letters in the mirror-reversed orientation. At the end of the session, the participants completed the Revised Edinburgh Handedness Inventory (EHI-R; Williams, 2010), and supplied their age and gender.

Results and Discussion

Efficacy. Our primary interest was whether the left bias was reduced by presenting the letters in the mirror-reversed orientation. The left bias was quantified as left-stream efficacy minus right-stream efficacy. For simplicity, we first test this directly, then subsequently report results from an ANOVA for the other effects. All numbers after “ $\pm$ ” are standard errors of the mean. Effect sizes for t tests are Hedges’ g ; for ANOVAs, partial eta-squared (η_p^2).

Figure 4. Efficacy in each condition in Experiment 1. The large left bias of the canonical condition is greatly reduced in the mirror-reversed condition. Error bars show ± 1 standard error, calculated via the method recommended for within-subjects designs by Loftus and Masson (1994).

The mean left bias in the canonical condition ($M = 23.1 \pm 5.8$) was significantly greater than that in the mirror-reversed condition ($M = 6.2 \pm 7.0$), according to a paired-samples t test, $t(15) = 3.52$, $p = .003$, $M = 16.9 \pm 4.8$, $g_{av} = .63$. Expressed in CL (common language) effect size calculated from the t test (McGraw & Wong, 1992; Lakens, 2013), there is an 81% chance that a randomly sampled participant will show a greater leftward bias in the canonical condition than in the

mirror-reversed condition ($CL = .81$). One-sample t tests indicate a significant bias in the canonical condition, $t(15) = 3.99$, $p = .001$, $g_s = 1.38$, $CL = .84$, but not in the mirror-reversed condition, $t(15) = .89$, $p = .390$, $g_s = 0.31$, $CL = .56$.

For completeness, we also followed the convention of analyzing the data with an ANOVA—a two-way, repeated-measures ANOVA (orientation $\times$ letter stream), for which our primary interest was the interaction term. But first, we note that there was a significant main effect of orientation, $F(1,15) = 8.70$, $p = .010$, $\eta_p^2 = .37$, with greater efficacy in the canonical condition (58.7 ± 3.2)

than in the mirror-reversed condition (52.8 ± 2.6) averaged over both streams. There was a significant main effect of stream, $F(1,15) = 6.06$, $p = .026$, $\eta_p^2 = .29$, with greater efficacy in the left stream (63.1 ± 3.8) than in the right stream ($M = 48.4 \pm 4.2$), averaged over orientations. The interaction between orientation and stream was significant, $F(1,15) = 12.38$, $p = .003$, $\eta_p^2 = .45$, confirming the difference in biases across conditions revealed by the above t tests.

Latency. A latency of zero would correspond to a distribution of serial position errors centered exactly on zero (i.e., on the target). In Experiment 1, because the stimulus onset asynchrony was 83 ms, a latency of 83 ms would indicate that the error distribution was centered on the item after the target. The latencies here were around 40 ms, which in combination with the precision (see *Precision*

below) indicates that a substantial proportion of reported items appeared before the target (this is also clear in the serial position error histograms, not shown). This finding is one reason that G&H, who found the same, suggested that the letters in the stream, including the non-targets, are buffered prior to a binding process that judges which letter was encircled by the ring.

The low latency observed was not significantly affected by the orientation (canonical or mirror-reversed) or stream (left or right), according to a two-way, repeated measures ANOVA. For the non-significant effect of orientation, $F(1,15) = 2.0$, $p = .18$, $\eta_p^2 = .18$, the canonical orientation yielded a mean latency of 39 ± 5 ms, and the mirror-reversed a mean of 35 ± 5 ms. Similarly, the effect of stream was not significant, $F(1,15)$

Prioritizing letters in the order of reading
 $= 1.56, p = .23, \eta_p^2 = .09$, left stream, $M = 40 \pm 5$ ms;
 right stream, $M = 34 \pm 6$ ms. Orientation and stream did
 not interact significantly, $F(1,15) = 1.78, p = .20, \eta_p^2 =$
 $.11$. Indeed, the difference between the streams (left –
 right; referred to as *left bias* in the context of efficacy)
 was negligible and not statistically significant in both the
 canonical condition ($M = 1.2 \pm 4$ ms; one-sample $t(15) =$
 $.26, p = .80$) and the mirror-reversed condition ($M = 11.7$
 ± 8.1 ms; one-sample $t(15) = 1.45, p = .16$), nor was it
 significantly different between those two conditions
 (paired t test, $t(15) = -1.33, p = .20$). Attention shifts are
 typically estimated to require at least several dozen
 milliseconds, which are unlikely to have occurred given
 the standard errors (4 and 8 ms) for the small latency
 differences found here.

At the request of a reviewer, we also analyzed
 latency as indexed by raw SPE. Again the ANOVA
 yielded no significant effects of condition ($F(1,15) = 1.87,$
 $p = 0.19$), stream ($F(1,15) = 2.37, p = 0.15$), or their
 interaction ($F(1,15) = 1.29, p = 0.28$). The non-significant
 trend in the canonical condition was for the right stream
 ($M = 25 \pm 15$ ms) to have slightly lower latency (lower
 SPE) than the left stream (31 ± 8 ms), inconsistent with
 an attentional shift from left to right. For the mirror-
 reversed condition the mean SPEs were $M = 30 \pm 9$ ms
 for the left stream and $M = 1 \pm 13$ ms for the right
 stream.

That the latencies were similar and small need not
 imply that selection was simultaneous. In principle, it is
 possible that participants report an early item from one
 stream, then shift their attention and sample a later item
 from the other stream. If this happened frequently, with
 each stream as a starting point on an approximately
 equal number of trials, similar mean latency would be
 observed in each stream. But the joint-SPE plot (Figure
 5) shows that participants' most common response is to
 report letters that occurred at the same time, as was also
 observed by G&H. If participants sampled one stream
 before sampling the other stream (but started with a
 different side on different trials), then the modal
 response would not correspond to the same SPE on
 both sides. Instead, the most common responses should
 be of SPEs that are different—two peaks or ridges would
 be seen on either side of the dashed line, as only the
 regions away from the dashed line correspond to the
 latencies for those trials being different for the two sides.

Precision. The spread (σ) of the distribution of
 reported letters (of the Gaussian component specifically
 is a measure of temporal precision. Positive but small
 latencies (see *Latency*, above) indicate that this spread
 of selection is centered near the time of the target, so
 that many items both before and after the target are
 erroneously reported. The values for σ observed here,
 60 to 100 ms, are similar to those found previously for
 RSVP tasks (G&H; Holcombe, 2009; Cellini et al., 2015;
 Goodbourn et al., 2016).

Figure 5. Joint serial position errors (left and right sides), in the Canonical (left panel) and Mirror-reversed (right panel) conditions of Experiment 1. Darker cells indicate more responses for the corresponding combination of left and right serial position error, with the darkness scale normalized to the maximum value within each condition. The most common response on individual trials corresponds to a serial position error of zero for the left and right. If a time-consuming attentional shift was required between sampling of the two streams, then the modal response would not correspond to the same SPE on both sides. Efficacy was high for the left side in the canonical condition, so almost all the responses correspond to serial position errors between -1 and 1 . Lower efficacy means more guessing responses, contributing to the scatter of serial position errors that is more conspicuous in the mirror-reversed condition. These guesses are most frequent when the other stream's serial position error is zero, simply because a serial position of zero is the most common response for each stream. The scales are truncated at -5 and 5 because large serial position errors could only occur on some trials (see *Details of mixture modeling*, above).

There were no significant effects for the precision measure, neither a main effect of orientation, $F(1,15) = .09$, $p = .77$, $\eta_p^2 = .01$ (canonical, $M = 72 \pm 3$ ms; mirror-reversed, $M = 71 \pm 3$ ms) nor a main effect of stream, $F(1,15) = .001$, $p = .98$, $\eta_p^2 = .00$ (left, $M = 71 \pm 3$ ms; right, $M = 72 \pm 4$ ms). We should note that in the previous sentence, the standard error of 4 ms and temporal precision of 71, 72, or 73 ms in every condition are not typos; temporal precision of attentional selection can be remarkably stable, both within and between observers (Goodbourn & Holcombe, 2015). There was no significant interaction between orientation and stream, $F(1,15) = .02$, $p = .89$, $\eta_p^2 = .001$. Indeed, for

each orientation, the difference between the streams (left – right) in precision was negligible (canonical, $M = 1 \pm 5$ ms; mirror-reversed, $M = -1 \pm 9$ ms), and neither was significantly different from zero.

Accuracy. For completeness, and to facilitate future comparison with others' results for which mixture modeling is not used, we here report the results with accuracy (percent correct) as the dependent variable. A repeated-measures ANOVA (orientation $\times$ letter stream) of accuracy revealed no significant main effect of orientation, $F(1,15) = 0.50$, $p = .49$, $\eta_p^2 = .03$ (canonical, $M = 22.6 \pm 2.7$; mirror-reversed, $M = 21.4 \pm 2.4$) or stream, $F(1,15) = 1.78$, $p = .20$, $\eta_p^2 = .11$ (left, $M = 23.8 \pm 2.8$; right, $M = 20.2 \pm 2.7$). There was a significant interaction between orientation and stream, $F(1,15) = 4.55$, $p =$

$.05$, $\eta_p^2 = .23$).

The canonical condition (left bias $M = 7.0 \pm 2.8$) yielded a significantly greater leftward bias than the mirror-reversed condition (left bias $M = 0.0 \pm 3.4$; paired $t(15) = 2.13$, $p = .05$, $M = 7 \pm 13.1$, $g_{av} = .54$, $CL = .70$). One-sample t tests revealed a statistically significant bias in the canonical condition, $t(15) = 2.51$, $p = .024$, $g_s = .09$, $CL = 0.73$, but not in the inverted condition, $t(15) = -.06$, $p = .95$, $g_s = 0.0$, $CL = .50$.

Report order. Because on half of trials participants were forced to report on the left stream first and in half of trials they reported on the right stream first, it is unlikely that the left bias can be explained by order of retrieval

Prioritizing letters in the order of reading from memory. Moreover, proportion correct was the same for the target that was queried first ($M = .22 \pm .02$) as for the target that was queried second ($M = .22 \pm .02$). Nevertheless, certain report-order effects would still be theoretically interesting. We did not use mixture modeling for this because too few trials were available when breaking down the data by report order.

The memory of the two items to be reported may be encoded as a spatial array with, in the canonical condition, the left item to the left and the right item to the right in memory. People may prefer to scan such a memory from left to right, and this retrieval process could contribute an advantage when the left side is queried first (Rinaldi et al., 2015). However, there was no support for this in the data. The percent correct in the canonical condition was very similar both when the left side was queried first ($M = .23 \pm .02$) and the right side was queried first ($M = .22 \pm .03$).

More generally, when report order was included as a factor (*queried first* or *queried second*) in an ANOVA together with condition and stream, neither the main effect of the report-order factor ($F(1,15) = 0.10$, $p = .75$) nor its interactions were significant ($F(1,15) = 3.59$, $p = .08$ for the interaction with stream; $F(1,15) = 1.28$, $p = .27$ for the interaction with orientation; $F(1,15) = 0.00$, $p = .97$ for the three-way interaction).

Experiment 2: Vertical and horizontal configurations

Our finding that mirror-reversing the letters eliminated the left bias suggests that reading order plays a large role in determining processing priority for briefly presented letters. Experiment 2 was designed to provide two kinds of additional evidence that would shore up this conclusion or undermine it.

For Experiment 2 we chose a set of conditions that included a comparison rather similar to that of Experiment 1, as a conceptual replication of Experiment 1's main result. Two conditions used two streams that were *horizontally* arrayed, like in Experiment 1. In one of the conditions the letters were canonically oriented. In the other, the letters were inverted by rotating them 180° . Because inversion—like the mirror reversal used in Experiment 1—causes text to face leftward rather than rightward, the reading-order theory predicts that the left bias will be eliminated.

A second purpose of Experiment 2 was to address a version of the hemispheric-differences theory, one that might be advanced to explain the findings of Experiment 1. Recall that the hemispheric theory, to explain why the left advantage doesn't occur in one-target conditions, suggests that the right hemisphere has a processing advantage that is engaged only in two-target conditions. How might advocates of this theory explain the elimination of the left bias with mirror-reversed letters? They might posit that letters that are not canonically oriented do not engage the same hemisphere-specific mechanisms, and therefore do not yield a left advantage. In other words: There is some process for which the right hemisphere has an advantage; this advantage only manifests with dual stimulation; and, further, it is specific to the canonical orientation of letters. This is not a parsimonious account, and would have to be further complicated to account for the fact that identification of a single letter is typically found to be superior in the right visual field, not the left visual field (Bryden, 1966; Kimura, 1961; Heron, 1957), even when the letters are presented mirror-reversed (Bryden, 1966). In any case, the conditions of Experiment 2 were designed to completely obviate the issue of differences between the cerebral hemispheres.

Experiment 2 included two conditions in which the streams were arrayed *vertically*, positioned one above the other rather than displaced left and right. We contrasted a condition in which the letters were rotated 90° clockwise (downward-facing) with one in which the letters were rotated 90° counter-clockwise (upward facing). The downward-facing condition may suggest that the letters be read from top to bottom, while the upward facing condition suggests bottom to top.

Because text in English is horizontally arrayed much more often than it is vertically arrayed, we expected that the vertical configuration would not be associated with as strong a bias to prioritize one position over another; thus, any asymmetry would be smaller than in the horizontal conditions. However, if any significant advantage for the top position occurred for the downward-facing condition, we expected it to be much smaller or reverse in the upward-facing condition.

Methods

The methods were very similar to those of Experiment 1. Only certain details, and the differences, are described here.

To improve task performance relative to Experiment 1, and thereby improve our ability to estimate model parameters, we reduced the rate of stimulus presentation. The Gaussian distribution models only the trials not modeled by the pseudo-uniform (guessing distribution), thus the parameters of latency (mean and precision of the Gaussian) are better estimated when performance is higher and there are more non-guessing trials. The presentation rate for this experiment was set to 8 items.s⁻¹ (against 12 items.s⁻¹ in Experiment 1) with each item presented for 89 ms followed by a 36 ms blank interval. We have found that while efficacy is higher for slower rates, estimates of latency and temporal precision are stable within this range of presentation rates (Goodbourn & Holcombe, unpublished data).

Letter streams were centered either 6.0° to the left and right of fixation (horizontal configuration), or 6.0° above and below fixation (vertical configuration). For vertical configurations, the response arrays (detailed in Experiment 1 methods) were horizontal arrays of the possible letters, situated at the top and bottom of the screen, arrayed in alphabetical order from left to right.

All conditions were blocked. They were administered in two sessions, a horizontal-arrangement session and a vertical-arrangement session. Each session ran for approximately 25 min and participants took a break in between. For the horizontal-arrangement session, two blocks contained letters presented in the canonical orientation and the other two contained letters presented in the inverted orientation. In the vertical-arrangement session, two blocks contained letters presented facing downwards (rotated 90° clockwise) and the other two contained letters facing upwards (rotated 90° counter-clockwise).

Session order was counterbalanced across participants: Half completed the horizontal-arrangement session first. Within a session, the orientation condition of the first block was counterbalanced across participants such that each condition was presented as the first block an equal number of times. The order of the remaining three blocks of the session was randomized.

Before each session, participants completed 15 practice trials for each of the orientations used in that session (30 practice trials per session, 60 practice trials overall). Participants completed 200 experimental trials in total: 50 trials for each of the four orientation conditions (canonical, inverted, downwards, and upwards).

Participants. Participants (N = 28; 21 female; age range 18-24 years, median = 18 years) were first-year psychology students who received course credit for their participation. Four participants were excluded from analysis because efficacy in one or both streams in one or more conditions was statistically indistinguishable from zero, leaving 24 participants whose data were analyzed further.

Based on the Revised Edinburgh Handedness Inventory, five participants were left- or mixed-handed, while the rest were right-handed. All analyses were also run with only the right-handed participants, and the same patterns of results were found.

Results and discussion

Efficacy. As in Experiment 1, our interest was in whether the efficacy difference between the streams (left bias in the horizontal configuration, and top bias in the vertical configuration) was affected by the orientation of the letters. This was assessed by paired-samples *t* tests, using left bias as the dependent variable (left efficacy – right efficacy) in the horizontal configuration and top bias (top efficacy – bottom efficacy) in the vertical configuration. The results detailed below indicate that changing the orientation of the streams shifted the efficacy difference between the streams substantially, and in the predicted directions (Figure 6).

Horizontal configuration. A significantly greater leftward bias was observed in the canonical condition ($M = 21.8 \pm 3.4$) than the inverted condition ($M = 1.7 \pm 4.9$), paired $t(23) = 5.34$, $p < .001$, $M = 20.1 \pm 3.8$, $g_{av} = .94$. Expressed in common language (*CL* effect size), there is an 88% chance that a randomly sampled participant will demonstrate a greater leftward bias in the canonical condition than in the inverted condition ($CL = .88$). One-sample *t* tests revealed a statistically significant bias in the canonical condition, $t(23) = 6.35$, $p < .001$, $g_s = 1.84$, $CL = .90$, but not in the inverted condition, $t(23) = 0.35$, $p = .73$, $g_s = .10$, $CL = .53$.

Vertical configuration. The top bias of the downwards condition ($M = 18.8 \pm 4.3$) was significantly

$t(23) = 4.33, p < .001, g_s = 1.24, CL = .81$, but not in the upwards condition, $t(23) = -1.43, p = .17, g_s = .41, CL =$

greater than the top bias of the upwards condition, $t(23) = 4.47, p < .001, M = 25.8 \pm 4.7, g_{av}$

$= 1.12$). Indeed, the upwards condition was suggestive of a bottom bias (-7.0 ± 4.9 , not statistically significant). Expressed in common language (CL) effect size, there is an 87% chance that a randomly sampled participant will have a greater top bias in the downwards condition than in the upwards condition ($CL = .87$). One-sample t tests revealed a significant bias in the downwards condition,

Figure 6. Efficacy in each condition in Experiment 2. The ‘dominant’ stream (dark grey) is the stream that should be prioritized according to standard reading order (left to right, top to bottom). The strong left bias of the canonical condition is largely eliminated in the inverted condition. Similarly, the top bias of the downwards condition was not present in the upwards condition. Error bars show ± 1 standard error within subjects (Loftus & Masson, 1994).

.61.

Latency. Latency was low in every condition - it ranged from 18 to 27 ms. A latency of 125 ms would correspond to being centered on the first item after the target, so even the largest value found of 27 ms is close to being correctly centered on the target.

Prioritizing letters in the order of reading

There were no significant differences across streams or orientations. A repeated-measures ANOVA (orientation $\times$ letter stream) of latency yielded no significant effects. In the ANOVA, stream was coded as dominant (top, left) or non-dominant (bottom, right). There was no main effect of orientation, $F(3,69) = 0.78$, $p = .51$, $\eta_p^2 = .03$ (downwards $M = 18 \pm 6$ ms; upwards $M = 24 \pm 6$ ms) nor a main effect of stream, $F(1,23) = 0.05$, $p = .82$, $\eta_p^2 = .002$ (dominant $M = 22 \pm 5$ ms; non-dominant $M = 23 \pm 5$ ms), nor a significant interaction of stream and orientation, $F(3,69) = 1.56$, $p = .21$, $\eta_p^2 = .06$. The trend was for a longer latency (but only by less than 10 ms) for the first position according to implied reading order (e.g., canonical condition left 22 ± 6 ms, right $31 \pm$

6 ms; downward condition top 13 ± 6 ms, bottom 23 ± 9 ms). We also analyzed raw SPE, which again yielded no significant effects of orientation ($F(3,69) = 0.99$, $p = .40$), stream ($F(1,23) = 0.01$, $p = .93$), or their interaction ($F(3,69) = 0.71$, $p = .55$).

As for Experiment 1, the joint SPE plots show that the most frequent response in each condition was to report both cued letters (a serial position error of zero for both streams; Figure 7). This rules out a possibility suggested by a reviewer, that participants could only identify one letter on any one trial, but attended to one side in some trials and the other side in the remaining trials.

Figure 7. Joint serial position errors for the left and right sides (horizontal configuration) and top and bottom positions (vertical configuration), in the four conditions of Experiment 2. See caption to Figure 5 for more details.

Precision. The precision of attentional selection (Figure 8) was better (by 25 ms) in the horizontal configuration than in the vertical configuration. In a repeated-measures ANOVA (orientation $\times$ letter stream), this led to a main effect of orientation, $F(3,69) = 7.91$, $p < .001$, $\eta_p^2 = .26$. Stream did not have a significant effect, $F(1,23) = 0.40$, $p = .53$, $\eta_p^2 = .017$ (dominant $M = 82 \pm 5$ ms; non-dominant $M = 79 \pm 3$ ms), nor was the interaction significant, $F(3,69) = 1.58$, $p = .20$, $\eta_p^2 = .06$.

Figure 8. Precision in each condition of Experiment 2. Precision was significantly worse (higher values) in the vertical configuration than in the horizontal configuration. However, orientation did not have a significant effect. Error bars show ± 1 standard error within subjects.

Accuracy. For completeness and to facilitate future comparison with others' results for which mixture modeling is not used, we here report the results with accuracy (proportion correct, for a particular stream) as the dependent variable.

A repeated-measures ANOVA (orientation $\times$ letter stream) of accuracy revealed a significant main effect of orientation $F(3,69) = 51.8$, $p < .001$, $\eta_p^2 = .69$, with a similar pattern as observed in the analysis of efficacy

(canonical $M = 49.7 \pm 2.7$; inverted $M = 40.5 \pm 2.9$; downwards $M = 29.8 \pm 1.6$; upwards $M = 28.8 \pm 1.8$). There was a significant main effect of stream, $F(1,23) = 11.6$, $p = .002$, $\eta_p^2 = .34$, with greater efficacy in the dominant stream ($M = 40.1 \pm 2.2$) than in the non-dominant stream ($M = 34.3 \pm 2.2$), averaged over orientations. The significant interaction between orientation and stream, $F(3,69) = 11.80$, $p < .001$, $\eta_p^2 = .33$, reflected the expected pattern: more left bias in the canonical condition ($M = .18 \pm .02$) than the inverted condition ($M = -.003 \pm .02$), and more top bias in the downward condition ($M = .12 \pm .03$) than the upward condition ($M = -.07 \pm .04$).

Report order. Proportion correct was the same for the target that was queried first ($M = .37 \pm .02$) as for the target that was not queried ($M = .37 \pm .02$). As mentioned for the previous experiment, people may prefer to scan such a memory from left to right, leading to higher performance in the canonical condition when the left stream is queried first. However, as for the previous experiment, there was no support for this (left stream queried first $M = .50 \pm .03$; right stream queried first $M = .50 \pm .03$). The aforementioned figures are not typos—the values were indeed the same down to two decimal places. A general ANOVA also found no significant effect of report order ($F(1,23) = .04$, $p = .83$) nor its interactions (with orientation $F(3,69) = .55$, $p = .65$; with stream $F(1,23) = .03$, $p = .86$; with both for the three-way interaction $F(3,69) = .92$, $p = .44$).

General discussion

The left advantage in the two-target task is large—efficacy (a measure comparable to raw accuracy) was thirty percentage points lower for targets on the right in the baseline, canonical orientation condition. This large left advantage was abolished by presenting the letter in a leftward-facing condition, both in Experiment 1 (mirror-reversed condition) and Experiment 2 (inverted condition). These findings suggest that reading direction is an important contributor to the usual left advantage.

More evidence that the direction letters face determines which stream is disadvantaged was provided by Experiment 2. With one stream above fixation and one below, and with the letters rotated to face downward, performance was superior for the upper

Prioritizing letters in the order of reading letter. When the letters were rotated to face upward, the performance advantage of the upper stream was abolished.

Together, these two experiments indicate that a substantial portion of the differences between the two streams in this task reflects implied reading order. Is there a viable alternative conclusion? In our introduction to Experiment 2, we described how a hemispheric theory might explain the results of Experiment 1, by making some additional assumptions. Experiment 2 used a vertical arrangement to reduce the viability of a hemispheric account, and still we found a large effect of reading direction. The effect of our manipulations was large, in that they appeared to eliminate the left and superior visual field advantages. However, they did not reverse the asymmetries to create a significant right- or lower-stream advantage. In addition to the effect of reading direction, there may well be an underlying hemispheric difference, as is traditionally claimed (e.g., Reuter-Lorenz et al., 1990). But another possible explanation of the incompleteness of bias reversals is the strength of the habit of reading left to right and top to bottom. This tendency to process from left to right, and from top to bottom, may not be entirely overcome by altering the direction that two letters face.

What stages of processing are affected by implied reading direction?

Our mixture modeling method provides some insight into the stages of processing affected by reading direction. The method separates the distribution of serial position errors of each participant into two components, guessing trials and non-guessing trials; and for the Gaussian distribution of errors corresponding to the non-guessing trials, it estimates efficacy, latency, and temporal precision. Efficacy was strongly and consistently affected by implied reading direction, with the large left and top biases eliminated by changing the letters' orientation.

The substantial left and top biases in the baseline conditions were not accompanied by a difference between the advantaged and disadvantaged positions in latency or precision. Dissociations between changes in efficacy and changes in latency and position were also reported by G&H and by Goodbourn et al. (2016), and led G&H to suggest that efficacy is set by a different

processing stage than is latency and precision. Specifically, G&H suggested that as items appear on the screen, they activate representations that persist beyond the appearance of the next item, and that this stage of processing does not differ for the left and the right streams. On this account, the cuing ring activates its own neural representation, which subsequently must be bound to one of the persisting letter representations. The workings of this binding process are obscure, but apparently it sometimes is bound to the target letter and sometimes to a letter that was presented before or after the target. The latency and precision reflect the characteristics of this process of binding that operates on the persisting item representations.

Processing up to and including the level of binding the representation of the cue with that of the letter is thus not thought to differ for the two streams. The difference in processing of the two streams begins, we believe, at a stage of tokenization (Kanwisher, 1987) or memory consolidation (Chun & Potter, 1995). Theorists have suggested that tokenization and memory consolidation are capacity-limited. It is at one of these stages that one of the two streams is prioritized based on reading direction. The activation of the cue-bound letter in the less-prioritized stream decays while it awaits processing resources. By the time the capacity-limited stages have finished with the prioritized letter, the representation of the other one may have fallen below threshold.

Consistent with this theory that binding of the cue to the ring is unaffected by stream prioritization, here we found that latency and precision were not affected by the direction the letters faced, nor by whether they were in the dominant or disadvantaged position. Only one significant effect on latency or precision was observed. It did not seem to reflect the manipulation of letter orientation; rather, it may be an effect of spatial arrangement of the two streams. Precision in the vertical arrangement was 25 ms poorer than in the horizontal arrangement. Vertical versus horizontal arrangement was not the manipulation of primary interest; that was implied reading direction (upward vs. downwards), so letter orientation co-varied with spatial arrangement. A substantial amount of additional work may be needed to understand why precision was poorer in the vertical arrangement. There are few studies of the precision of temporal binding, and those that exist have found it to be

Prioritizing letters in the order of reading quite robust to various stimulus manipulations (Linares, Holcombe, & White, 2009; Holcombe, 2009). General (not necessarily binding) performance on some tasks, however, is poorer for stimuli on the vertical meridian than for stimuli on the horizontal meridian (Abrams, Nizam, & Carrasco, 2012). The possible contribution of poor temporal binding to this difference has not been examined. Carrasco, Giordano, and McElree (2004) found evidence for markedly slower accrual of information from the vertical meridian than from the horizontal meridian, but only if the location was not cued. This should affect latency, but also might affect precision. Yet when Carrasco et al. used exogenous cues, making their task more like ours, no difference was observed, consistent with the lack of a difference in latency observed here. Thus the reason for the precision difference here remains unknown.

The bottleneck isolated?

The attentional blink (AB) task is perhaps the most popular paradigm for studying the limitations of attention. The blink is a deficit in identifying a second target that comes after a first in a rapid stream. We recently applied our mixture modeling technique to data from several attentional-blink experiments, including two with very similar presentation parameters to those of the present study (Goodbourn et al., 2016; Cellini et al., 2015). We found that the efficacy deficit for the second target in the blink is similar in size to the second-target deficit studied here. Moreover, in both cases temporal precision is equivalent for both targets. A difference was found, however, in selection latency, which is delayed for the second target letter (or object) in the attentional blink task but not for the disadvantaged letter here.

Several researchers have found evidence that a disruption of selection contributes to the difficulty encoding the second target in the AB task (Di Lollo, Kawahara, Ghorash, & Enns, 2005; Nieuwenstein, Chun, Van Der Lubbe and Hooge, 2005; Vul, Kanwisher, & Nieuwenstein, 2008; Zhivony & Lamy, in press; Nieuwenstein & Potter, 2006; Wyble, Bowman, Potter, & Nieuwenstein, 2011; Olivers & Meeter, 2008). Both the present findings and earlier ones (Bay & Wyble, 2014; G&H) suggest that selection of *simultaneous* targets is effective, whereas selection of the second of the

successive targets in the AB paradigm is disrupted or delayed. To explain this difference, Bay and Wyble (2014) proposed a convergent gradient-field theory that describes how selection might transiently be allocated to two simultaneous or near-simultaneous targets as effectively as to a single target. Their suggestion can account for both the low latency we documented for simultaneous targets and the longer latency observed for the second target in the attentional-blink paradigm.

Based on our finding of unimpaired selection latency and precision for two simultaneous targets, we suggested that the difficulty in reporting one of them (the right one, when the letters are in the canonical orientation) is due to later, post-selection stages. This deficit in later stages may be identical to the portion of the AB that is unrelated to the disruption of selection. Our task appears to allow study of the difficulty of encoding a second target without the complication of disrupted selection.

Some researchers have suggested that capacity limits play no role in the attentional blink (Olivers & Meeter, 2008; Wyble, Bowman, & Nieuwenstein, 2009) and may also question whether there is any capacity limit that would restrict the identification of just two stimuli. It is certainly a challenge for theories to reconcile the second-target deficit in conditions of simultaneous presentation with the ability to accurately report at least three successive items in a single stream (e.g. di Lollo et al., 2005). Rather than explaining the second-target deficit with a capacity limit, it might be explained by the dynamics of sampling by attention. There is evidence that attention can be briefly allocated equally to two or more locations but after about 100 ms converges on a single location (Dubois, Hamker, & vanRullen, 2009; Bay & Wyble, 2014). In the present experiments however, such convergence does not seem relevant—the succeeding stimulus had already appeared 100 ms after the ring in Experiment 1, and 120 ms after the ring in Experiment 2. The attentional convergence account may still be salvaged, however: although the succeeding stimulus has already been presented by the time attention begins to converge, attention can perhaps converge onto the *internally persisting representation* of the left letter. If it were a post-binding representation, the temporal errors having neither a longer latency nor greater dispersion (poorer precision) would follow.

Prioritizing letters in the order of reading

However, it is unlikely that temporal binding occurs before the action of attention, given the close association of attention with tokenisation, which may be tantamount to binding. To salvage an attentional-convergence account that converges at processing at or earlier than binding, the temporal binding must occur all-or-none. Having less attention on one of the targets would then, despite on some proportion of trials preventing report of a relevant letter entirely, on the remaining trials leave the temporal binding no poorer than when full attention is available. These are important issues for further investigation.

The bottleneck in reading

It has long been known that processing of the initial letter of a string or word is advantaged relative to the terminal letter (Hammond & Green, 1982). But as we argued in the previous section, the two streams of the present experiments seem to be represented separately, rather than as a single object or word. The mechanisms that result in first-letter advantages may therefore be different from those that resulted in prioritizing one stream.

Like the present task, reading involves the rapid processing of letters that appear successively at the fovea. During the gaze fixations of naturalistic reading tasks, behavioral measures show that often more than one word is processed (e.g., Rayner et al., 1981). The spatial span of such processing extends further to the right from fixation than to the left for fluent readers reading left-to-right text. However, for fluent readers of Hebrew reading right-to-left text, this span instead extends further to the left (Pollatsek et al., 1981). EZ-reader theory explains this extension of processing to upcoming word(s) as the result of an attentional shift that occurs after some processing of the fixated word has occurred. The attentional shift is required because the theory posits that only one word can be identified at a time (Reichle et al., 2009). This identification bottleneck may be the reason for the second-letter deficit studied here. The widely separated letters of our task are treated like separate words, we believe (see the previous section). Theories of reading that allow for simultaneous identification of multiple words may find the large second-letter deficit more difficult to explain (Engbert, Longtin, & Kliegl, 2002; Engbert et al., 2005; Reilly & Radach, 2003, 2006).

The models that allow for simultaneous identification of multiple words generally do posit limited capacity, with more processing resources allocated to the fixated word than to

subsequent words. However, as there is ample capacity to process two letters, there is little or no reason to predict that much more resource would be devoted to one of the two targets.

Spatial asymmetries in processing during reading are sometimes explained by a structural mechanism, rather than a flexible attentional shift or attentional gradient. According to *modified receptive field* (MRF) theory (Tydgate & Grainger, 2009), the shape of receptive fields for letter recognition is affected by the language one reads. As a person learns a language that is written left to right, these receptive fields are elongated such that stimuli to the left of a letter cause more interference than stimuli to the right; as a result, the initial letters of a word are subject to less interference than those later in the word. This theory predicts that changing the orientation of letters should not eliminate the left advantage, because it reflects receptive fields that are shaped by years of reading experience. Such structural theories have difficulty explaining our results, and those that apply to individual words such as Tydgate & Grainger have difficulty explaining the effects of letter orientation found by Hommel (1995) and reviewed in the Introduction.

To explain the results found with our dual-RSVP paradigm—especially the temporally symmetric error distributions—we introduced the notion of persistent letter activation that serves as a buffer representing recently-presented letters. Evidence from the study of acquired dyslexia also supports the notion of persistent letter activation. Schubert and McCloskey (2014) studied a patient with acquired dyslexia who made many perseveration errors in a reading task. The task was to read aloud an individual word or pronounceable nonword that was presented on a screen. The patient's response sometimes included intrusions of individual letters from the previous trial. The pattern of errors indicated that representations of the previous trial's letters had persisted, at both an abstract letter-identity level and a letter-shape level. In the present experiments, persistent letter activation was thought to give rise to the time-symmetric error distributions when selecting a letter from a rapid stream. Future work should investigate whether it is the same type of representation that can yield perseveration errors across trials.

The EZ-reader theory has not described a role for representations of not-yet-identified words persisting (buffered) after they are attended or after the eyes have moved on; nor, as far as we know, have any competing computational theories. The evidence reported here that

Prioritizing letters in the order of reading letter activations, apparently at a pre-tokenization stage, persist after disappearance of the stimulus suggests that this should be considered in models of reading. The ability to buffer letters or words expands the realm of possibility for the order of operations in reading and other tasks. The attentional shift posited by EZ-reader, rather than being one that samples the word from early cortex after having processed the previous word, may instead involve sampling from a buffer that contains multiple graphemic representations.

Relation to serial-order memory

In studies of serial-order memory, readers of European languages have been shown to associate sequences of items with positions from left to right. Items presented later in a list are associated with spatial positions further to the right, even when all stimuli are presented at the same position (Rinaldi et al., 2015; van Dijck et al., 2013). These studies further suggest that when people retrieve a list of items in order, they scan a mental representation from left to right, which facilitates retrieval in the correct temporal order. So far, the effect of implied reading order has not been tested in this literature, but it has been suggested that it will have an effect (Abrahamse, van Dijck, Majerus, & Fias, 2014).

In the present experiments, it seems likely that in the canonically-oriented conditions, the left stream's target is represented mentally as associated with a position to the left, and the right target to the right. This relation may be partially or entirely reversed when the letters are oriented so that implied reading order is from right to left. It is also possible that at retrieval and during maintenance, participants habitually scan this mental representation from left to right. However, such processes are not expected to be able to explain the large accuracy advantage for the left stream that we observe with canonically oriented letters. In the experiments cited above, accuracy is very high for all the items (>93%), even though several items must be memorized rather than just the two in our experiment (Rinaldi et al, 2015; van Dijck et al., 2013). Moreover, our finding of no effects of report order do not support a role for retrieval processes in the second-target deficit. It seems that the second-letter disadvantage studied here reflects a process distinct from position-based maintenance and retrieval from short-term memory.

While our effects are therefore unlikely to be rooted at the memory-retrieval stage, it is certainly possible that implied reading order affects *both* retrieval and tokenization or memory consolidation. Indeed, it may be that the first letter consolidated into memory is habitually associated with a position to the left, and thus the two processes are tightly linked. This should be explored in future work.

Coordinate frames and location information

A mental coordinate system must be used to allocate resources differentially to two locations, as a location can only be defined relative to a coordinate frame. To favor the first letter as defined by implicit reading direction, the mind must recognize the orientation of the letters and determine which of the two letters is on the left (for the canonical orientation) or which on the right (for the mirror-reversed or inverted condition). Studies of brain-injured patients have revealed aspects of how such relative spatial locations are represented.

Among patients with parietal neglect, some neglect the left visual field, some neglect the left half of each word, and some neglect the first part of each word, even if the letters are mirror-reversed so that the first part of the word is to the right (Hillis et al., 2005; Haywood & Coltheart, 2001). The reference frame thought to underpin the last phenomenon is sometimes referred to as object-centered or word-centered (Caramazza & Hillis, 1990). Conceivably, it could be critical to the implicit reading-direction bias documented in the present experiments: If the two letters acted like a single word, the word-centered frame would represent the location of the first letter that can then be prioritized for processing. While some scheme for calculating the first letter is clearly needed, we deem it unlikely that it is the same as that used to represent a word. We give our reasons below.

The present experiments used widely separated letters, which did not appear to form a single word or even a group. Moreover, the present finding of a very large advantage for the first letter relative to the last letter is not a typical characteristic of individual-word processing. Although the literature on individual-word recognition does show that the first letters of a word are more informative than the last, the effect is not as large as the left advantage in our dual-RSVP paradigm (e.g.

Prioritizing letters in the order of reading (Blais et al., 2009). The RSVP literature does not seem to note a particularly large advantage either. In pilot experiments with a single RSVP stream of four-letter words (rather than two RSVP streams of individual letters) we have not observed a large advantage for the first two letters. Thus it appears that the bias towards the first letter in our experiments does not reflect a word-centered processing frame and may be unrelated to the processes that yield word-centered neglect and normal word identification.

While two letters within a word may be processed in parallel (Ans, Carbonnel, & Valdois, 1998; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Perry, Ziegler, & Zorzi, 2007; cf. Blais et al., 2009; Davis, 2010; Whitney & Cornelissen, 2008), some evidence indicates that widely spaced letters are identified serially (Risko, Lanthier, & Besner, 2011; Cohen et al., 2008). This serial processing may be a characteristic of the extraction of spatial relationships between arbitrary objects as well as letters. In particular, attentional shifts between objects may be critical to extracting the spatial relationship between them (Holcombe, Linares, & Vaziri-Pashkam, 2011; Franconeri et al., 2011). Our latency results suggest that the two target letters are sampled in parallel, but a subsequent stage may process them serially. Reading experience may have led to this learned visual routine (Ullman, 1984) of beginning with the first letter according to letter orientation. Training monkeys on spatial-relationship judgments can result in parietal neurons tuned to relative location for the trained stimuli (Olson, 2003). Such neurons may be involved in coding the relative location of the letters, in combination with task-related (reading) top-down signals (Filimon, 2016).

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Appendix: No evidence of skewed response distributions

Our model assumes that the distribution of reports informed by the cue (i.e., non-guesses) is sufficiently symmetric so as to be approximated by a Gaussian. This is difficult to verify directly, as the overall response distribution is likely to appear skewed, even if the non-guess component is not. One source of asymmetry is the latency - Unless the peak of the non-guess component falls either exactly at a serial position or falls exactly halfway between two adjacent positions, one of the two adjacent positions is expected to be more frequent than the other.

Here, we present a simulation demonstrating that the distributions we observed are no more skewed than would be expected if non-guess responses were in fact drawn from a symmetrical Gaussian. We simulated distributions from one million participants and calculated the skew of each. To simulate a distribution, first a participant in Experiment 1 was selected at random. The efficacy, latency and precision parameters for that

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participant were then used to generate responses on 100 simulated trials, matching the number of trials per condition in Experiment 1. Responses were generated under the assumption that errors in target responses are normally distributed. The histograms in figure A1 show the distributions of skewness values that should be expected under such a model. Comparing the histograms to the red discs above them, which show the 16 skewness values of the 16 participants' observed error distributions, suggests that all are in the expected range. Standard Bayes factors (inset in the Figure) on the comparison between expected and observed distributions, shown in the figure, indicate that evidence favors the null hypothesis in all cases.

Figure A1. Skewness of simulated and observed serial-position-error (SPE) distributions in Experiment 1. Distributions of the skewness measure (*not* serial position error itself) are shown separately for (a) the left stream in the canonical condition, (b) the right stream in the canonical condition, (c) the left stream in the reversed condition, and (d) the right stream in the reversed condition. In each panel, the histogram of open blue bars shows the distribution of skewness in simulated error distributions ($N = 1\,000\,000$). The dashed red and blue lines show the mean skewness of observed and simulated distributions, respectively. The Bayes factor in red indicates the strength of evidence for the null hypothesis that the mean for the observed distributions does not differ from zero. The Bayes factor in blue indicates the strength of evidence for the null hypothesis that the mean for the observed distributions does not differ from the mean of the distributions simulated under a normal model. Both are greater than one for all four conditions, favoring the null hypothesis that the empirical distributions are not different from the model's distributions.