'Pseudoextinction': Asymmetries in simultaneous attentional selection

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Abstract

We report robust visual field asymmetries associated with selecting simultaneous targets. One letter embedded in a rapid serial visual presentation (RSVP) of letters was encircled by a white ring, cueing it as the target to report. In some conditions, 2 RSVP streams were presented concurrently, and targets appeared simultaneously in both. When only 1 stream was cued, performance was similar regardless of whether it was in the left or right visual field. Cueing 2 streams barely affected performance in the left stream, but performance in the right stream suffered markedly. We term this phenomenon *pseudoextinction*, by analogy to *pseudoneglect* whereby observers bisect lines to the left of center. Such attentional asymmetries are often believed to originate from a processing imbalance between the 2 cerebral hemispheres. But pseudoextinction also occurred with vertically arrayed streams, with higher efficacy in the superior than in the inferior stream. Mixture modeling of errors indicated that pseudoextinction did not affect the temporal precision or latency of selection episodes; rather, only the efficacy of selection suffered. These findings lead us to suggest that pseudoextinction arises because perceptual traces are activated simultaneously in a visual buffer but must be tokenized serially. Observers succeed in selecting simultaneous targets because trace activation occurs in parallel. However, observers often fail to report both targets because tokenization proceeds serially: While 1 target is being tokenized, the other's trace may decay below the activation level necessary for tokenization.

Keywords

Under what conditions can we perceive two things at once, and at what cost? While the classical attentional spotlight theory (Posner, Snyder, & Davidson, 1980) proposes that visual attention occupies one location at a time, more recent evidence from cognitive and neuroimaging studies suggests that attention can be simultaneously allocated to two or more noncontiguous locations. Often, it has been implicitly assumed that when attention is spatially divided, stimuli at each location are processed with equal efficacy. Yet striking spatial asymmetries in selective attention have been observed in both clinical and neurologically healthy populations. This raises the possibility that during simultaneous selection, efficacy is dependent on the visual-field locations of the items to be selected.

In the experiments presented here, we verified that perceptual selection can occur simultaneously for two items presented in different visual field locations. We found that selecting two locations occurs with no cost to the latency or temporal precision of attentional selection relative to selection of a single item. Simultaneous selection was associated, however, with a robust *pseudoextinction* phenomenon: Despite the ability to select two items in parallel, and an absence of visual field differences for single item selection, the ability to report an item's identity was consistently impaired at one location compared with another.

Simultaneous Attentional Selection

Under certain conditions, the attentional spotlight appears to be divisible between two or more spatial locations (Bay & Wyble, 2014; Bichot, Cave, & Pashler, 1999; Dubois, Hamker, & VanRullen, 2009; Duncan, Ward, & Shapiro, 1994; Franconeri, Alvarez, & Enns, 2007; Kawahara & Yamada, 2006; Kyllingsbæk &

Bundesen, 2007; McMains & Somers, 2004, 2005; Morawetz, Holz, Baudewig, Treue, & Dechent, 2007; Muller, Malinowski, Gruber, & Hillyard, 2003). Early evidence of divided attention was provided by Duncan *et al.* (1994), who found that two postmasked letters could be reported accurately when presented briefly and simultaneously at different locations. Bichot *et al.* (1999) asked participants to make judgments about attentional targets (colored digits or oriented gratings) presented either simultaneously or sequentially. Response accuracy was indistinguishable between conditions, suggesting that simultaneous presentation did not impair target encoding. Kyllingsbæk and Bundesen (2007) presented pairs of bars and asked observers to report both the color and the orientation of each. Attention to a single location per trial should have caused statistical dependence between correct reports for pairs of features at the same location, but the authors found reports to be independent for each of the four features. Bay and Wyble (2014) showed that cueing two spatial locations in a rapid serial visual presentation (RSVP) task (Forster, 1970) benefited identification of targets at each of those locations by nearly the same amount as a single cue benefited identification of a single target.

Neuroimaging studies have also provided evidence for split attentional foci. Deploying attention simultaneously in multiple locations enhances blood oxygenation level-dependent (BOLD) signals corresponding to attended locations in retinotopic cortex (McMains & Somers, 2004, 2005; Morawetz, et al., 2007). Similarly, attentional enhancement of steady-state visually evoked potentials (SSVEPs) to stimuli tagged by temporal frequency can be elicited simultaneously in multiple visual field locations (Muller, et al., 2003).

Several studies have indicated that observers required to attend to multiple locations can genuinely divide attention between noncontiguous regions, as opposed to encompassing those locations within a single large attentional spotlight. Precueing the probable locations of two target letters in a briefly presented array increases observers' accuracy for reporting the identity of letters at the cued locations, but not letters at intermediate locations (Awh & Pashler, 2000). Bichot *et al.* (1999; see also Dubois, et al., 2009; Zirnsak, Beuth, & Hamker, 2011) had participants compare two target shapes in an array of eight, after which postmasked letters appeared briefly in the same locations as the shapes; letter report was enhanced at both target locations, but not at locations between the two targets. Likewise, while reporting of targets embedded in RSVP streams is enhanced at two cued locations (Bay & Wyble, 2014), or two locations at which targets have just occurred (Kawahara & Yamada, 2006), it is not enhanced in the interstice.

What are the costs of attending to multiple locations simultaneously? Under some circumstances, splitting the focus of attention does not incur obvious performance deficits: For example, if two targets in multiple object tracking (MOT) are split between the left and the right hemifield, tracking performance for each target is as good as if a single target had been presented (Alvarez & Cavanagh, 2005). Yet dividing attention often comes at a cost, with overall performance worse when two targets must be processed compared with just one (see Duncan, 1980, for an early review). Franconeri *et al.* (2007), for example, found that the spatial precision of location-based attentional selection trades off against the number of regions to be simultaneously selected. Whether or not simultaneous selection incurs an overall cost, it is often assumed that

attentional resources are divided equally among attended locations. However, several lines of evidence have pointed to marked spatial asymmetries in attentional processing; these are briefly reviewed in the two following subsections.

Attentional Asymmetries: Neglect and Pseudoneglect

Despite intact perceptual processing, patients with hemispatial *neglect* fail to attend to objects presented in one visual field—most commonly the left visual field, contralateral to a lesion of the right temporoparietal junction (Rafal, 1994). Spatial asymmetries in attention are also evident in neurologically healthy observers: *Pseudoneglect* (Bowers & Heilman, 1980) is one such asymmetry. It is traditionally revealed in line-bisection tasks, during which observers typically mark a line to the left of its true center (see Jewell & McCourt, 2000, for a review). A leftward attentional bias is also evident in tasks requiring an observer to bisect mental alphabet lines (Nicholls & Loftus, 2007), number lines (Loftus, Nicholls, Mattingley, Chapman, & Bradshaw, 2009), or remembered lines (Darling, Logie, & Della Sala, 2012); to judge the relative brightness of two gradients (the *grayscales task*; Mattingley et al., 2004); to retrieve representations from long-term memory (McGeorge, Beschin, Colnaghi, Rusconi, & Della Sala, 2007); or to mentally construct visuospatial representations (Brooks, Logie, McIntosh, & Sala, 2011). Like its clinical counterpart, pseudoneglect is susceptible to alteration by adaptation to prism goggles that laterally shift the visual scene (Loftus, Vijayakumar, & Nicholls, 2009) and by transcranial direct current stimulation (Loftus & Nicholls, 2012) or theta-burst stimulation of the parietal cortex (Varnava, Dervinis, & Chambers, 2013). Pseudoneglect is often explained by reference to the *activation– orientation* hypothesis (Reuter-Lorenz, Kinsbourne, & Moscovitch, 1990), according to

which attention is biased contralaterally to the more active cerebral hemisphere. Specifically, the right hemisphere is thought to be more active in the above-mentioned tasks, causing a bias toward the left side of space and leading to an exaggerated representation of the left part of the stimulus.

Attentional Asymmetries: Extinction and Pseudoextinction

When items at two or more locations compete for attention, processing at certain locations may be consistently prioritized relative to others. This effect is striking in some patients with temporoparietal lesions, usually of the right hemisphere, who show neglect-like symptoms only in the context of competing stimulation. In such cases of visual *extinction*, patients can usually detect a single stimulus presented to either visual field, but a contralesional stimulus will go undetected when a second stimulus is presented simultaneously to the ipsilesional field (Baylis, Driver, & Rafal, 1993).

Several studies have provided evidence for what might be termed *pseudoextinction*—that is, an analog of visual extinction in neurologically healthy observers. The term has been used to describe visual field performance asymmetries in a bilateral attentional blink task (Scalf, Banich, Kramer, Narechania, & Simon, 2007). In the standard attentional blink paradigm (Raymond, Shapiro, & Arnell, 1992), two target letters are embedded in an RSVP stream of distracter letters. Participants can usually report the earlier target (T1) with ease. However, they regularly fail to detect T2 if it occurs within 200–500 ms of T1—during the so-called "attentional blink." In the bilateral version of the task, T1 and T2 are distributed between different RSVP streams presented to the left and right hemifields. This results in superior T2 reporting (a reduced attentional blink) relative to unilateral arrangements, but the effect is laterally

asymmetric: There is a marked performance advantage when T1 is presented in the right hemifield and T2 in the left, but little or no advantage when T1 is presented in the left hemifield and T2 in the right (Holländer, Corballis, & Hamm, 2005; Holländer, Hausmann, Hamm, & Corballis, 2005; Scalf, et al., 2007; Śmigasiewicz et al., 2010; Verleger, Śmigasiewicz, & Möller, 2011; Verleger et al., 2009).

Scalf *et al.* (2007) suggested that pseudoextinction for sequential stimuli results from a disadvantage of the left cerebral hemisphere in a competition for attentional resources: When targets and distracters are perceptually similar, prior engagement of the left hemisphere (through presentation of T1 in the right visual hemifield) does not hamper processing of T2 directed to the right hemisphere (presented in the left hemifield); yet prior engagement of the attentional system when T1 is presented in the *left* hemifield compromises processing of T2 subsequently presented to the right. This pseudoextinction effect is absent under easy selection conditions, when targets and distracters are perceptually dissimilar; Scalf *et al.* thus proposed that it arises from a serial bottleneck in perceptual *selection* under difficult selection conditions.

However, visual-field asymmetries in *sequential* selection (with two targets presented at different times) are only a partial analog of clinical extinction. A corresponding pattern of deficits in processing sequentially presented lateralized stimuli has certainly been observed in a patient with extinction (di Pellegrino, Basso, & Frassinetti, 1998); similarly, while patients benefit from a valid precue when detecting a single target in either visual field, they are disproportionately impaired when they are initially miscued to the ipsilesional field (Posner, Walker, Friedrich, & Rafal, 1987; Posner, Walker, Friedrich, & Rafal, 1984). Yet the classical definition of the deficit is

extinction to double *simultaneous* stimulation (Anton, 1899; Bender, 1952; Loeb, 1885; Oppenheim, 1885); indeed, spatial extinction is generally maximal under simultaneous presentation (di Pellegrino, et al., 1998; Rorden, Jelsone, Simon-Dack, Baylis, & Baylis, 2009; cf. Cate & Behrmann, 2002). Further, it is not clear whether clinical extinction reflects a failure of perceptual selection. For example, Baylis, Driver, and Rafal (1993) found that extinction was more pronounced when bilaterally presented stimuli were identical on one dimension—either color or shape—but only when the task required the patient to report on that dimension. This implies that the relevant attribute, or *type*, is extracted correctly by the visual system, but it is not available for report; such evidence has led to a common conceptualization of visual extinction as a failure of *tokenization*, or the consolidation of types in working memory (Baylis, Gore, Rodriguez, & Shisler, 2001; Driver, 1996; Ptak & Schnider, 2005; Rorden, et al., 2009).

Extinction-like deficits for simultaneous stimuli can be evoked in neurologically healthy observers using bilateral displays of letters or words (Boles, 1983, 1987, 1990), and full-field visual search displays (Fecteau, Enns, & Kingstone, 2000; Pollmann, 1996, 2000). Pollmann (1996), for example, presented a field of elements and measured reaction time for the detection of a low-salience target in the presence of a singleton pop-out distracter; performance was considerably worse when the target was presented in the left visual field and the distracter in the right, than when the opposite arrangement occurred. The question remains, however, whether in such briefly presented displays—often without a backward mask—visual-field asymmetries are driven by a constraint on *serial perceptual selection*, as may be the case for sequential presentation (Scalf, et al., 2007).

Characterizing an Attentional Selection Episode: Efficacy, Latency, and Precision

In a single-stream RSVP task, a sequence of items is presented rapidly at a single spatial location. When the observer's task is to report a target item defined by co-occurrence with a transient cue, such as an auditory tone or a ring encircling the RSVP stream, analysis of the observer's responses can reveal the temporal properties of an attentional episode (Wyble, Potter, Bowman, & Nieuwenstein, 2011). By *attentional episode*, we refer to a discrete event in which one or more stimuli are selected and encoded to the exclusion of other spatially and temporally proximate stimuli; the task of reporting a target embedded in an RSVP stream thus requires an attentional episode to successfully individuate the target from the distracters. When items are presented sufficiently rapidly, observers often report temporally proximate distracters in place of the target. Aggregated across trials, the distribution of *serial position error* (SPE)—the serial position in the RSVP stream of a reported item relative to the cued target—can reveal properties of the attentional processes underlying temporal selection (Chun, 1997; Martini, 2013; Popple & Levi, 2007; Reeves & Sperling, 1986; Vul, Hanus, & Kanwisher, 2008; Vul, Nieuwenstein, & Kanwisher, 2008).

On some trials, an observer may fail to successfully initiate or complete an episode in response to the cue. In those cases, the observer must guess randomly, contributing a flat, uniform component to the distribution of SPEs. Here, we will refer to the complement—that is, the proportion of trials on which the observer successfully completed a selection episode—as the *efficacy* of selection.

On those trials in which a selection episode succeeds, its average timing may be estimated from the peak of the SPE distribution. When the peak coincides exactly with

the cue, we refer to the *latency* of selection as zero, but it may be delayed with respect to the cue (positive latency) or occur earlier than the cue (negative latency).

Finally, the timing of successful episodes may vary around the mean latency. The temporal *precision* of selection can be estimated by calculating the dispersion in the distribution of SPE for successful trials.

In principle, experimental manipulations may affect any combination of the parameters of efficacy, latency, and precision. Martini (2013) found that the serial position of the target affected the efficacy and latency of selection, but not its temporal precision. Vul, Nieuwenstein and Kanwisher (2008), using an attentional blink paradigm, found that a first episode was minimally affected by the need to select a second target in the same stream, but all three parameters of the second episode were affected by the time between the two targets. To date, however, it is not known how the parameters of an attentional episode are affected by the requirement to select simultaneous targets from two locations.

Summary of Experiments

Here we measure the properties of attentional episodes during simultaneous selection and examine spatial asymmetries in those selection properties. Several past studies have offered evidence of divided attention; but, to our knowledge, none has provided a detailed analysis of spatial asymmetries in attentional episode parameters. Spatial asymmetries in attentional selection have been demonstrated, however, in a wide range of other circumstances. The analyses employed in the present study enable us to estimate the efficacy, latency, and temporal precision of attentional selection at different locations in the visual field, under different conditions.

The current study comprised three experiments. In **Experiment 1**, we compared performance in single-target and dual-target conditions, and showed that dual-target selection is neither delayed nor less temporally precise relative to selection of a single target. Dual-target selection does have an effect, however, on efficacy—the proportion of trials in which the participant reports a letter from around the time of the cue. The efficacy of target selection in the right visual hemifield is adversely affected by the requirement to select a simultaneous target in the left. Yet targets in the left visual hemifield are only marginally affected by the requirement to select and report a simultaneous target from a stream in the right hemifield. We argue that this *pseudoextinction* effect (a target on the left "extinguishing" a target on the right) results from a form of cortical competition, and not from a serial bottleneck in perceptual selection. In **Experiment 2**, we investigated the effects of spatial configuration on simultaneous selection by comparing conditions in which two streams were either situated in the same visual hemifield or distributed across the left and right hemifields. In the different-hemifield condition, we replicated the left visual-field advantage seen in the previous experiment and, in the same-hemifield condition, we found an advantage of the upper (superior) stream over the lower (inferior). These results indicate that pseudoextinction cannot be explained solely by reference to differences between the left and the right cortical hemispheres in their representation or use of information. To rescue a hemispheric theory, we must invoke an additional source of spatial asymmetry such as differences between the dorsal and ventral visual pathways. **Experiment 3** explored this possibility by assessing the interaction between pseudoextinction in horizontal and vertical configurations, using streams arranged diagonally. We found no

differences in efficacy between main-diagonal (superior left, inferior right) and antidiagonal (inferior left, superior right) conditions, with a left-stream advantage in both. This suggests that horizontal and vertical pseudoextinction do not combine or interact; rather, the left–right bias supplants the superior–inferior bias in diagonal arrangements. In the **General Discussion** section, we have considered two families of models that might be proposed to account for our findings. *Hemispheric* models posit that the dual-target spatial asymmetries arise from processing differences between the cerebral hemispheres. *Type-token* models propose that the effects arise from a process by which multiple perceptual types are activated in parallel in an iconic buffer, and must be tokenized for consolidation into short-term memory (STM). Two forms of type–token model are considered. According to a *parallel tokenization* model, pseudoextinction occurs because competitive interactions between the activated types, which are biased in favor of certain visual-field locations, can force items at the extinguished location out of the tokenization process. In comparison, a *serial tokenization* model assumes that tokenization of noncontiguous items must occur serially, and proceeds in a stereotyped spatial path. Pseudoextinction occurs because type activation at the extinguished location dissipates during tokenization of the item at the prioritized location. We argue that the results of our three experiments speak against hemispheric models, and support a serial tokenization account of pseudoextinction over its parallel counterpart.

General Method

Participants

Six experienced observers and 20 naïve observers completed each experiment. Our initial motivation for using the authors and psychophysically experienced colleagues

as observers was to ensure sustained concentration and accurate fixation. However, to increase the number of participants and thus improve statistical power, we replicated each experiment with undergraduate observers. Most observers were right-handed as defined by the Revised Edinburgh Handedness Inventory (EHI-R; Williams, 2010), but a small number were left-handed or ambidextrous (from four to seven per experiment). The EHI-R ranges from –400 (complete left-handedness) to 400 (complete right-handedness); scores above 200 are taken to indicate right-handedness. The results reported here consider all observers as a single group, with each observer's data receiving equal weight. However, all reported effects are highly consistent between subgroups defined by experience or handedness (see General discussion section and Figure 6). The sex and handedness of experienced observers, and the experiments in which each observer participated, are indicated in Table 1; summaries for naïve observers are in the Method section of each experiment.

Apparatus

Experiments were controlled by a MacBook Pro (Apple Inc., Cupertino, CA) with a 2.5 GHz Intel Core i7 processor and 8 GB of RAM, running Mac OSX 10.7.5. They were programmed in MATLAB R2012b (MathWorks, Natick, MA) using Psychtoolbox-3 extensions (Brainard, 1997; Pelli, 1997). Stimuli were processed on a Radeon HD 6770M video card (AMD, Sunnyvale, CA). For experienced observers, they were displayed on a Trinitron® CPDG520 monitor (Sony Corp., Tokyo, Japan) with a spatial resolution of 1024 × 768 pixels and a refresh rate of 120 Hz; for naïve observers, they were displayed on a Diamond View® DV154MT-C TFT LCD monitor (Mitsubishi Electric Australia, Rydalmere, Australia) with a spatial resolution of 1024 ×

768 pixels and a nominal refresh rate of 60 Hz. Experiments were conducted in a

darkened room. Observers used a chinrest to maintain a viewing distance of 57 cm, and

provided responses using a standard Apple mouse.

Table 1.

Experienced Observer Sex and Handedness

Observer	Experiments			Sex	EHI-R
	1	2	3		
P.T.G.	•	•	•	M	+325
A.O.H.		•		M	–200
S01	•			M	+400
S02	•			F	+350
S03	•			M	+400
S04	•	•		M	+375
S05	•	•		M	+400
S06		•		F	+300
S07		•		F	–350
S08			•	M	+375
S09			•	F	–275
S10			•	F	+325
S11			•	M	+200
S12			•	M	+300
Total	6	6	6	5 F + 9 M	

Note: EHI-R scores can range from –400 (complete left handedness) to +400 (complete right handedness). EHI-R: Edinburgh Handedness Inventory (Revised) score; F: female; M: male.

Stimuli

Stimuli were white uppercase letters rendered in Sloan font (Committee on

Vision, 1980; Pelli, Robson, & Wilkins, 1988) at a luminance of 82 cd/m^2, presented on

a dark background of less than 1 cd/m^2. Each letter had a maximum vertical and

horizontal subtense of 4.0°. A stream comprised a serial presentation of 24 letters,

ordered according to a random permutation of the English alphabet. The letters C and

V were excluded, because our pilot studies indicated that they were particularly

confusable with other letters. Each stream could appear at one of four possible locations.

The locations were equally spaced around the circumference of an imaginary circle of radius 6.0°, such that there was one location in each of the left superior, right superior, left inferior and right inferior visual-field quadrants. Fixation was a white circle subtending 0.25°, located at the center of the screen. Figure 1a shows the spatial properties of the stimuli.

The presentation rate was 12 items per second, with a presentation interval of 50 ms (six CRT monitor frames, or three LCD monitor frames), followed by a blank interval of 33 ms (four CRT monitor frames, or two LCD monitor frames) per item. In dual-target conditions, target letters were always simultaneous in both streams. Targets could appear in any serial position from the seventh to the 18th inclusive, with equal probability. They were indicated by a visual cue, which was a white ring with a subtense of 5.0° and a thickness of 0.1° surrounding each target letter. Cues were of 50 ms duration, with abrupt onset and offset synchronized to the target. Figure 1b shows the temporal properties of the stimuli.

Procedure

Precues. In most conditions, visual precues indicated the spatial locations of the RSVP streams on that trial. Each precue comprised a white ring with a subtense of 5.0° and a thickness of 0.1°. Precues were presented for 250 ms, and the first frame of the RSVP stimulus appeared 1.0 s after precue onset.

Responses. A response screen appeared 500 ms after offset of the final RSVP item. On the response screen, the former locations of the streams were marked with a dash. The set of response alternatives (the 24 possible letters) was arrayed in two places,
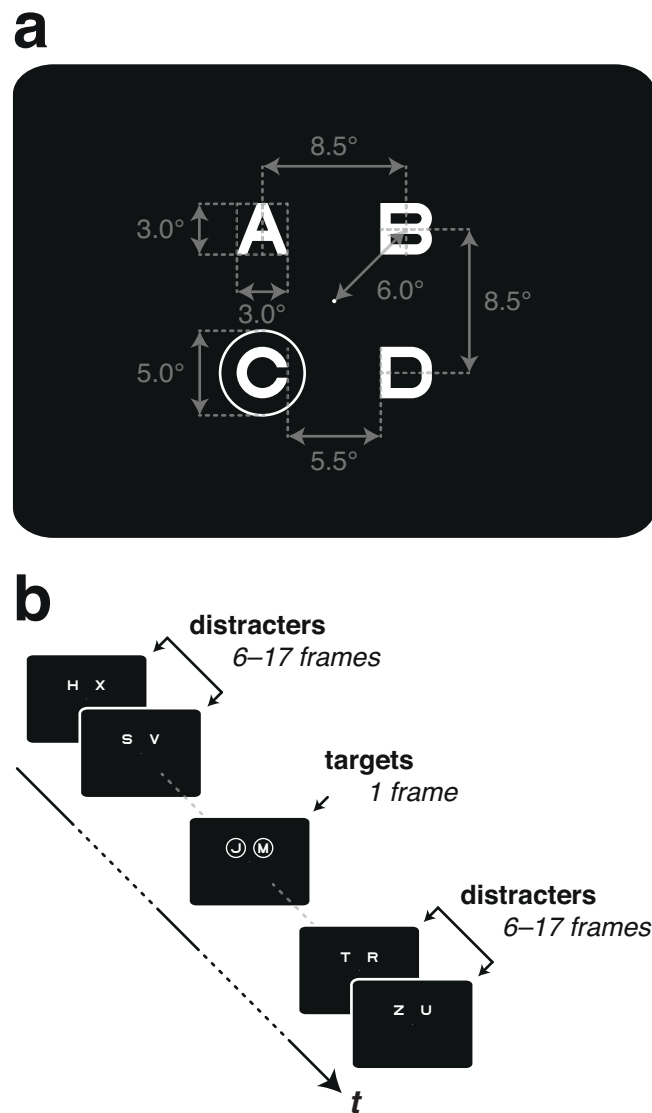
Figure 1. Spatial and temporal properties of the stimulus. Panel (**a**) shows a schematic diagram of the possible locations of rapid serial visual presentation streams. In most conditions, two streams were present on any one trial, located in the superior left quadrant (Stream A), superior right quadrant (Stream B), inferior left quadrant (Stream C) or inferior right quadrant (Stream D). Here, the visual cue used to denote a target letter is shown in stream C. Panel (**b**) shows a schematic diagram of the temporal properties of the stimulus. Each trial consisted of 24 frames separated by blank intervals, presented at a rate of 12 frames per second. The targets could appear on any of the middle 12 frames (the seventh to the 18th inclusive).

one near each of the former stream locations. In the *bilateral* conditions (Streams A and B or Streams C and D, in Figure 1a), vertical arrays were positioned on the left and

right of the screen for report of the left and right targets. In the *unilateral* conditions (Streams A and C or Streams B and D), horizontal arrays were positioned at the top and bottom of the screen for report of the superior and inferior targets. In *diagonal* conditions, arrays were either vertical and positioned on the left and right, or horizontal and positioned at the top and bottom; these two alternatives were balanced across trials. In *single-target* conditions, only one array appeared, either on the left or the right of the screen, corresponding to the position of the target to be reported.

For each condition involving two streams, we randomly varied the order in which the participants were required to report the targets. The array of letters corresponding to the first stream from which the participant was required to report was white until the participant's first response, while the other array was drawn in gray. Observers used the mouse to select the target letter from the white array, at which point the selected letter appeared at the corresponding stream location. Observers were free to reselect as many times as desired, after which the response was confirmed by selecting a button marked "OK" at the center of the screen. In dual-target conditions, the second array became white after the first response was confirmed, and the process was repeated. No feedback was provided. The precue for the subsequent trial appeared 2.0 s after confirmation of the final response.

Blocks and sessions. There were four blocks of 25 trials per experimental session. Conditions within an experiment were either blocked and counterbalanced with a Latin-square design (Experiment 1) or randomly interleaved (Experiments 2 and 3). Each experienced observer completed four sessions per experiment, resulting in 100 trials (Experiment 1) or 200 trials (Experiments 2 and 3) per condition. Each naïve

observer completed two sessions per experiment, resulting in 100 trials per condition. Observers completed practice trials prior to the first session, six trials (Experiment 1) or 12 trials (Experiments 2 and 3) per condition.

Analysis

Serial position error. For each stream on each trial, the SPE was calculated as the difference between the serial position of the reported item and the serial position of the target item. Thus, a correct report of the target item would correspond to an SPE of 0; a report of the item preceding the target would correspond to SPE = –1; and a report of the item following the target would correspond to an SPE of +1. Figure 2a shows a sample distribution of SPE for a single condition across a full experiment.

Mixture model. We assumed that a distribution of SPE comprises two categories of trial: (a) *target-related* trials in which the response was informed by the cue, and (b) *guess* trials in which the response was a guess. (The latter type could also some include trials in which the reported item was confused with another similar letter, and trials in which the reported item was drawn from another concurrent RSVP stream.) We expected target-related trials to be drawn from a probability distribution with a modal value not far from SPE = 0. Here, we assumed a Gaussian distribution, which provided excellent fits for our dataset. We expected guess trials to be drawn from a uniform probability distribution across the full range of possible SPE values. Thus, the SPE distribution should be a windowed Gaussian–uniform mixture,

$$f(x, p_T, \mu, \sigma) = W(x) \left[\left(\frac{p_T}{c_{\mathcal{N}}} \right) \mathcal{N}(x, \mu, \sigma) + \left(\frac{1 - p_T}{c_U} \right) U(x) \right],$$
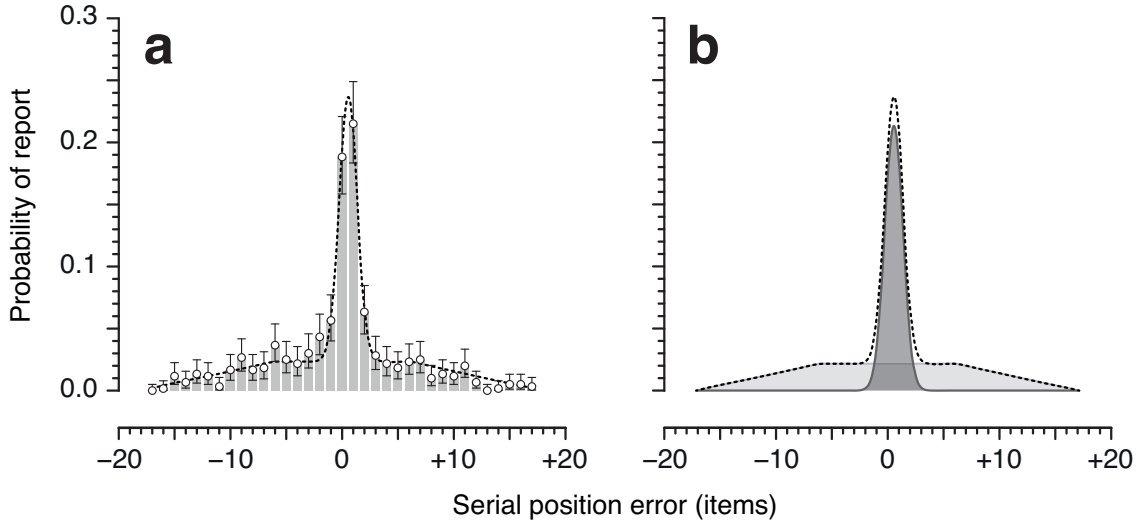
(Equation 1)

Figure 2. Example analysis and mixture model. Panel (**a**) shows an example distribution of serial position error (SPE) for a single stream in one condition. Light bars represent the proportion of trials on which a particular error value was observed; error bars show bootstrapped 95% confidence intervals. The dotted line shows the mixture model fit to the data. Panel (**b**) shows the mixture model fit to the distribution of SPE. The model comprises a mixture of two distributions: a pseudo-Gaussian distribution accounting for target-related responses (dark shading), and a pseudouniform distribution accounting for random guesses and errors caused by letter confusions (light shading). The dashed line is the sum of the distributions. Efficacy is defined as the proportion of trials on which a target-related item was selected; that is, the mixture proportion of the pseudo-Gaussian distribution. Latency and precision of selection are defined as the mean and standard deviation of the pseudo-Gaussian distribution, respectively.

where x is SPE, p_T is the mixture proportion of the Gaussian distribution from which target-related trials are drawn, $\mathscr{N}(x,\mu,\sigma)$ is the Gaussian distribution with mean μ and standard deviation σ, and $U(x)$ is the uniform distribution. An extreme negative serial position can only occur when the target appears late in the stream, and an extreme positive serial position can only occur when the target appears early in the stream; thus the Gaussian–uniform mixture is windowed by $W(x)$, a uniform distribution tapered at its extrema,

$$W(x) = \begin{cases} 0 & x \leq -SP_l \\ SP_l + x & -SP_l < x < (1 - SP_f) \\ SP_l - SP_f + 1 & (1 - SP_f) \leq x \leq (SP_t - SP_l - 1) \\ SP_t - SP_f - x & (SP_t - SP_l - 1) < x < (SP_t - SP_f + 1) \\ 0 & x \geq (SP_t - SP_f + 1) \end{cases} \text{, (Equation 2)}$$

where SP_f is the first serial position in which the target could appear, SP_l is the last serial position in which the target could appear, and SP_t is the total number of items in the stream. As the integral of the overall mixture must be equal to 1, normalizing constants apply to the windowed mixture components: $C_{\mathcal{N}}$ is the normalizing constant for the windowed Gaussian distribution,

$$C_{\mathcal{N}} = \sum_{x=-SP_l}^{SP_t - SP_f + 1} W(x) \, \mathcal{N}(x, \mu, \sigma) \,, \qquad \text{(Equation 3)}$$

and C_U is the normalizing constant for the windowed uniform distribution,

$$C_U = \sum_{x=-SP_l}^{SP_t - SP_f + 1} W(x) U(x) \,. \qquad \text{(Equation 4)}$$

The $W(x)$ distribution is tapered below SPE = –6 and above SPE = +6, which is determined by the number of items in the stream and possible target positions. Targets could appear in any of the middle 12 of 24 serial positions; thus SPEs between –6 and +6 (inclusive) were possible on every trial. However, SPEs below –6 and above +6 were only possible when the target appeared in certain positions. For example, an SPE of +17 was only possible on trials in which the target appeared in the earliest serial position (i.e. the seventh item), which occurred once in every 12 trials on average.

We fit the Gaussian–uniform mixture (Equation 1) to the empirical distribution of SPE separately for each observer, condition, and location. We used a likelihood maximization procedure, repeated 100 times with different randomized starting values

for the three free parameters. Figure 2b shows an example of a maximum likelihood fit of the mixture model to an empirical distribution of SPE.

The *efficacy* of selection was defined as the mixture proportion of the Gaussian distribution (p_T in Equation 1); that is, the number of target-related trials as a proportion of the overall number of trials. The *latency* of selection was defined as the mean of the Gaussian distribution (μ in Equation 1); that is, the average SPE for target trials. The temporal *precision* of selection was defined as the standard deviation of the Gaussian distribution (σ in Equation 1); that is, the dispersion of SPE around the average value for target-related trials. We have reported latency and precision in milliseconds; in a pilot study, we found these parameters were inversely proportional to presentation rate when considered as a number of items, but were relatively invariant with presentation rate when considered as an amount of time. This is consistent with the findings of previous studies (Martini, 2013; Vul, Hanus, & Kanwisher, 2008).

Initially, we also fit the model to SPE distributions derived by calculating the difference between the serial position *in the other stream* of the reported item, and the serial position of the target item. Here, the Gaussian mixture component would capture *reversal* trials, in which a letter is reported in the wrong location, while the uniform component would capture both target trials and guess trials. Thus the mixture proportion of the Gaussian distribution for each stream estimates the proportion of trials on which an item selected in the other stream was accidentally reported in that stream. We found that this almost never occurred, so we have not reported the outcome of these analyses here. A similar finding has been reported in at least one previous study (Bahcall & Kowler, 1999).

Statistical tests. After fitting the models, we performed within-subjects tests on each of the parameters to determine whether they differed between conditions and stream locations. An observer's data were excluded from statistical analysis if they failed to demonstrate simultaneous selection (i.e., efficacy was indistinguishable from zero in one or both streams) in *all* dual-target conditions within an experiment. Data were analyzed using either analysis of variance (ANOVA) or *t* tests, depending on the design of the particular experiment. Where effects describe a difference between a pair of experimental factors, we have reported parametric 95% confidence intervals (CIs) on the mean difference. Further details of the statistical analysis are given in the Method section of each experiment.

Experiment 1: Dual-Target Versus Single-Target Selection

In Experiment 1, we compared conditions under which observers were required to select a single target with a condition requiring selection of two simultaneous targets. The aim of the experiment was to evaluate the costs of dual-target selection compared with single-target selection, and to examine whether costs were equivalent for attentional episodes sampling from the left and right visual hemifields.

Method

Participants. Experienced observers were one of the authors (P.T.G.) and five colleagues unaware of the aims of the experiment. Naïve observers were 20 undergraduates (13 female) ranging in age from 17–25 years (*Mdn* = 19.0 years, *M* = 19.6, *SD* = 2.3), with EHI-R scores ranging from –200 to 400 (*Mdn* = 388, *M* = 288, *SD* = 191). One experienced and one naïve observer showed zero efficacy in at least one

stream in the dual-target condition; their data were excluded from the analysis, although their results were otherwise consistent with those of other observers.

Stimuli. Streams could be located in the superior left and superior right quadrants (streams A and B in Figure 1a). In the *dual-target* condition, both streams appeared on all trials, and the observer was asked to report both targets. In the *single-target* condition, both streams appeared on all trials, but a target was cued in only one of the streams; the observer was asked to report only the cued target. In the *single-precue* condition, one of the two locations was precued to indicate the stream from which the target should be reported. Both streams appeared on all trials, and cues appeared in both streams, but the observer was asked to report only the target in the precued stream. In the *single-stream* condition, one of the two locations was precued, and a single stream appeared in that location; the observer was asked to report the target in that stream. Experienced observers completed all four conditions, while naïve observers completed the *dual-target* and *single-target* conditions only.

Statistical tests. In Experiment 1, visual field locations could be equated across all conditions. Stream location (two levels) and condition (for experienced observers, four levels; for combined experienced and naïve observers, two levels) constituted the two factors of a repeated-measures analysis of variance (ANOVA) performed for each parameter. We have reported eta-squared as a measure of effect size. ANOVA analyses were conducted using SPSS Statistics for Mac, Version 21.0 (IBM Corp., Armonk, NY); eta-squared was calculated manually from the SPSS output.

Results

Efficacy. Efficacy as a function of condition and hemifield is shown in Figure 3a. We conducted a two-way, repeated-measures ANOVA with Condition (dual-target and single-target) and Hemifield (left and right) as within-subject factors, using data from all observers. The ANOVA revealed a significant main effect of Condition on efficacy, $F(1, 23) = 66.60$, $p \ll .001$, $\eta^2 = .31$, 95% CI [0.11, 0.19]; a significant main effect of Hemifield on efficacy, $F(1, 23) = 21.72$, $p \ll .001$, $\eta^2 = .14$, 95% CI [0.06, 0.14]; and a significant Condition × Hemifield interaction, $F(1, 23) = 25.40$, $p \ll .001$, $\eta^2 = .15$. Tests of simple effects by Hemifield showed lower efficacy in the dual-target than in the single-target condition for both the left hemifield, $p = .03$, Dunn-Šidák correction, 95% CI [0.01, 0.09], and the right hemifield, $p \ll .001$, 95% CI [0.18, 0.32]. Tests of simple effects by Condition showed higher left-hemifield than right-hemifield efficacy in the dual-target condition, $p \ll .001$, 95% CI [0.13, 0.28], but no difference between left-hemifield and right-hemifield efficacy in the single-target condition, $p = .871$, 95% CI [−0.05, 0.04].

Experienced observers completed two additional single-target conditions. Using their data, we conducted an additional two-way, repeated-measures ANOVA with Condition (dual-target, single-target, single-precue and single-stream) and Hemifield (left and right) as within-subject factors. The ANOVA revealed a significant main effect of Condition on efficacy, $F(3, 12) = 7.20$, $p = .005$, $\eta^2 = .34$; no significant main effect of Hemifield on efficacy, $F(1, 4) = 0.91$, $p = .395$, $\eta^2 = .01$, 95% CI [−0.12, 0.06]; and a significant Condition × Hemifield interaction, $F(3, 12) = 20.51$, $p \ll .001$, $\eta^2 = .34$. Tests of simple effects by Hemifield revealed no significant differences ($p > .05$ for

all pairwise comparisons). Tests of simple effects by Condition showed higher left-hemifield than right-hemifield efficacy in the dual-target condition, $p = .010$, 95% CI [0.09, 0.36]; higher right-hemifield than left-hemifield efficacy in the single-target condition, $p = .011$, 95% CI [0.05, 0.20]; and no difference between left-hemifield and right-hemifield efficacy in the single-precue and single-stream conditions (ps > .05). In summary, the right-hemifield disadvantage specific to the dual-target condition was documented again. There was also a small right-hemifield *advantage* in the single-target condition.

Figure 3. Results of Experiment 1. In the *dual-target* condition, targets appeared in each of two streams. In the *single-target* condition, a single target appeared in one of the two streams. In the *single-precue* condition, a single target appeared in one of the two streams; cues appeared in both streams, but a target stream was cued prior to each trial. In the *single-stream* condition, a single target appeared in a single stream. All observers ($N = 24$) completed the dual-target and single-target conditions; experienced observers ($n = 5$) completed the single-precue and single-stream conditions. Panel (**a**) shows efficacy for each condition and hemifield. Panel (**b**) shows latency for each condition and hemifield. Panel (**c**) shows precision for each condition and hemifield. Panel (**d**) shows the correlogram of left-stream versus right-stream serial position error for the dual-target condition.

Latency. Latency as a function of Condition and Hemifield is shown in Figure 3b. A two-way, repeated-measures ANOVA revealed no significant main effect of Condition on latency, $F (1, 23) = 2.30$, $p = .143$, $\eta^2 = .03$, 95% CI [−18.8, 2.5 ms]; no

significant main effect of Hemifield on latency, $F(1, 23) = 0.77$, $p = .391$, $\eta^2 = .02$, 95% CI [–18.3, 6.9 ms]; and no significant Condition × Hemifield interaction, $F(1, 23) = 0.25$, $p = .620$, $\eta^2 = .00$. As an additional check for the dual-target condition, a paired t test showed no difference in latency between the left hemifield and the right hemifield, $t(23) = –1.03$, $p = .315$, $d = 0.21$, 95% CI [–26.1, 8.8 ms].

For experienced observers, using data from all four conditions, a two-way, repeated-measures ANOVA revealed no significant main effect of Condition on latency, $F(3, 12) = 0.26$, $p = .853$, $\eta^2 = .01$; no significant main effect of Hemifield on latency, $F(1, 4) = 0.11$, $p = .757$, $\eta^2 = .02$, 95% CI [–51.1, 40.2 ms]; and no significant Condition × Hemifield interaction, $F(3, 12) = 1.47$, $p = .271$, $\eta^2 = .04$.

Precision. Precision as a function of Condition and Hemifield is shown in Figure 3c. A two-way, repeated-measures ANOVA revealed no significant main effect of Condition on precision, $F(1, 23) = 1.73$, $p = .202$, $\eta^2 = .04$, 95% CI [–4.2, 19.0 ms]; no significant main effect of Hemifield on precision, $F(1, 23) = 0.32$, $p = .577$, $\eta^2 = .00$, 95% CI [–6.0, 10.5 ms]; and no significant Condition × Hemifield interaction, $F(1, 23) = 0.28$, $p = .604$, $\eta^2 = .00$. As an additional check for the dual-target condition, a paired t test showed no difference in precision between the left hemifield and the right hemifield, $t(23) = 0.05$, $p = .964$, $d = 0.01$, 95% CI [–12.4, 13.0 ms].

For experienced observers, using data from all four conditions, a two-way, repeated-measures ANOVA revealed no significant main effect of Condition on precision, $F(3, 12) = 1.65$, $p = .230$, $\eta^2 = .29$; no significant main effect of Hemifield on precision, $F(1, 4) = 0.01$, $p = .942$, $\eta^2 = .00$, 95% CI [–32.4, 30.6 ms]; and no significant Condition × Hemifield interaction, $F(3, 12) = 1.28$, $p = .327$, $\eta^2 = .24$.

Correlogram. The correlogram relating left-hemifield SPE to right-hemifield SPE for the dual-target condition is shown in Figure 3d. The most common combinations of left-hemifield and right-hemifield error corresponded to items that were presented simultaneously: Observers most often reported the item following the target in both streams (SPE = +1).

Discussion

Observers were able to report targets that appeared simultaneously in different spatial locations. In the dual-target condition, we observed no difference in the latency of selection between left and right hemifields; and the most common occurrence was reporting letters with the same SPE in both hemifields. Furthermore, there were no temporal costs associated with selection of two simultaneous targets compared with selection of a single target: neither latency nor precision of selection differed between the dual-target condition and the single-target conditions.

Although the temporal parameters of latency and precision were invariant between hemifields and across conditions, the efficacy of selection varied substantially. For those single-target conditions in which the target location was precued (*single-precue* and *single-stream*), efficacy did not differ significantly in the two hemifields. When the target location was not precued (*single-target*), efficacy was marginally higher in the right hemifield than in the left hemifield for experienced observers, and did not differ significantly between hemifields for naïve observers. In contrast, in the dual-target condition, efficacy was strikingly higher in the left hemifield than in the right hemifield. Although for the left hemifield, efficacy in the dual-target condition was similar to that

of the single-target condition, for the right hemifield, a striking decrease in efficacy resulted from the requirement to also report a target in the opposite hemifield.

Could eye movements have influenced these results? Observers were instructed to fixate centrally, but eye movements were not monitored. Thus, observers might have moved their eyes to fixate on the precued stream in the *single-precue* condition, and on the solitary stream in the *single-stream* condition. This would be problematic, because single targets might not be constrained to the appropriate retinal eccentricity and visual hemifield. However, we believe that this is unlikely, for two reasons. First, our experienced observers were practiced at fixation, and only they completed the two conditions in question. Second, if observers had benefited from moving their eyes in these conditions, we would expect their performance to be better than in the *single-target* condition, in which two streams were present and there was no precue to indicate the target stream. Yet performance was equivalent in all three conditions that required report of a single target.

Experiment 1 was a demonstration of pseudoextinction to double simultaneous stimulation in neurologically healthy observers. Importantly, we found no evidence of a left-hemifield advantage—instead, some indication of a right-hemifield advantage— when selection was required from a single, lateralized stream. As in past studies that have reported much more substantial visual field differences in bilateral than in unilateral displays (Boles, 1983, 1987, 1990; Fecteau, et al., 2000; McKeever, 1971), pseudoextinction was only revealed when simultaneous selection was required across two streams. The effect, then, is due to cortical *competition* in the use of information

directed to each hemisphere, rather than inherent differences in the *representation* of that information (Boles, 1983; Fecteau, et al., 2000).

Scalf *et al.* (2007) proposed that the extinction-like phenomenon they observed for sequential targets resulted from competition at the level of perceptual selection. Specifically, sequential presentation caused a serial bottleneck in selection when an initial target presented in the left hemifield—and presumably directed to the right cerebral hemisphere—had already engaged the attentional system. For the present phenomenon, however, we can rule out serial selection, because it would have been discernible in our examination of response errors. In light of our evidence that perceptual selection proceeds in parallel, pseudoextinction to double simultaneous stimulation must arise from other forms of cortical competition.

Experiment 2: Bilateral Versus Unilateral Presentation

Experiment 1 showed that participants could select simultaneous targets when those targets were distributed between the left and the right visual hemifields. In MOT, the relevant attentional resources appear to be independent—or that competitive interference between targets is virtually absent—when targets are distributed across hemifields in this manner; yet there are considerable costs when multiple targets are tracked within the *same* hemifield (Alvarez & Cavanagh, 2005; Holcombe & Chen, 2012). Similar constraints apply to certain other attentional tasks (Alvarez, Gill, & Cavanagh, 2012; Holt & Delvenne, 2014). Thus in the present task, we tested whether simultaneous selection is possible when targets are distributed between hemifields, but becomes difficult or impossible when both targets are contained within the same hemifield. To investigate this possibility, in Experiment 2, we compared the selection of

simultaneous targets between hemifields with the selection of simultaneous targets within a hemifield.

Method

Participants. Experienced observers were the two authors and four colleagues unaware of the aims of the experiment. Naïve observers were 20 undergraduates (10 female) ranging in age from 18–24 years (Mdn = 19.0 years, M = 19.4, SD = 1.6), with EHI-R scores ranging from –150 to 400 (Mdn = 350, M = 286, SD = 162). Three naïve observers showed zero efficacy in at least one stream in both conditions; their data were excluded from analyses, although their results were otherwise consistent with those of other observers.

Stimuli. In the *bilateral* condition, streams were located either in the superior left and superior right quadrants (streams A and B in Figure 1a), or in the inferior left and inferior right quadrants (streams C and D). In the *unilateral* condition, streams were located either in the superior left and inferior left quadrants (streams A and C), or in the superior right and inferior right quadrants (streams B and D).

Statistical tests. We pooled data from two subconditions in each of two conditions, and fit a single model for each condition. Data for the *bilateral* condition included data for the *bilateral-superior* subcondition, in which streams were located in the superior left and superior right quadrants, and the *bilateral-inferior* subcondition, in which streams were located in the inferior left and inferior right quadrants. To compare parameters in different conditions and at different locations, we used a series of between-subjects paired t tests. We assessed (a) whether a parameter differed between locations in the bilateral condition; (b) whether a parameter differed between locations

in the unilateral condition; (c) whether the parameter value, collapsed across locations, differed between bilateral and unilateral conditions; and (d) whether the absolute difference between parameter values across locations differed between bilateral and unilateral conditions. The latter measure indicated whether any asymmetry between stream locations was of a similar magnitude between experimental conditions. We have reported Cohen's *d* as a measure of effect size. Analyses were conducted using MATLAB.

Results

Efficacy. Efficacy as a function of condition and stream location is shown in Figure 4a. In the bilateral condition, a paired *t* test showed higher efficacy in the left stream than in the right stream, $t(22) = 8.70$, $p \ll .001$, $d = 1.81$, 95% CI [0.26, 0.42]. In the unilateral condition, efficacy was higher in the superior stream than in the inferior stream, $t(22) = 8.32$, $p \ll .001$, $d = 1.74$, 95% CI [0.30, 0.50]. Consistent with semi-independent resources for the two hemifields, mean efficacy was higher in the bilateral condition than in the unilateral condition, $t(22) = 6.52$, $p \ll .001$, $d = 1.36$, 95% CI [0.08, 0.16]. The absolute difference between streams—that is, the magnitude of the difference in efficacy between left and right streams in the bilateral condition, and between superior and inferior streams in the unilateral condition—did not differ statistically between conditions, $t(22) = -1.32$, $p = .199$, $d = 0.28$, 95% CI [−0.15, 0.03]. This indicated that the decrement in efficacy of selection at the extinguished location was comparable in unilateral and bilateral conditions.

Latency. Latency as a function of condition and stream location is shown in Figure 4b. There was no statistical difference in latency between left and right streams in the bilateral condition, $t(22) = -1.47$, $p = .156$, $d = 1.20$, 95% CI [−23.3, 4.0 ms]; and

no difference between superior and inferior streams in the unilateral condition, t (17) = −0.47, p = .646, d = 0.73, 95% CI [−35.8, 22.8 ms]. Mean latency did not differ between conditions, t (22) = −0.20, p = .216, d = 0.04, 95% CI [−16.3, 13.4 ms]; nor did the absolute difference between streams, t (17) = −1.28, p = .216, d = 0.30, 95% CI [−41.6, 10.1 ms].
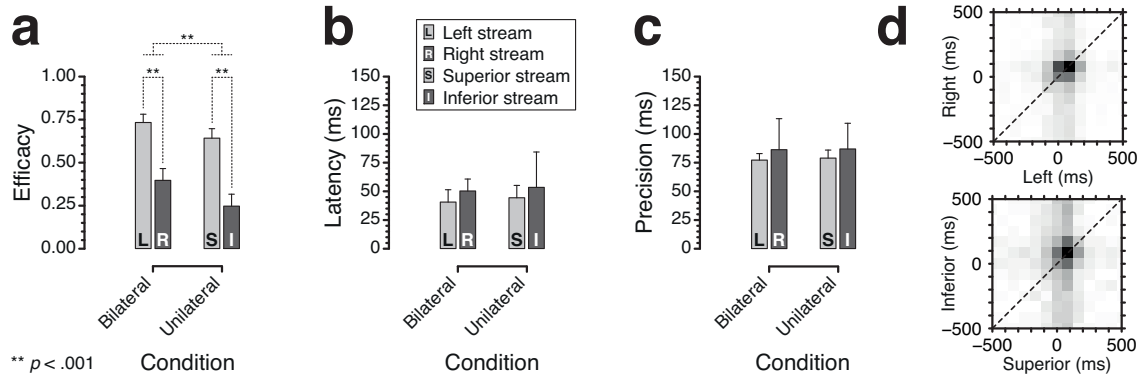

Figure 4. Results of Experiment 2. In the *bilateral* condition, streams were arrayed horizontally, with one in each hemifield. In the *unilateral* condition, streams were arrayed vertically, both in the same hemifield. Panel (**a**) shows efficacy for each condition and stream location. Panel (**b**) shows latency for each condition and stream location. Panel (**c**) shows precision for each condition and stream location. Panel (**d**) shows correlograms of left-stream versus right-stream serial position error (SPE) for the bilateral condition (upper panel) and of superior-stream versus inferior-stream SPE for the unilateral condition (lower panel).

Precision. Precision as a function of condition and stream location is shown in Figure 4c. There was no statistical difference in precision between left and right streams in the bilateral condition, t (22) = −0.69, p = .498, d = 0.70, 95% CI [−36.5, 18.3 ms]; and no difference between superior and inferior streams in the unilateral condition, t (17) = −0.73, p = .475, d = 0.59, 95% CI [−32.1, 15.6 ms]. Mean precision did not differ between conditions, t (22) = −0.04, p = .967, d = 0.01, 95% CI [−19.3, 18.5 ms]; nor did the absolute difference between streams, t (17) = 0.37, p = .718, d = 0.09, 95% CI [−22.1, 31.5 ms]

Correlograms. The correlogram of left-hemifield SPE versus right-hemifield SPE for the bilateral condition, and the correlogram of superior-hemifield SPE versus inferior-hemifield SPE for the unilateral condition, are shown in Figure 4d. In both conditions, the most common combinations of left-hemifield and right-hemifield reports comprised items that were presented simultaneously: The modal report was of the item following the target in both streams (SPE = +1).

Discussion

Experiment 2 replicated and extended the findings of Experiment 1, showing simultaneous selection when targets were presented within the same hemifield as well as when they were distributed between hemifields: Latency and temporal precision were indistinguishable in the two streams, in both conditions. Placing both streams in the same hemifield did not incur a temporal cost relative to distributing them between hemifields. As in Experiment 1, we observed higher efficacy in the left than in the right visual field; additionally, we observed a similar efficacy advantage for the superior stream over the inferior stream in unilateral conditions.

Mean efficacy was higher in bilateral conditions than in unilateral conditions, suggestive of less competition or greater resource independence when the streams were distributed between hemifields. These findings are consistent with previous research that has demonstrated an advantage for processing multiple stimuli presented between hemifields compared with within hemifields (Alvarez & Cavanagh, 2005; Awh & Pashler, 2000; Davis & Schmit, 1971; Sereno & Kosslyn, 1991). However, the advantage we observed in the bilateral condition may not inevitably follow from simply

dividing targets between the two hemifields; we explore this issue in Experiment 3, and the results lead us to posit another reason for the bilateral advantage.

The absolute difference in efficacy between the two streams did not differ between the two conditions, suggesting that pseudoextinction is just as pronounced in a vertical, unilateral arrangement as it is in a horizontal, bilateral arrangement. Although a theory of pseudoextinction based on hemispheric competition might be capable of explaining the left-hemifield advantage in bilateral processing, it cannot straightforwardly explain the superior-stream advantage when two streams are presented in the same hemifield. Past reports of such superior–inferior differences sometimes have been attributed to putative differences in connectivity of the superior and inferior visual fields to the dorsal and ventral visual streams (e.g., Edwards & Badcock, 1993; Fecteau, et al., 2000; Previc, 1996); a hemispheric account might thus be preserved by proposing that left–right pseudoextinction is mediated by a form of cortical competition that is different from superior–inferior pseudoextinction. In this case—given that the effect was equally strong across both axes—we would expect to see evidence of both forms of competition when stimuli are divided across both the horizontal and vertical midlines. We tested this prediction in Experiment 3.

Experiment 3: Bilateral Presentation With Vertical Offset

Experiment 2 showed that pseudoextinction operated across both horizontal and vertical axes. What might we predict, then, when the targets are placed in a diagonal configuration? We contrasted a *main-diagonal* configuration (targets in the superior–left and inferior–right quadrants) with an *antidiagonal* configuration (targets in the inferior–left and superior–right quadrants). In the main-diagonal configuration, the target in the

superior–left stream is in the prioritized position on both horizontal and vertical axes, whereas the target in the inferior–right stream is in the extinguished position on both axes. In the antidiagonal configuration, each of the targets is in the prioritized position on one axis, and the extinguished position on the other. If horizontal and vertical pseudoextinction arise from independent processes, we would expect pseudoextinction to be more pronounced in the main-diagonal than in the antidiagonal configuration.

We also found in Experiment 2 that efficacy was higher overall in the bilateral condition than in the unilateral condition; such a bilateral advantage would usually be attributed to the placement of the two targets in different hemifields. An alternative explanation is that the horizontal configuration of the streams in the bilateral condition confers an advantage because the two target letters are in a more natural configuration for reading. Reading English text in a vertical "marquee" orientation is more difficult than reading in a horizontal orientation (Byrne, 2002; Yu, Park, Gerold, & Legge, 2010). In Experiment 3 we presented one stream in each hemifield in a diagonal configuration, so that the vertical offset of the streams would impair grouping of the two target letters.

Method

Participants. Experienced observers were one of the authors (P.T.G.) and five colleagues unaware of the aims of the experiment. Naïve observers were 20 undergraduates (9 female) ranging in age from 17–23 years (Mdn = 18 years, M = 18.8, SD = 1.5), with EHI-R scores ranging from –400 to 400 (Mdn = 300, M = 255, SD = 177). Two naïve observers showed zero efficacy in at least one stream in both

conditions; their data were excluded from analyses, although their results were otherwise consistent with those of other observers.

Stimuli. In both conditions, streams were positioned bilaterally in diagonally opposing locations. In the *main-diagonal* condition, streams were located in the superior left and inferior right quadrants (Streams A and D in Figure 1a). In the *antidiagonal* condition, streams were located in the inferior left and superior right quadrants (Streams C and B).

Statistical tests. Data for each of the two conditions (*main-diagonal* and *antidiagonal*) were pooled from the data for two subconditions: One in which the letters of the response screen were vertically arrayed, and one in which the letters of the response screen were horizontally arrayed. A single model was fit to the data from each condition. To compare parameters in different conditions and at different locations, we used a series of between-subjects paired *t* tests, as in Experiment 2.

Results

Efficacy. Efficacy as a function of condition and stream location is shown in Figure 5a. In the main-diagonal condition, a paired *t* test showed higher efficacy in the left stream than in the right stream, $t(23) = 9.04$, $p \ll .001$, $d = 1.99$, 95% CI [0.20, 0.32]. Likewise, in antidiagonal conditions, efficacy was higher in the left stream than in the right stream, $t(23) = 3.64$, $p = .001$, $d = 1.63$, 95% CI [0.09, 0.31]. Mean efficacy did not differ between conditions, $t(23) = 1.91$, $p = .068$, $d = 0.39$, 95% CI [−0.003, 0.08]; nor did the absolute difference between streams, $t(23) = −0.38$, $p = .710$, $d = 0.08$, 95% CI [−0.09, 0.06].
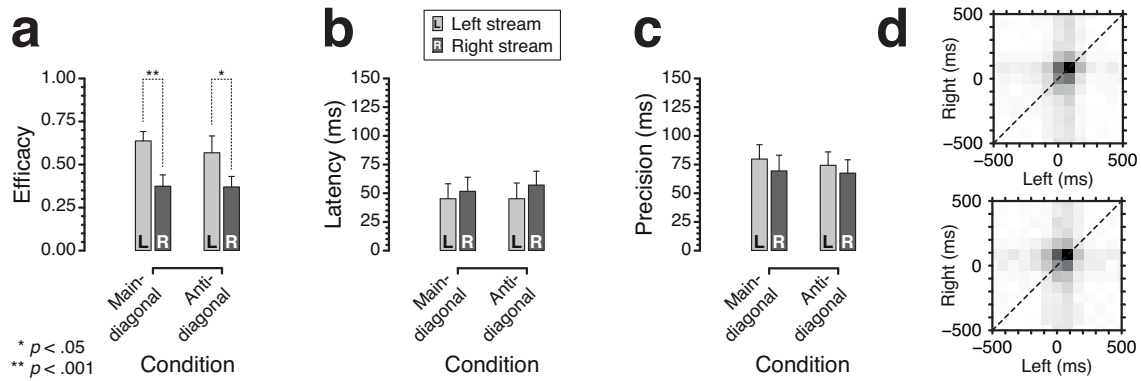
Figure 5. Results of Experiment 3. In the *main-diagonal* condition, streams were positioned in the superior left and inferior right quadrants. In the *antidiagonal* condition, streams were positioned in the inferior left and superior right quadrants. Panel (**a**) shows efficacy for each condition and stream location. Panel (**b**) shows latency for each condition and stream location. Panel (**c**) shows precision for each condition and stream location. Panel (**d**) shows correlograms of left-stream versus right-stream SPE for the main-diagonal condition (upper panel) and for the antidiagonal condition (lower panel).

Two-sample t tests showed that mean efficacy in the diagonal conditions of Experiment 3 was statistically indistinguishable from the unilateral condition of Experiment 2, $t(45) = 1.21$, $p = .231$, $d = 0.35$, 95% CI [−0.03, 0.11], and significantly lower than in the bilateral condition of Experiment 2, $t(45) = −2.13$, $p = .039$, $d = 0.62$, 95% CI [−0.15, −0.004].

Latency. Latency as a function of condition and stream location is shown in Figure 5b. There was no statistical difference in latency between left and right streams in the main-diagonal condition, $t(23) = −1.06$, $p = .302$, $d = 1.00$, 95% CI [−19.2, 6.2 ms], nor in the antidiagonal condition, $t(22) = −1.92$, $p = .067$, $d = 1.27$, 95% CI [−26.0, 1.0 ms]. Mean latency did not differ between conditions, $t(23) = −0.67$, $p = .512$, $d = 0.14$, 95% CI [−11.1, 5.7 ms]; nor did the absolute difference between streams, $t(22) = −1.01$, $p = .325$, $d = 0.21$, 95% CI [−17.9, 6.2 ms].

Precision. Precision as a function of condition and stream location is shown in Figure 5c. There was no statistical difference in precision between left and right streams in the main-diagonal condition, t (23) = 1.67, p = .109, d = 1.05, 95% CI [–2.5, 23.3 ms]; and no difference between streams in the antidiagonal condition, t (22) = 1.40, p = .175, d = 1.20, 95% CI [–4.0, 20.6 ms]. Mean precision did not differ between conditions, t (23) = 0.47, p = .645, d = 0.10, 95% CI [–10.8, 17.1 ms]; nor did the absolute difference between streams, t (22) = 0.27, p = .791, d = 0.06, 95% CI [–9.5, 12.3 ms].

Correlograms. The correlograms of left-hemifield SPE versus right-hemifield SPE for the main-diagonal and antidiagonal conditions are shown in Figure 5d. For both conditions, the most common combinations of left-hemifield and right-hemifield error comprised items that were presented simultaneously, when observers reported the item following the target in both streams (SPE = +1).

Discussion

The results of Experiment 3 suggest that the higher efficacy observed in bilateral conditions is not simply a result of splitting the targets between the two visual hemifields. Mean efficacy in Experiment 3 (which used bilateral, diagonal configurations) was indistinguishable from unilateral efficacy, but significantly lower than for the bilateral configurations measured in Experiment 2. We further assess the evidence regarding a bilateral advantage in the General Discussion section.

The advantage of the left visual field over the right persisted even in the antidiagonal condition, in which it might instead have been offset by the disadvantage of the inferior stream location compared with the superior location also observed in

Experiment 2. This is difficult to reconcile with a model in which independent factors (e.g., a hemispheric difference and a dorsal–ventral difference) cause the left–right and superior–inferior differences. The result instead suggests that all instances of pseudoextinction emerge from the same form of competitive interaction, which operates to the same degree between any two stimuli. In the General Discussion below, we present several of the most promising candidate models of pseudoneglect, and evaluate them in light of these findings.

General Discussion

Summary of Findings

In three experiments, we found spatial asymmetries in the efficacy of simultaneous selection across horizontal (Experiments 1 and 2), vertical (Experiment 2), and oblique (Experiment 3) axes. These asymmetries appear to be specific to circumstances under which selection of two targets is required, because they were absent or reversed in conditions requiring selection of a single target (Experiment 1). The spatial asymmetries did not combine additively. Rather, the horizontal asymmetry, by which the target in the right stream is often extinguished, overrides the vertical asymmetry, by which the target in the inferior stream is extinguished (Experiment 3). Overall efficacy in dual-target conditions was higher when targets were distributed between hemifields than when they were both situated within the same hemifield (Experiment 2); but no bilateral advantage was apparent when streams were placed in a diagonal configuration (Experiment 3). Each of these findings was remarkably consistent, with nearly every observer showing an effect in the same direction. Figure 6

(left panel) shows, for all conditions in each of the three experiments, a forest plot of the difference between streams in efficacy (i.e., the degree of pseudoextinction).
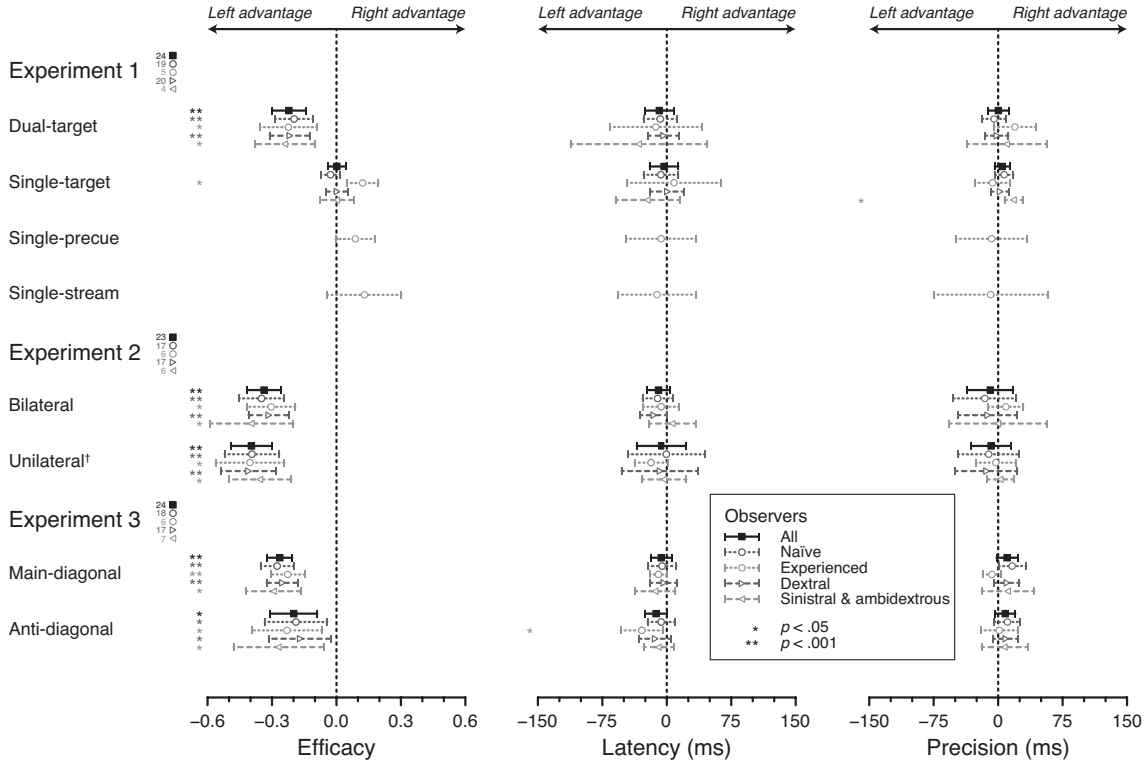

Figure 6. Forest plots of the difference between streams in efficacy, latency and precision for all experimental conditions and observer subgroups. The estimated effect in each condition is shown for all observers combined (filled squares), as well as separately for subgroups of naïve observers (dark open circles), experienced observers (light open circles), dextral observers (revised Edinburgh Handedness Inventory [EHI-R] score > 200; dark rightward-pointing triangles), and sinistral and ambidextrous observers (EHI-R score ≤ 200; light leftward-pointing triangles). The number of observers in each subgroup is shown near the title of each experiment. Error bars show parametric 95% confidence intervals on the mean difference between streams. [†]In the unilateral condition of Experiment 2, negative values (leftward deviations) indicate a superior stream advantage, and positive values (rightward deviations) indicate an inferior stream advantage.

Latency of selection did not differ between single-target and dual-target conditions (Experiment 1), nor did it differ between streams in dual-target conditions in which streams were arrayed horizontally or vertically (Experiments 1 and 2) or in a

diagonal configuration (Experiment 3). Mean latency of selection across observers and conditions was 32 ms in Experiment 1 (SD = 17), 48 ms in Experiment 2 (SD = 26) and 49 ms in Experiment 3 (SD = 28). Figure 6 (middle panel) shows, for all three experiments, a forest plot of the difference between streams in latency.

Mean precision of selection across observers and conditions was 84 ms in Experiment 1 (SD = 20), 85 ms in Experiment 2 (SD = 32) and 74 ms in Experiment 3 (SD = 25). This is comparable to the 72 ms precision found by Martini (2013) for a single-stream, single-target RSVP task. Other tasks requiring binding of changing stimuli have yielded a similar precision of approximately 70 ms. Linares, Holcombe and White (2009) asked participants to report the position of a moving object at the time of a color change of fixation or the sound of a beep. In both cases the position reports had a standard deviation of about 70 ms, with little effect of eccentricity or contrast of the moving object. With certain assumptions, a temporal precision of 70 ms can also explain the 3 Hz binding limit found with other tasks (Holcombe, 2009; Holcombe & Chen, 2012). Figure 6 (right panel) shows, for all three experiments, a forest plot of the difference between streams in precision.

Simultaneous Selection

The experiments reported here provide novel evidence of simultaneous selection across multiple spatial locations. There has been some debate about the criteria that should be satisfied in order to demonstrate genuinely divided attention (Cave, Bush, & Taylor, 2010; Jans, Peters, & De Weerd, 2010); a consistent concern has been that displays should be designed such that attention cannot be shifted rapidly between elements. Past studies have generally relied on brief presentation times to limit stimulus

exposure to durations shorter than the hundreds of milliseconds expected for a spatial shift of attention (Logan, 2005; Reid & Travers, 1968; Remington & Pierce, 1984; Theeuwes, Godijn, & Pratt, 2004). In the present study, we adopted such a strategy by embedding each of two simultaneous targets in an RSVP stream of distracter letters. In theory, this should preclude correct reporting of both letters unless a shift of attention can be executed during one RSVP frame (one twelfth of a second, or about 83 ms). Additionally, we analyzed the distribution of response errors to estimate precisely the time at which attentional selection occurred at each stream. The relative latency was statistically indistinguishable from zero, with 95% CIs spanning a very small range—typically around 25 ms. Across all participants and experiments, the mean difference between streams in selection latency estimates was less than 4 ms ($SD = 39$; see Figure 6, middle panel). The present analysis of response errors thus provides a unique line of behavioral evidence for genuinely simultaneous attentional selection.

A Bilateral Advantage?

In Experiment 2 of the present study, we found that overall efficacy of simultaneous selection was higher when the two targets were distributed between the visual hemifields than when both were situated within the same hemifield. This is consistent with many previous studies showing that, relative to unilateral presentation, bilateral stimulus presentation expands the capacity of visual working memory (Delvenne, 2005; Delvenne & Holt, 2012; Umemoto, Drew, Ester, & Awh, 2010), improves attentional tracking performance (Alvarez & Cavanagh, 2005), aids processing of sequentially presented targets in multiple-stream RSVP (Scalf, et al., 2007), helps to break visual crowding (Chakravarthi & Cavanagh, 2009), increases accuracy in the

enumeration of large numbers (Delvenne, Castronovo, Demeyere, & Humphreys, 2011), and enhances performance on basic visual detection and discrimination tasks in the presence of distracters (Reardon, Kelly, & Matthews, 2009). Findings of this nature are commonly thought to reflect independence between the processing resources devoted to each stimulus, or to indicate the extent to which competitive interactions inhibit the neural representation of one or more of the stimuli (Franconeri, Alvarez, & Cavanagh, 2013; Scalf, Torralbo, Tapia, & Beck, 2013).

The difference in performance between conditions in Experiment 2 is unlikely to be due to enhanced crowding in the unilateral condition relative to the bilateral condition. Studies of crowding (Bouma, 1970; Pelli et al., 2007; Toet & Levi, 1992) have indicated that the letters in our experiments—presented at a retinal eccentricity of 6.0°—should be free from crowding when separated by about 3.0° or more. In fact, they were separated by 8.5° (see Figure 1a), suggesting that crowding played no appreciable role in either condition.

We found no evidence of a bilateral advantage when streams were arranged diagonally (Experiment 3). One possible explanation is that target locations must be mirror-symmetric across the midline for simultaneous selection to be facilitated in a bilateral configuration. Other studies have found similar symmetry-dependent effects: For example, Tanaka, Miyauchi and Misaki (2007) found enhanced contrast sensitivity to a Gabor stimulus when a cue was presented in a horizontally symmetric location relative to fixation, but not in vertically or diagonally symmetric locations. Such effects could be mediated by preferential callosal connectivity between areas of retinotopic cortex that respond to mirror-symmetric locations (Abel, O'Brien, & Olavarria, 2000).

We note, however, that Bay and Wyble (2014; their Experiment 1) found no evidence of a bilateral advantage for reporting simultaneous letters from concurrent RSVP streams, whether or not target streams were in mirror-symmetric locations. In their study, four streams were positioned in a horizontal row, two on either side of fixation. This leads us to suspect that the apparent bilateral advantage in Experiment 2 is instead an advantage in deploying attention to multiple locations that are horizontally aligned, regardless of whether targets are distributed between hemifields.

Why, then, did Scalf *et al.* (2007) find a bilateral advantage for reporting targets presented sequentially? We propose that any serial bottleneck in perceptual selection—which Scalf *et al.* believed was alleviated in their case by parallel bilateral processing—is circumvented under simultaneous presentation conditions. Bay and Wyble (2014; their Experiment 2) showed that performance for simultaneous targets (*lag 0*) is in fact better than performance for immediately sequential targets (*lag 1*). They noted that this is well explained by a *convergent gradient field* model of attention (Wyble & Tan, 2014; see also Zirnsak, et al., 2011, for a model with similar behavior) by which cues or targets cause attention to be deployed to their location in the visual field, after which the spatial reallocation of attention is inhibited until stimulus processing is complete. When multiple targets appear at once, attention can be deployed simultaneously to their locations; but when one target appears earlier, attention converges on its location and inhibits perceptual selection of the subsequent target. Thus, as Scalf *et al.* suggested, bilateral presentation might facilitate performance on some tasks owing to parallel *perceptual selection* by each cerebral hemisphere (see also Alvarez & Cavanagh, 2005; Delvenne, 2005): Even after attention has converged on the location of a single initial

target in the right visual hemifield, it remains possible to select a subsequent target in the left. According to the account we suggest here, however, the independent capacities of the two hemispheres do not convey any additional benefit when parallel selection has been initiated by simultaneous presentation of cues or targets.

Hemispheric Models of Pseudoextinction

Under single-target conditions in Experiment 1, observers showed no significant lateral bias in efficacy. In contrast, in the dual-target condition, observers showed a consistent and substantial *leftward* bias in efficacy. Efficacy in the left hemifield was similar whether or not the observer was also required to select a simultaneous target in the right hemifield, whereas efficacy in the right hemifield was markedly lower when the observer was also required to select a simultaneous target in the left. This pattern of results is reminiscent of *pseudoneglect*—the leftward attentional bias usually exhibited by observers in tasks such as line bisection—but with the notable difference in the current case that the asymmetry is only elicited in the presence of competing attentional targets. We thus refer to this as *pseudoextinction*, by analogy to the clinical visual extinction that often accompanies hemispatial neglect (Wortis, Bender, & Teuber, 1948). Patients with extinction can detect a single target presented to either visual hemifield, but fail to detect the target contralateral to their lesion when targets are presented simultaneously to both hemifields (Baylis, et al., 1993).

The *activation–orientation* hypothesis (Reuter-Lorenz, et al., 1990)—which posits that attention is biased toward the visual field contralateral to the more "active" cerebral hemisphere—is often invoked to explain pseudoneglect. Tasks that elicit pseudoneglect typically require spatial judgments, traditionally ascribed to the right

hemisphere (Milner, 1971); this is believed to produce an exaggerated representation of stimuli or parts of stimuli that are situated in left hemispace. Could the activation–orientation hypothesis explain our finding of pseudoextinction? First, if the nature of the task demands right-hemisphere engagement, one should predict better performance in the left hemifield even in single-target conditions; yet we observed no such difference. As noted in our discussion of Experiment 1, the discrepancy between single-target and dual-target conditions points to cortical competition in the use of stimulus representations, rather than differences in the representations themselves (Boles, 1983; Fecteau, et al., 2000). Second, it is not clear which hemisphere should be most engaged in our task. Dual-target conditions contain a spatial component (mapping letter identities to spatial locations) that is not critical to single-target conditions, and this might account for the absence of bias when only one target must be reported. But other, arguably more fundamental, components of the task would predict left-hemisphere engagement: The requirements for letter identification (e.g., Polk et al., 2002) and fine temporal judgments (e.g., Elias, Bulman-Fleming, & McManus, 1999; Nicholls, 1996) both predict a right-hemifield advantage.

Related hemispheric models of pseudoextinction emerge from the observation that an overwhelming majority of cases of hemispatial neglect occur after insult to the right cerebral hemisphere. In comparison, it is relatively uncommon after left-hemisphere damage. Various models of neglect attribute this asymmetry to the intact right hemisphere's ability to compensate for the lost functions of the left. That is, they propose that relevant temporal and parietal regions of the weaker left hemisphere contain unilateral maps of the right visual field, while the corresponding regions of the

dominant right hemisphere contain bilateral maps (Heilman & Van Den Abell, 1980; Mesulam, 1981, 1999; Pouget & Driver, 2000). In the case of a right-hemisphere lesion, the spared left hemisphere can process contralateral (right hemifield) but not ipsilateral (left hemifield) stimuli, resulting in hemispatial neglect, while in the case of a left-hemisphere lesion, the spared right hemisphere can process both contralateral and ipsilateral stimuli. Many such models do not posit a strict dichotomy of bilateral processing in the right hemisphere and unilateral processing in the left hemisphere; instead, they suggest a graded representation in both hemispheres, which is much more heavily biased to the contralateral field in the left hemisphere and more balanced between contralateral and ipsilateral fields in the right. Sheremata, Bettencourt and Somers (2010) reported corroborating evidence from functional imaging of neurotypical observers: In a visual STM task, activity in the left intraparietal sulcus (IPS) correlated with memory for items in the right visual field, while activity in the right IPS was load-dependent regardless of the visual field location of remembered items.

The *callosal relay* model (Boles, 1987; Bryden & Bulman-Fleming, 1994) is a version of the aforementioned theory, and Figure 7 shows how it is consistent with some of the present results. The afferent retinogeniculate pathway connects single targets presented to the left hemifield to the dominant right cerebral hemisphere (Figure 7a), while single targets presented to the right hemifield are processed not only contralaterally by the left hemisphere, but also by the right hemisphere owing to transfer of information by the corpus callosum (Figure 7b). In dual-target conditions, the dominant right hemisphere is consumed with processing the target in the contralateral left hemifield. The situation for the left target is thus the same as when a

single target is presented, and efficacy is identical for single-target and dual-target conditions. The target in the right hemifield, however, is processed only by the weaker left hemisphere (Figure 7c). Thus compared with the single-target case, in which the right target also benefits from processing in the ipsilateral right hemisphere, right-target
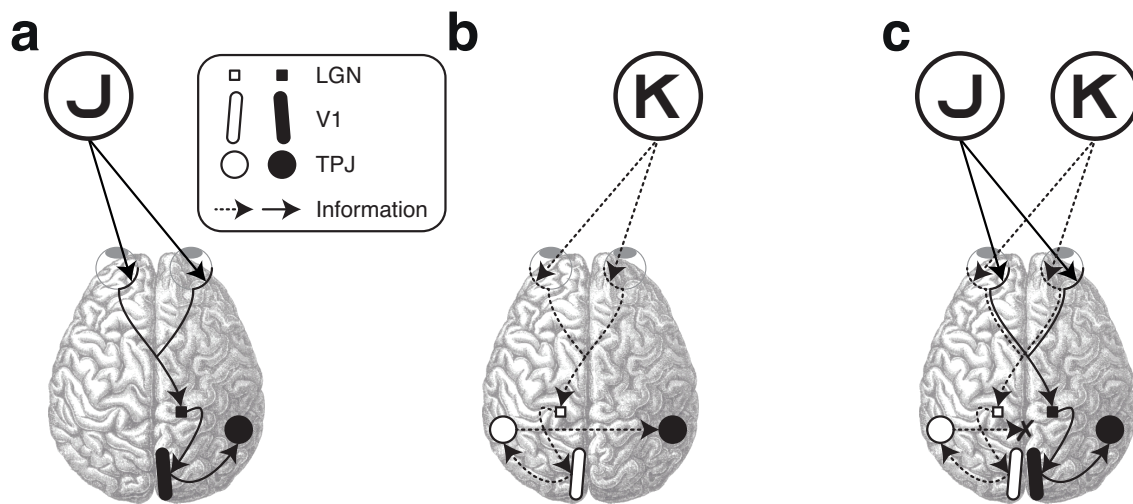

Figure 7. Hemispheric model of pseudoextinction. Panel **(a)** depicts the processing of a single target (the letter *J*) presented to the left visual field. Visual information is registered on the left nasal and right temporal hemiretinae, and proceeds via the right lateral geniculate nucleus (LGN) to right primary visual cortex (V1). The information is subsequently directed through the visual processing hierarchy to arrive at the right temporoparietal junction (TPJ). Attentional processing thus occurs primarily in the dominant right hemisphere. Panel **(b)** depicts the processing of a single target (the letter *K*) presented to the right visual field. Visual information is registered on the left temporal and right nasal hemiretinae, and proceeds via left LGN to left V1. The information is subsequently directed to left TPJ; however commissural fibers also allow information to be projected to right TPJ. Attentional processing can thus occur in the dominant right hemisphere. Panel **(c)** depicts the processing of dual targets presented simultaneously to the left and right visual fields. The left-hemifield stimulus is processed exactly as in the single-target case, and attentional processing occurs in the dominant right hemisphere. The right-hemifield stimulus is processed as in the single-target case until the information reaches left TPJ. As right TPJ is engaged in processing the left-hemifield stimulus, however, information is inhibited from crossing the commissure. Consequently, attentional processing is restricted primarily to the weaker left hemisphere.

efficacy in dual-target conditions is much reduced compared with single-target conditions.

Although such a model suitably captures the cortical competition that is evident in our findings, it fails to account for other key aspects. Critically, it is difficult to reconcile any hemispheric model with the superior-stream advantage that we observed during unilateral presentation. Attentional biases to the superior visual field have been demonstrated previously for normal observers in line bisection (reviewed in McCourt & Garlinghouse, 2000, p. 718) and visual search tasks (reviewed in Fecteau, et al., 2000, pp. 386–387); there also have been several reports of neglect patients who have shown biases across superior–inferior axes, though the direction of the bias has been inconsistent (McCourt & Garlinghouse, 2000, pp. 716–717). As we noted in our discussion of Experiment 2, biases on this vertical axis have been attributed to the preferential connectivity of occipital areas representing the superior visual field to temporal cortex (the *ventral* pathway), and of occipital areas representing the inferior field to parietal cortex (the *dorsal* pathway). With respect to clinical neglect, this is consistent with the observation that occipitotemporal and occipitoparietal lesions may be associated with neglect of the superior and inferior fields, respectively (Adair, Williamson, Jacobs, Na, & Heilman, 1995; Drain & Reuter-Lorenz, 1996). If the ventral pathway is specialized for object recognition (Goodale & Milner, 1992; Mishkin & Ungerleider, 1982), the present experiments might reasonably be expected to invoke a superior field advantage. However, in the case that the competitive advantage of a target is a function of both preferential access to the ventral visual stream and preferential access to the right cerebral hemisphere, we should expect a difference in the

magnitude of pseudoextinction between the two diagonal configurations of Experiment 3. In the main-diagonal condition, the target in the superior left quadrant is preferentially connected to both the ventral stream and the right hemisphere in comparison to the target in the inferior right quadrant; while in the antidiagonal condition, the target in the inferior left quadrant has privileged access to the right hemisphere, but diminished access to the ventral stream, compared to the target in the superior right quadrant. Pseudoextinction should thus be exaggerated in the main-diagonal condition relative to the antidiagonal condition. Yet we observed no difference in magnitude between conditions, suggesting that pseudoextinction is not driven by different sources of bias across horizontal and vertical axes.

We also note that the sinistral and ambidextrous observers in our study showed a pattern of pseudoextinction indistinguishable from that of dextral observers (see Figure 6). Further, across all participants in the study, the magnitude of the pseudoextinction effect in each experiment and condition was uncorrelated with participant handedness as measured by the EHI-R (all $|r| \leq .200$, $p > .360$). A significant body of research has indicated that left- and mixed-handed individuals show a higher incidence of atypical behavioral lateralization, which is believed to reflect atypical lateralization of cerebral organization (Willems, Van der Haegen, Fisher, & Francks, 2014). Anatomical and functional asymmetries can be influenced even by familial sinistrality (Hancock & Bever, 2013). The high degree of inter-observer consistency in pseudoextinction thus provides additional evidence against any theory positing that it originates from hemispheric asymmetries in cerebral structure and function.

We therefore conclude that hemispheric models—although superficially attractive—cannot convincingly explain the pseudoextinction effects observed in the present study. In the following section, we consider an alternative family of models that can account for our observations without necessarily appealing to cerebral asymmetries.

Type-Token Models of Pseudoextinction

Baylis *et al.* (1993) conceptualized clinical extinction as a failure of *tokenization* in the extinguished field. Such an account rests on a commonly held distinction between two basic stages in the visual perception of a stimulus (Bowman & Wyble, 2007; Chun, 1997; Kanwisher, 1987). The first is the activation of a stimulus trace or *type*. A type is a representation of stimulus features in some temporary buffer. Multiple types can be activated in parallel, but their representation rapidly decays. The second stage is the consolidation of an activated type as a *token*, which provides a robust representation in visual STM that can be used for report. Many instantiations of type–token models contain extra elements (e.g., a *binding pool* intermediate to type and token layers); in the present discussion, we need only consider the general components of the model family.

Figure 8a depicts a type–token model of single-target processing in the current task. Presentation of the target will activate the relevant type node, which in turn inhibits other nodes. On reaching a given threshold, the type node will activate a token, which sustains its own activation and serves as an index for retrieval of the type. By this account, the *latency* and temporal *precision* of attentional selection reflect the accuracy with which a cue and an RSVP item can be temporally colocalized during type
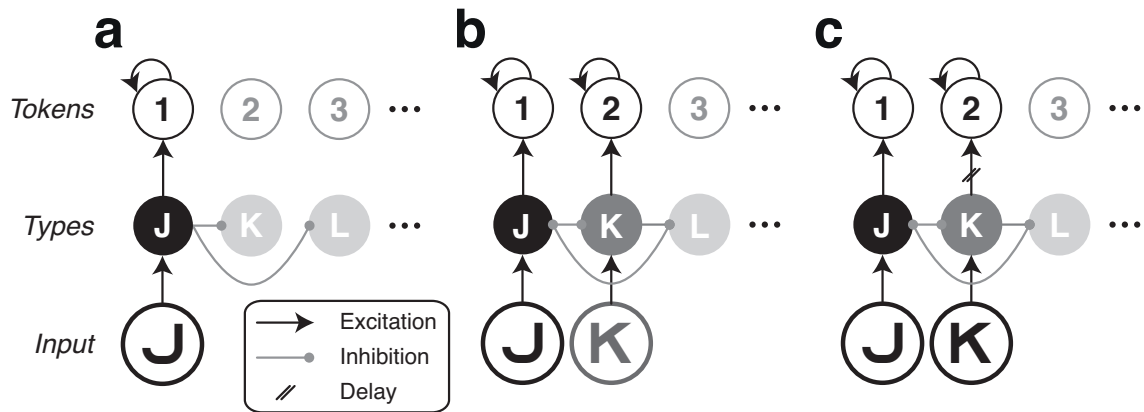
Figure 8. Type–token models of pseudoextinction. Panel **(a)** depicts the processing of a single target (the letter *J*) presented to the left visual field. Presentation of the stimulus activates the corresponding *type* in a temporary buffer. On activation, the *J* unit inhibits other type units. Transfer into working memory is achieved by *tokenization*: On reaching threshold, the *J* unit excites the corresponding *1* token. The *1* token sustain its own activation, serving as an index for retrieval of the letter *J* from working memory. For clarity, only a selection of relevant types and tokens are shown here. Panel **(b)** depicts the processing of dual targets presented to the left and right visual fields according to a parallel tokenization model. Presentation of the stimuli simultaneously activates the corresponding types, which compete against one another and inhibit other types. The type activated in response to the left visual field stimulus has an inherent advantage in this competition. On most trials, as depicted here, both items are tokenized in parallel. Each corresponds to a different token, which provide indices for retrieval of the letters *J* and *K*. On some trials, however, the competition between types is sufficient to force the disadvantaged right-hemifield item out of the encoding process. Panel **(c)** depicts processing of dual targets according to the serial tokenization model we favor. Presentation of the stimulus simultaneously activates the corresponding types, which compete against one another and inhibit other types. Neither of the activated types has an inherent advantage. Tokenization occurs serially, and typically proceeds from left to right. Tokenization usually succeeds for both items; however on some trials, during the tokenization of the left-hemifield item, the activation of the right-hemifield type decays such that it can no longer excite a token to threshold.

activation. Martini (2013) proposed that temporal tags with a Gaussian noise distribution are assigned to the cue and RSVP items; the item with the temporal tag closest to that of the cue is reported, resulting in a symmetrical Gaussian distribution of SPEs as observed in the present study. By this same account, the *efficacy* of attentional

selection reflects the average strength of type activation at the time of tokenization: That is, it is the proportion of trials on which activation of a type is sufficient to allow it to be tokenized.

When two simultaneous RSVP items appear, the corresponding types are activated in parallel in the type buffer, and they must be tokenized if they are to be reported at the end of the trial. Figure 8b depicts the processing of simultaneous targets according to a generalized form of *parallel tokenization model* (e.g. Wyble, Bowman, & Nieuwenstein, 2009; Wyble, et al., 2011). As in the single-target case, activated type nodes will inhibit other nodes; in the dual-target case, though, mutual inhibition between the two activated nodes causes weak competition for representation. These two targets can be tokenized in parallel, and both instances of tokenization are successful on many trials, which accounts for the ability of observers to report simultaneous targets. On other trials, however, one target is less strongly represented than the other, and competition forces it out of the tokenization process. If we suppose that a target in the left or superior field has an inherent competitive advantage over a target in the right or inferior field, such a model might account for pseudoextinction effects. Competition between activated types may also help to explain why Bay and Wyble (2014) found that simultaneously cueing two locations improved dual-target report by almost the same amount as cueing a single location improved single-target report, while we found pseudoextinction under similar circumstances. The categorically defined targets used by Bay and Wyble could alleviate competition for representation among activated types by allowing suppression of distracter type nodes based on task demands; distracter

inhibition of this kind is a component of prominent type–token models (e.g., Wyble, et al., 2009).

As is the case for a hemispheric model, the challenge for a parallel tokenization model is to convincingly explain how the magnitude of pseudoextinction is apparently unaffected by the spatial arrangement of two target stimuli. Whatever the mechanism by which competition occurs, the strength of the representational bias is constant regardless of the locations of the two streams. The relative position of the streams determines only *which* stream receives the advantage, and not the strength of that advantage. We have already ruled out visual-field differences in representation, because no asymmetry is observed in single-target conditions; the inherent advantage of the favored location must instead arise from competition. Accordingly, one should propose that inhibition of right-hemifield activation by left-hemifield activation is stronger than the converse, and that there is an *identical* asymmetry of inhibition between the superior and inferior fields. Although this is possible in principle, it would be quite a coincidence. An additional complication arises from the left-hemifield advantage and equivalence of pseudoextinction in the two vertically offset arrangements of Experiment 3. Inhibition of the right hemifield by the left hemifield must occur regardless of the distribution of targets between the superior and inferior fields; but inhibition of the inferior field by the superior field must be absent when targets are positioned bilaterally. Again, although this seems possible in principle, we can think of no reason to predict such an arrangement.

Explaining these effects becomes considerably simpler if we suppose that, under the conditions of the present experiments, tokenization must proceed serially. Figure 8c

depicts the processing of simultaneous targets according to a *serial tokenization model*. Target presentation excites the corresponding type nodes, which weakly compete for representation. The first tokenization operates on a recently activated type. However, during this first tokenization process, the activation of the second item decays. By the time the second tokenization begins, the corresponding node's activation may have decayed below a critical threshold. Pseudoextinction may thus result from delayed tokenization of the second of two simultaneously activated types.

Most type–token models use parallel tokenization to account for *lag-1* sparing (preserved T2 report when it appears immediately following T1) and *spreading the sparing* (the ability to report multiple consecutive targets; Di Lollo, Kawahara, Shahab Ghorashi, & Enns, 2005; Olivers, van der Stigchel, & Hulleman, 2007) phenomena in attentional blink paradigms. Yet lag-1 sparing is rarely found when T1 and T2 appear in different spatial locations (Visser, Zuvic, Bischof, & Di Lollo, 1999; cf. Lunau & Olivers, 2010), suggesting that parallel tokenization may not operate under these circumstances.

In the present study, participants were required to encode the location of each target, and they virtually never reported a correct target (or an item in temporal proximity to the target) in the wrong location. There is increasing evidence that encoding the spatial relationship between items requires some form of spatial attentional shift: Relative position may be inferred from the direction of the shift and the temporal order of the items (Cavanagh, Hunt, Afraz, & Rolfs, 2010; Franconeri & Handy, 2007; Franconeri, Scimeca, Roth, Helseth, & Kahn, 2012; Holcombe, Linares, & Vaziri-Pashkam, 2011). The duration of the attentional shift between targets is likely

to necessitate their serial tokenization. Further, serial processing could be required to encode explicit temporal order information, which is compromised when two items are tokenized in parallel (as in lag-1 sparing; Hommel & Akyürek, 2005; Wyble, et al., 2009).

Notably, it appears that such an attentional shift can operate on representations in visual iconic memory (i.e., activated types), without requiring the stimulus itself to remain physically present. Franconeri *et al.* (Franconeri, et al., 2012) found lateral modulation of the electroencephalographic *N2pc* component consistent with an attentional shift around 300 ms after the onset of stimuli that were presented for only 120 ms. Recent studies using the part-report technique (Sperling, 1960) have indicated that iconic representations of stimuli can survive postmasking, but decay rapidly over the course of around 500 ms (Bhardwaj, Mollon, & Smithson, 2012; Smith, Mollon, Bhardwaj, & Smithson, 2011; Smithson & Mollon, 2006). Given an attentional dwell time in the order of 300 ms, this would mean that the second instance of tokenization would typically commence before type activity had decayed entirely (explaining the ability to report simultaneous targets), but often would operate on a considerably degraded trace (explaining pseudoextinction).

If tokenization is serial, what determines the order in which items are tokenized? Higher efficacy in the left stream compared with the right stream, and in the superior stream compared with the inferior stream, suggests that tokenization consistently proceeds left-to-right, top-to-bottom. A possible origin of this bias is the attentional strategies adaptive for reading English text. Most examples of English text are written from left to right (as in our bilateral condition), possibly inducing the left to right bias.

When unrotated text is arrayed vertically in a marquee arrangement, it is almost invariably read from top to bottom; this would explain the results in our unilateral condition. Note that our proposal here differs from other directional reading and scanning hypotheses, which often have been dismissed as an explanation for visuospatial biases (e.g. Boles, 1990; Fecteau, et al., 2000). We do not suggest that scanning biases *cause* pseudoextinction; rather, we suggest that pseudoextinction arises from a need for serial tokenization, which tends to proceed—at least, under the circumstances of the present study—in an order influenced by reading habits. Literacy has an influence on other fundamental properties of visual object recognition, such as mirror invariance (Pegado et al., 2014); future research into pseudoextinction will reveal whether, as we suggest, reading shapes visual field biases in a similar manner.

Concluding Remarks

The present study shows that observers can select two simultaneous targets. The temporal parameters of simultaneous selection are indistinguishable from single-target selection; yet relative to selection of a single target, simultaneous selection incurs costs in efficacy, and the costs vary according to the spatial arrangement of the stimuli. Simultaneous selection reveals pseudoextinction, a systematic efficacy advantage for one of two visual field locations. We argue that pseudoextinction is caused by a requirement to tokenize selected items in a serial manner, and suggest that the order of tokenization is determined by attentional strategies adaptive for reading.

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