# Capacity Limits in Visual Processing Revealed by Spatial Biases

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This is to certify that to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

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I co-designed the study with the co-authors, extracted and analysed the data and wrote the drafts of the manuscript.

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As supervisor for the candidate upon which this thesis is based, I can confirm that the authorship attribution statements above are correct.

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# Abstract

Our early visual system extracts fine grained information about our rapidly changing world, yet in certain laboratory conditions, participants fail to report some items that are clearly presented within their field of vision. These failures are likely to occur because later stages of the visual system do not have capacity to process all of the information extracted at the retina. In this thesis, I investigate a particular failure of awareness that occurs when two target letters are briefly presented at the same time in different spatial locations. A clue to the cause of these failures may lie in the spatial pattern of errors that participants make. A recent theory suggests that the consistency in spatial errors across participants may reflect a functional strategy used by the brain to prioritise information at a key processing bottleneck. I investigate this claim, and conduct research to investigate other aspects of the limitation, such as the processing stage at which it occurs, and its implications for visual processing tasks such as reading.

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# Chapter 1: Introduction

## 1.1 Capacity Limits in Visual Processing

The early visual system has excellent spatial and temporal resolution. However, in certain laboratory conditions, participants fail to report some items that are clearly presented within their field of vision. These failures to report items tend to occur when more rather than fewer items must be reported in a given interval, suggesting that they may be the result of a capacity limit in visual processing.

The term capacity limit is used throughout this thesis to refer to any functional processing limitations that occur when more rather than fewer items must be processed. Capacity limits are closely related to visual attention in that they necessitate selection, and visual attention describes the process that guides selection. While constraints of our sensory organs pose certain limitations on visual awareness (for example, visual acuity in parts of the visual field is limited by the arrangement of cones in the retina), these are beyond the scope of this thesis, which is limited to discussion of processing that occurs in cortical brain regions.

Many researchers have investigated the cause of these capacity limits by investigating the pattern of reporting errors that participants make when presented with certain stimuli under temporally constrained conditions (for some seminal examples, see Duncan, Ward, & Shapiro, 1994; and Shapiro, Raymond, & Arnell, 1997). These studies have inspired detailed theories about the neural mechanisms that may underpin capacity limited processing (and Dehaene, Sergent, & Changeux, 2003; for example, Raffone, Srinivasan, & van Leeuwen, 2014). However, after decades of development and refinement of several competing theories, the field is yet to fully resolve the stages of processing at which the capacity limits occur or the method by which information is prioritised for processing when competing for limited processing resources.

In this thesis, I continue with the tradition of analysing the pattern of reporting errors in behavioural experiments, but differ from other studies in this field by focussing on spatial biases in reporting, with a focus on a particular spatial bias reported in a recent study by Goodbourn and Holcombe (2015) that shows a robust advantage reporting the item on the left when the stimuli are two letters. Spatial biases are easily obtained from behavioural experiments and provide particular insight into the way the brain prioritises information at the capacity limit, which affects the likelihood that a particular item will be reported. A key challenge in using spatial biases to make inferences about capacity limits is that other factors may also contribute to measured biases. In particular, it is well established that the two cerebral hemispheres, which each receive initial projections pertaining to visual information in the opposite visual field, differ in their ability to process certain types of stimuli (Gazzaniga, Bogen, & Sperry, 1965). This thesis addresses the contribution of hemispheric factors to spatial biases, and the implications that this has for the understanding of capacity limits.

In the remainder of this Chapter, I describe previous literature relating to:

(1) documented limits in visual awareness;

(2) neural arrangements that give rise to capacity limits in visual processing;

(3) documented spatial biases in awareness.

(4) spatial biases in the reading process.

I then discuss the goals of the thesis.

## 1.2 Documented Limits in Visual Awareness

### 1.2.1 Selection in space - the Attentional Spotlight

It is now well established that processing can be enhanced at a particular location relative to other locations (Posner, 1980). Adopting the common metaphor, visual attention acts as a spotlight, where anything under its ‘beam’ is processed, and anything outside its beam is not. There is a large body of research using cueing paradigms to inspect the effects of shifting the location of the spotlight on perception (for reviews, see Carrasco, 2011; or Posner, 2016). These paradigms have demonstrated three main findings:

(1) attending to a location enhances a number of aspects of visual processing (Posner, 1980).

(2) enhancement can occur independently of eye-gaze, meaning that processing enhancements are not attributable to advantages of focal vision (Helmholtz, 1866; Posner, 2016; Posner & Petersen, 1990); and

(3) the spotlight can be deployed as a result of salient aspects of the stimulus (exogenous cueing), or by the volitional intent of the participant (endogenous cueing). Exogenous cueing rapidly (within 100ms of cue onset) deploys a spotlight at the location of a cue that is a categorically defined target or has salient visual features (Nakayama & Mackeben, 1989). In contrast, endogenous cueing deploys a spotlight more slowly (it requires around 300ms) to a location that is different from the cued location (H. J. Müller & Rabbitt, 1989).

Several researchers have argued that spatial selection is not accurately described by the spotlight model. In particular, (Eriksen & St. James, 1986) argued that the size of the beam indicating the location of selection is not fixed, as the spotlight model implies, but instead can be zoomed in or out to focus on locations of different size. Several subsequent studies have confirmed that manipulating the size of the attended area can inversely affect the speed at which a target can be detected (Castiello & Umiltà, 1990; Greenwood & Parasuraman, 2004); and discriminated (Eriksen & Yeh, 1985).

More recently, researchers have demonstrated that, in contrast with the traditional notion of a unitary spotlight, multiple locations in the visual field can, in certain conditions, be selected concurrently (Awh & Pashler, 2000; Bay & Wyble, 2014; Bichot, Cave, & Pashler, 1999; Dubois, Hamker, & VanRullen, 2009; Duncan et al., 1994; Franconeri, Alvarez, & Enns, 2007; Kawahara & Yamada, 2006; Kyllingsbæk & Bundesen, 2007; McMains & Somers, 2004, 2005; Morawetz, Holz, Baudewig, Treue, & Dechent, 2007; M. M. Müller, Malinowski, Gruber, & Hillyard, 2003; Tan & Wyble, 2015). In a seminal study, Duncan and colleagues (1994) found that two spatially separated characters (letters and digits) could be discriminated when concurrently presented for between 45 and 60 ms and subsequently masked. Other studies have found that the ability to report two briefly and simultaneously presented targets is at least as good as (Bichot et al., 1999), and in some conditions even better than (Bay & Wyble, 2014), the ability to report items presented successively with a short intervening interval. A range of studies have established that the enhancement of detection or discrimination of items presented at cued locations does not extend to intervening locations, thus ruling out the possibility that the benefits represent attention to a larger area encompassing both targets, rather than a genuine selection of two non-contiguous areas (Awh & Pashler, 2000; Bay & Wyble, 2014; Bichot et al., 1999; Dubois et al., 2009; Kawahara & Yamada, 2006). Several electrophysiological studies have found evidence that simultaneous, non-contiguous targets are associated with activation in multiple distinct brain regions (McMains & Somers, 2004, 2005; M. M. Müller et al., 2003). While evidence for multiple spotlights has been found using both exogenous (for example, Bay & Wyble, 2014) and endogenous (for example, Awh & Pashler, 2000) cuing paradigms, Jans and colleagues (2010) argue that humans do not passively attend to two locations simultaneously, and that the ability to do so in response to an endogenous cue may be a learned skill.

### 1.2.2 Selection in time - the Attentional Blink

In addition to limits in processing spatially separated items, there are also limits to how many items can be processed in a single location when the items are separated by time. Rapid Serial Visual Presentation (RSVP) experiments, which use dynamic streams of letters as stimuli, were originally developed as a means of pushing temporal processing mechanisms to the limit, so allowing researchers to assess the rate at which information is processed and encoded when the spatial location of this content was held constant (Chun & Wolfe, 2001). Early experiments presented a single stream of items at fixation at a rate of around 10 items per second, and required participants to report two targets — defined either by feature (for example, colour) or category (for example, digits amongst letters) — with a variable separation between the two targets. These experiments demonstrated that participants' ability to report a target (T2) is impaired if it appeared between 2 to 6 items (equivalent to 200 to 600 ms) after an earlier target (T1) that also had to be reported (Raymond, Shapiro, & Arnell, 1992) — a phenomenon known as the attentional blink.

Three additional aspects of this phenomena have been widely reported.

(1) The deficit only occurs if participants are required to report both targets. If participants are told to ignore T1, the ability to report T2 improves. As such, the deficit has

been attributed to a limitation that prevents the processing of two items in quick succession (Shapiro et al., 1997).

(2) If T2 is the next item in the sequence after T1, the ability to report T2 is better than if it occurs after an intervening distractor. This is termed ‘lag 1 sparing’ (Potter, Chun, Banks, & Muckenhoupt, 1998; T. A. Visser, Bischof, & Di Lollo, 1999) and is usually attributed to either attentional enhancement of T1 that extends to temporally proximate targets (Olivers & Meeter, 2008), a lack of disengagement from T1 due to the continued presentation of goal relevant targets (Nieuwenstein, 2006), or a delay in the suppression mechanisms that are usually associated with the attentional blink (Raymond et al., 1992). Bowman and Wyble (2007) have reported that sparing is extended to lag 2 when the speed of the streams is increased to 54 ms per item. This suggests that the typical lag 1 sparing result occurs as a result of T1 and T2 having a separation of 100 ms, rather than T2 occurring at lag 1 (that is, having a categorical identity of T1 + 1) per se.

(3) Sparing can be extended beyond lag 1 if three successive targets of the same category are presented in a sequence. This phenomenon is known as ‘spreading of sparing’ (Olivers, Van Der Stigchel, & Hulleman, 2007), and has been attributed to a limitation of an attentional filter that must switch between monitoring and consolidation (Di Lollo, Kawahara, Ghorashi, & Enns, 2005).

Different researchers have attributed the attentional blink to different mechanisms, including post perceptual suppression triggered by an item following T1 (Olivers & Meeter, 2008; Raymond et al., 1992); an attentional bottleneck for late stage processing (Chun & Potter, 1995); temporary loss of control over a filter that discriminates between targets and distractors (Di Lollo et al., 2005); and a delay in attentional re-engagement following a target (Wyble, Potter, Bowman, & Nieuwenstein, 2011). The recent RAGNAROC model by Wyble and colleagues (Wyble et al., 2018) combines aspects from several previous models, and is discussed in detail in Chapter 6.

### 1.2.3 Selection in space and time

A natural extension of the single stream RSVP paradigms used in attentional blink research was to present multiple dynamic streams, usually either side of fixation, either with both targets in one stream, or one target in each (Holländer, Corballis, & Hamm, 2005; T. A. Visser et al., 1999). This allowed researchers to investigate temporal attention and spatial attention in the same experiment.

By comparing the attentional blink when targets were both in the left visual field with that obtained when targets were both in the right visual field, researchers could investigate hemispheric differences in temporal attention, and so test a common theory of the time that the left hemisphere was specialised for temporal attention (Nicholls, 1996), which juxtaposed the theorised right hemisphere specialisation for spatial attention (Kinsbourne, 1970). On this question, Holländer and colleagues (2005) found that the attentional blink was greater in the right visual field. The authors canvassed several possible explanations for this asymmetry. One was that the greater attentional blink in the right visual field reflected biased attention towards the left side of place. However, this account does not explain a finding that lag one sparing occurred when the two targets both in the right stream, but not when the first target was in the left stream and the second target was in the right stream. Another possibility was that the asymmetry reflected deeper processing for letters stimuli in the right visual field as a result of a left hemisphere advantage for lexical processing. However, the authors discounted this, citing evidence from unpublished experiments that the attentional blink also occurred with shape stimuli, despite shapes being right hemisphere dominant for shape processing. Their final alternative explanation was that the right hemisphere (which processes the left visual field) may actually have an advantage for temporal attention. This interpretation is consistent with findings from neuropsychological studies that temporal processing impairment is specific to right hemisphere lesions (Battelli, Pascual-Leone, & Cavanagh, 2007). However, a recent study by Asanowicz, Kruse, Smigasiewicz and Verleger (2017), has found that deficits in a two stream RSVP task were eliminated when targets both always appeared in either the left visual field or right visual field for each block, but was not sensitive to changes in the relative timing between the two targets, leading them to conclude that the better performance when T2 was on the left reflected a bias in stimulus driven orienting of spatial attention.

By comparing the attentional blink obtained when the targets were in the same location with that obtained when items were in different locations, researchers could also investigate whether distributing targets across left and right visual fields would reduce the attentional blink, which might indicate that the targets were being processed by independent mechanisms. Here, researchers found that the performance deficits typically recorded in single stream RSVP when targets were separated between 200 and 600 ms were sustained when targets were in different streams, which suggests that mechanisms co-opted to process items in the left and right visual fields were not independent of each other (Kristjánsson & Nakayama, 2002).

The pattern of errors in dual RSVP experiments have provided additional insights into our understanding of processing limitations with briefly presented stimuli. In contrast to the consistent findings from single-stream RSVP paradigms, experiments with multiple RSVP streams typically do not find evidence of lag 1 sparing when T1 and T2 appear in different streams (Bay & Wyble, 2014; Holländer et al., 2005; Kristjánsson & Nakayama, 2002; T. A. Visser et al., 1999). (An exception to this is a study by Potter, Staub and O'Connor (2002) that did find evidence of lag 1 sparing in a multiple stream RSVP experiment where participants were told in advance the stream in which the targets would appear.) The lack of lag 1 sparing in multiple stream RSVP experiments is generally thought to reflect a mechanism whereby the presentation of a target triggers a shift of attention to that location where it remains for several hundred milliseconds — a phenomenon known as attentional dwell time (Duncan et al., 1994).

A practical advantage of presenting targets in multiple streams was that it allowed researchers to present the two targets simultaneously, and so extend the range of lags at which the attentional blink was tested to include lag 0. Recently, Wyble and Swan (2015) mapped the processing limitation spatiotemporally by presenting targets among a dynamic sequence of letters where each letter was presented at a random location within a grid of 600×600 possible locations (with item size adjusted to control for acuity decrements with increased eccentricity from fixation and masks applied after each letter exposure). They found that, regardless of spatial separation, participants were better able to report both targets when they appeared at lag 0 compared with lag 1. In line with other studies using spatial and temporal separation of targets, they only found evidence of lag 1 sparing when targets were presented at the same location. Performance decreased with greater spatial separation at most lags. An exception to this was that performance was particularly poor when spatial and temporal separation were both very low (particularly lag 1), which Wyble and Swan interpreted as an effect of a brief but intense form of inhibition surrounding the location of the target.

## 1.3 Neural Architecture

### 1.3.1 Neural representation of spatial relationships

Ultimately, the capacity of a visual processing stage depends on the number of neurons that are available and their structural organisation. Visual information is extracted at the retina, with each cell processing information that corresponds with a particular region of space. At early processing stages, the region in space that each cell processes — that cell's receptive field — is small. However, as the information is channelled through later processing stages, inputs from multiple cells are combined such that the downstream cells have much larger receptive fields. Notwithstanding this, the topographic organisation of cells is retained through at least some later stages of visual processing (Hubel & Wiesel, 1959). Critically, projections from certain retinal cells cross over in the brain prior to reaching the primary visual cortex, such that cells that receive information from the right visual field initially project to the left hemisphere, and vice versa. As a result of this, lesions specific to a particular hemisphere may result in functional impairments in reporting visual information from the visual field contralateral to the lesioned hemisphere (Brain, 1941), and importantly, functional advantages that derive from specialisation of one of the hemispheres for a particular task are most likely to affect performance in the opposite visual field. For example, left hemisphere lateralisation of language processing areas in the brain is likely to result in better reporting of linguistic material in the right visual field (Gazzaniga, 1983; Patterson, Vargha-Khadem, & Polkey, 1989).

### 1.3.2 Hierarchical organisation of the visual system

A defining aspect of the visual system is that it contains regions that are selective for specific visual stimuli (Kanwisher, 2010). These regions are broadly organised along two pathways — ventral and dorsal (so named for their respective locations in the brain) — with regions early in each pathway specialising in basic aspects of visual processing (for example, colour or orientation discrimination), and later regions specialising in progressively more complex functions (for example, recognising faces or words) (DeYoe & Van Essen, 1988; Mishkin & Ungerleider, 1982). While this generally hierarchical organisation is considered to describe the majority of cells within the pathways, physiological and psychophysical studies have identified both feedback from later regions to earlier regions on a pathway (Felleman & Van, 1991), and cross-talk between the two pathways (Tse & Logothetis, 2002), suggesting the potential for departures from the hierarchical framework.

A consequence of hierarchical organisation is that a failure to perform a processing task located early in a particular pathway can compromise downstream processing. As such, identifying the original source of processing failures is a key challenge for researchers in visual processing.

### 1.3.3 Parallel and serial processing

Visual objects may comprise many sub-components (for example: words contain letters; letters contain lines and curves etc), which must all be processed before recognition can occur. Parallel processing refers to a mechanism in which multiple sub-components are processed at the same time. Serial processing refers to a mechanism in which multiple items are processed sequentially without overlap in processing time.

Triesman (1991) drew a distinction between parallel and serial processing in her seminal experiments concerning visual search. She showed that, when presented with a busy array of visual items, participants took very little time to identify items defined by a single feature (for example, find all the green items in a display). Moreover, the response time showed little sensitivity to the number of items in the display. The insensitivity to the number of items was thought to occur because all items could be processed in parallel. In contrast, when a task was to identify a conjunction (or combination of features), participants took longer overall, and the response time showed much greater sensitivity to the number of items. This was thought to reflect reliance on a serial processing mechanism. Triesman demonstrated the difference in the sensitivity to the number of items for feature and conjunction searches over a number of paradigms, leading to the general conclusion that an object's features (colour, shape etc) are activated in parallel, but binding these together to form objects requires serial processing.

More recent mathematical approaches have demonstrated that increasing response time is a necessary but not sufficient indication of serial processing. Algom and colleagues (2015) showed that certain parallel models can mimic the linearly increasing search slopes that have long been taken as a signature for serial processing. Recently, systems factorial technology methodology has been used to discriminate between parallel and serial processes in several low level visual processing tasks (Fific, Little, & Nosofsky, 2010; Fific, Nosofsky, & Townsend, 2008; Fitousi, 2015; Townsend & Wenger, 2004). While most applications of systems factorial technology involve simple dot detection tasks, some recent studies have used it successfully to investigate the processes involved in making discriminations across multiple dimensions (Fific et al., 2008). In a recent study, White, Boynton and Palmer (2018) use a similar methodology to determine whether semantic judgments about two words are made in parallel. More details about this study are provided in Chapter 5.

### 1.3.4 Types and tokens

*Type* is used throughout this thesis to refer to feature exemplars (for example: 'red', '45 deg', 'circle', 'bottom-left', 'R' ) of a stimulus on a particular dimension (for example: 'colour', 'orientation', 'shape', 'location', 'letter' etc). Types are generally considered to be represented by the activity of distinct neural units. Where features of a dimension are discrete (for example, letters), a type may be indicated by the activation of a single neuron. Where features are continuous, (for example, colour), a type may be interpolated from the value of multiple neurons (Bowman & Wyble, 2007).

*Token* refers to episodic representations of an object, which can distinguish one encounter with the object from other instances of the same object (Kanwisher & Driver, 1992). In all respects that are important to this thesis, the term token is synonymous with *object file*, which is used in some previous literature (Kahneman, Treisman, & Gibbs, 1992). Tokens have been associated with functions such as object individuation, and maintaining a coherent representation of an object as it changes across time and space (Goodhew, Pratt, Dux, & Ferber, 2013). Token representations are transient, and so are unlikely to be 'hard-wired' to a fixed contingent of neurons in the same way as type representations.

### 1.3.5 Forms of capacity limited processing

Traditionally, models of visual processing have tended to conceptualise capacity limits as a *bottleneck*, with a subset of items being selected for processing at the capacity limited stage, and the remainder of items not receiving processing and hence being unavailable for report. Seminal studies by Sperling (1960) and Potter (1976) refined the bottleneck account by demonstrating that various temporary memory mechanisms existed that could hold information for a short time, and so allow items to be queued for later processing when the capacity of the system was exceeded. In his iconic study, Sperling presented a 4 × 4 grid of letters for a limited duration and required participants to report all of the letters in one condition (the whole-report condition); and all of the letters in a particular row or column (indicated by a tone) in another condition (the partial-report condition). Crucially, the tone indicating which row or column to report in the partial-report condition was usually presented after the letter grid had been removed from the screen. As such, performance in the partial report condition provided an indication of the information that was available in memory at the time of the tone. The performance rate for the probed row/column could then be multiplied by the total number of rows/columns to convert the estimate to a form that was comparable to the number of items reported in the whole report condition. Sperling found that participants were particularly poor at reporting random letters from the 4 × 4 grid in the whole-report condition, with mean performance being 4.3 items. However, when performance for the whole array was estimated from the results of the partial-report condition, the rate of reporting increased to 9.1, suggesting that more items were available (in some form of memory) after the tone than could be reported. These results form the basis of Sperling's conceptualisation of iconic memory, which is that representations of stimuli can maintain their activation for a short time after the offset of a stimulus, but must be converted into a more stable (and capacity limited) memory format in order to be reported. The experiments in Chapter 4 of this thesis use a partial-report methodology that is similar to that used by Sperling.

Potter (1976) made a related finding using a study where participants were shown an RSVP stream of images. If asked to name the image in the series, participants could only name a few. However, if asked to recognise whether an exemplar of a given category had occurred in the stream, participants would have a large chance of correctly identifying the item. She argued that broad category information must be briefly available in a temporary memory storage that she termed conceptual short term memory. Temporary memory stages play an important role in serial bottleneck accounts by allowing neural activity to be maintained while items cannot be immediately processed at the capacity limited stage. If the bottleneck is cleared while the items are still in the buffer, they can be forwarded for processing.

While bottlenecks continue to play an important role in our understanding of capacity limits, recent advances in neural network modelling have identified a range of other neural mechanisms that could explain gaps in conscious awareness without a strict categorical limit on the number of items that can proceed to a certain processing stage. Many such models have been built on the basic assumptions described in parallel distributed processing theories that cognition is achieved through the integration of large numbers of reciprocally connected neurons in parallel, which allows a more graded, probabilistic understanding of capacity limits (McClelland & Rumelhart, 1988; Rogers & McClelland, 2014). One approach that has been important in the understanding of processing limitations in attentional blink is the binding pool model first conceptualised in Bowman and Wyble, (2007) and advanced in subsequent research (Swan & Wyble, 2014; Wyble, Bowman, & Nieuwenstein, 2015; Wyble et al., 2011). In this model, information is stored as a series of links between types and tokens, which can be activated for multiple items in parallel. In contrast to bottleneck models, there is no limit on the number of links that can be active at a particular time. However, increasing the number of links increases the amount of mutual interference between the concurrently active links, resulting in a loss of memory precision and interference between the various stimuli (Swan & Wyble, 2014). Bottleneck and parallel models are discussed in more detail in Chapter 6.

## 1.4 Spatial Biases in Visual Awareness

### 1.4.1 Spatial biases in visual processing

Many studies have sought to gather insight into the nature of capacity limits by studying the pattern of errors that participants make when reporting visual information. It is a central contention of this thesis that the spatial composition of these errors may reflect prioritisation of processing resources at capacity limited stages, and so the direction and size of spatial biases can potentially provide insight into questions about the source of capacity limits, and the neural mechanisms that cause them. However, factors other than prioritisation may cause spatial biases, and understanding these is critical to interpreting their influence on results presented in this thesis.

The study of spatial biases originally developed largely in response to a number of clinical conditions which were associated with large spatial biases in the ability to report perceptual phenomena. The most well known is *neglect*, which is experienced as a result of a lesion to the parietal cortices (most frequently of the right hemisphere) and affects a patient's ability to attend to objects presented to the side of the body contralateral to the lesioned hemisphere (Beschin, Cubelli, Della Sala, & Spinazzola, 1997). When judging the midpoint of a horizontal line (a line bisection task), patients will typically neglect the side of space contralateral to their lesion, and so a patient with a lesion to the right hemisphere will bisect the line to the right of the objective midpoint (Heilman, Bowers, Valenstein, & Watson, 1993). Similar spatial biases are evident from the greyscales task (figure 1), which requires patients to judge the darker (or lighter) of two luminance gradients. The gradients are equivalent in luminance, but are mirror-reversals of each other, so that one has the darker side on the left and the other has the darker side on the right. Here, patients with a right side lesion will typically judge the bar with the dark region to the right to be darker overall (Mattingley et al., 2004). Some patients with temporoparietal lesions will neglect objects contralateral to their lesion only in the case of competing stimulation in the opposite hemifield. This condition is known as visual extinction (Becker & Karnath, 2007).

*Figure 1:* Stimulus for a greyscales task. Participants are asked to report which bar is darkest. Despite the bars being mirror-images of each other, participants are more likely to report the bar with dark side on the left as being darker overall.

Much smaller spatial biases are also evident in non-clinical populations, though in contrast to the tendency of clinical populations to neglect the left visual field (consistent with the greater prevalence of neglect symptoms after right hemisphere lesions), non-clinical populations typically show a reliable advantage in the left visual field for line bisection (Jewell & McCourt, 2000; Mark E McCourt & Jewell, 1999) and greyscales tasks (Nicholls, Hughes, Mattingley, & Bradshaw, 2004). Bowers and Heliman (1980) have termed this phenomenon “Pseudoneglect”. In line bisection and greyscales tasks, participants generally view the stimulus for a long time (often around 3000ms) and may move their eye-movements during the procedure. While it is possible that a preference for scanning the eyes in a particular direction may contribute to the bias, the left advantage also occurs when scanning is controlled, which suggests that the bias has a strong basis in visual-spatial attention (Nicholls and Roberts, 2002). Notwithstanding this, the measured biases from each task do not correlate well, which is thought to reflect that fact that attention is sensitive to specific task demands (Thomas, Loetscher & Nicholls, 2014). Left visual field advantages have also been shown for tasks that require local (rather than global) processing (Evans, Shedden, Hevenor, & Hahn, 2000; Fink et al., 1996; Flevaris, Bentin, & Robertson, 2011; Gable, Poole, & Cook, 2013), perception of shape from shading (Smith, Szelest, Friedrich, & Elias, 2015) and inhibition of return (Spalek & Hammad, 2005). In addition, distractors that are similar to a target in respect of a goal-relevant dimension cause more interference when the distractor appears in the left visual field than in the right visual field (Burnham, Rozell, Kasper, Bianco, & Delliturri, 2011).

A spatial bias for vertically arranged non-linguistic stimuli have been reported for healthy participants in line bisection (Bradshaw, Nettleton, Nathan, & Wilson, 1985; Mark E. McCourt & Olafson, 1997; van Vugt, Fransen, Creten, & Paquier, 2000) and the greyscales task (Nicholls, Mattingley, Berberovic, Smith, & Bradshaw, 2004). In both cases, participants will bisect a line above the objective midpoint, with the extent of the bias exaggerated in clinical populations.

There are well documented right visual field advantages in a number of tasks that use language stimuli. For example, participants are faster and more accurate to name both words and letters when these are presented unilaterally in the right visual field (Bryden, 1966; Mishkin & Forgays, 1952; M. J. White, 1969). Here, stimulus exposure is often brief compared to line bisection and greyscales tasks (for example, Bryden used an exposure time of 10 ms), and participants are generally required to fixate centrally. As such, processing is more likely to rely on representations stored in iconic memory (Sperling, 1960), and is not affected by differences in scanning patterns. Right visual field advantages are also found in experiments that require participants to report bilaterally presented words (Davis & Bowers, 2004; Hunter & Brysbaert, 2008), or make semantic judgements about bilaterally presented words (A. L. White et al., 2018). In these studies, exposure time is still quite low (for example, A.L. White presented stimuli for 42 ms), though stimuli are masked, which is argued to terminated information in iconic memory (Enns & Di Lollo, 2000, though see Smithson & Mollon, 2006, for limitations in this approach). However, studies that require participants to report bilaterally presented *letters* have tended to find left advantages (Goodbourn & Holcombe, 2015; Holcombe, Nguyen, & Goodbourn, 2017), though these studies have tended to use more elaborate paradigms with target letters embedded in streams of distractors. Chapter 3 investigates the basis of left biases when letter targets are simultaneously presented to the left and right visual fields.

### 1.4.2 Hemispheric accounts of spatial biases

Given the strong influence of clinical cases in the literature, spatial biases have often been attributed to differences between the cerebral hemispheres. By this account, spatial biases occur because one of the hemispheres has a functional advantage in performing a particular processing task, and thus items that are presented in the visual field contralateral to the specialised hemisphere will be more efficiently processed than the items presented in the visual field ipsilateral to the specialised hemisphere.

The left visual field advantages usually observed in horizontally aligned non-linguistic tasks are traditionally explained as a corollary of Kinsboune's activation theory (1970). Here, the right hemisphere is thought to be preferentially activated by spatial tasks, leading to an overestimation of the extent of the left visual field that causes participants to perceive the middle of an object to the left of where it objectively is (Bowers & Heilman, 1980; Bradshaw, Nathan, Nettleton, Wilson, & Pierson, 1987). Right hemisphere selectivity for spatial stimuli has been confirmed by neuroimaging studies that show that centrally presented spatial tasks tend to activate right regions of the brain (Marshall et al., 1997).

The right visual field advantage usually observed with language stimuli are traditionally explained by the left lateralisation of language areas of the brain (Bryden, 1966; Cohen et al., 2000; M. J. White, 1969). Recent imaging studies have found evidence that the left hemisphere shows more activation than the right hemisphere to words and frequent quadrigrams (four letter combinations), but not letters. Vinckier and colleagues (2007) argue that neural units representing letters are distributed across both hemispheres, but converge to the left hemisphere at later processing stages where letter combinations and ultimately orthographic representations of words are formed.

Critically, while the standard pattern of right hemisphere lateralisation of spatial attention and left hemisphere lateralisation of language occurs for most people, it is common for healthy subjects to demonstrate different patterns, including where both language and spatial attention are lateralised to the same hemisphere (Flöel, Buyx, Breitenstein, Lohmann, & Knecht, 2005). Exceptional patterns of lateralisation are more common in, but not exclusive to, left handers (Geschwind & Galaburda, 1987).

Often, spatial biases in cases where objects are presented simultaneously in the left and right visual fields are larger than when a single item is presented in either of the visual fields. Boles (1990) argues that this occurs because, in cases of a single item, processing is transferred to the preferred hemisphere and so can access the superior processing resources albeit after a short delay. In the case of dual stimulation, the relevant processing areas in the superior hemisphere is already engaged, and so the processing must occur in the inferior hemisphere, creating a larger deficit.

Vertically aligned stimuli do not differently stimulate the two cerebral hemispheres, and so spatial biases in these tasks cannot be explained by differences between the hemispheres. However, Drain & Reuter-Lorenz (1996) argue that upward biases in line bisection and similar tasks are consistent with an asymmetry in relative activation of the dorsal and ventral streams, which would suggest that the biases in horizontally and vertically aligned tasks both derive from structural differences in brain organisation that are likely to be innate. According to their argument, the upper stream bias occurs through a mechanism that is similar to that proposed under Kinsbourne's activation theory (described above). Neurophysiological evidence has demonstrated that the ventral stream receives stronger input from the upper visual field, and the dorsal stream receives stronger input from the lower visual field (Previc, 1990). The ventral pathway is thought to be specialised for object processing (Mishkin & Ungerleider, 1982), and so is strongly activated by the task requirement to identify letters. This activation biases attention to items in the upper visual field, allowing enhanced processing of items located in the upper region than the lower region.

### 1.4.3 Cultural accounts of spatial biases

The hemispheric accounts of a number of spatial biases have been challenged by evidence that the biases observed in some paradigms are eliminated or reversed in participants with experience reading from right to left (Chokron & De Agostini, 2000; Sylvie Chokron & Michel Imbert, 1993; Rinaldi, Di Luca, Henik, & Girelli, 2014; Sakhuja, Gupta, Singh, & Vaid, 1996; Jyotsna Vaid & Maharaj Singh, 1989). As these participants would be expected to have the same division of processing across the hemispheres as left to right readers, a hemispheric account of the differences cannot explain the different results.

In particular, left biases have been found to reverse to give right biases when participants are native readers of right to left language in line bisection (Chokron & De Agostini, 2000; Sylvie Chokron & Michel Imbert, 1993) and inhibition of return tasks (Spalek & Hammad, 2005). Similarly, greyscales tasks have also been found to be modified in participants that have experience reading right to left. However, in this case, the bias was merely eliminated, rather than reversing (Friedrich & Elias, 2014). Reading direction has also been found to modulate left biases in a task in which participants are shown ‘chimeric faces’ which are formed by splitting a photo down the midline and joining each half with a mirror-image of itself, to create two new faces (one based on the left side of the face and the other based on the right side of the face). When participants are asked to compare each chimeric face with the original face, they typically judge the face composed of two left sides as being more similar to the original (Gilbert & Bakan, 1973). However, several studies have found that this left side bias is eliminated in right to left readers (Sakhuja et al., 1996; Jyotsna Vaid & Maharaj Singh, 1989). A recent study has found that this bias in matching chimeric faces with the original is also sensitive to the direction of reading when manipulated using Chinese text, which can be read from left to right or right to left. However, this experiment found no effect of reading direction on a line bisection or greyscales task, leading the authors to suggest that spatial biases may be strongly task dependent (Chung, Liu, & Hsiao, 2017).

Reading direction also moderated left biases in two experiments that required participants to report two targets within dual RSVP streams. The first was an experiment which presented targets at different times in the streams (Śmigasiewicz et al., 2010). When the stimuli were presented in a script normally read left to right, participants with experience reading that script were better at reporting the second target when it was presented in the left visual field, regardless of whether the first target and second targets were presented in the same or different streams. However, when the stimuli were presented in a script read from right to left, this left advantage was smaller. The second was an experiment where participants must report both targets at the same time (Holcombe et al., 2017). In this experiment, English letters were presented in their canonical orientation in one condition, and in different orientations (for example, mirror-reversed) in other conditions. Holcombe and colleagues argued that the different orientations would encourage different reading directions (for example, mirror reversed text would be read from right to left). They found that with the canonical presentation, participants were more likely to accurately report the item on the left, but that this effect diminished when the stimulus was presented in mirror reversed text.

### 1.4.4 Goodbourn and Holcombe (2015)

In a series of experiments, Goodbourn and Holcombe (2015) found robust spatial biases in a paradigm in which participants must report two briefly presented targets, which are always presented at the same time in different locations and are embedded in dynamic streams of letters. I describe their methodology and results in detail here, as this paradigm forms the basis for several experiments in this thesis.

Goodbourn and Holcombe presented two RSVP streams of upper case letters (see Figure 2), each 6 deg from fixation. At some time during the RSVP sequence, a circle appeared around either a single item in one of the streams; or around items in both streams simultaneously. Participants were required to report targets by selecting them from an array of letters. The order in which the targets from the left and right streams were reported varied randomly from trial to trial and was not signalled until the response arrays appeared.

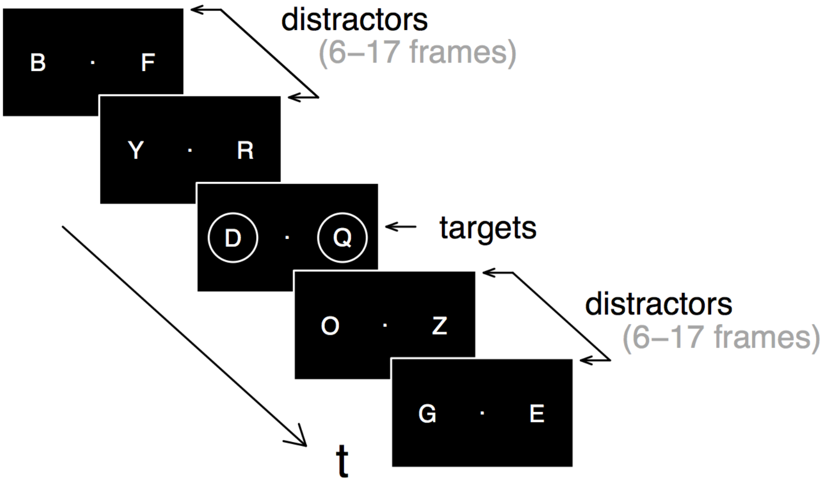

*Figure 2:* Schematic of dual RSVP stimulus used by Goodbourn and Holcombe. Participants must report both target letters. This stimulus forms the basis for experiments conducted as part of this thesis.

A key finding was that when a single target was presented, participants achieved similarly high rates of accuracy for reporting the letter for targets in the left and right streams. However, when targets were presented in both streams simultaneously, and participants were required to report both, performance was close to that achieved in the single target condition for one of the streams, but was much lower in the other stream. Goodbourn and Holcombe referred to this phenomenon as Pseudoextinction, however subsequent articles finding similar results have referred to this as the second-target deficit, which I adopt here. The effect was large, with participants scoring on average 20 percentage points lower in the deficient stream relative to single-stream performance.

A feature of Goodbourn and Holcombe's results is that the location of the deficient stream was remarkably consistent across participants. When the streams were aligned horizontally, with one stream to the left of fixation and the other to the right, participants typically showed impaired performance in the right stream. When the streams were aligned vertically, with one above fixation and the other below, participants typically showed impairment for the lower stream. As discussed in the previous section, consistent spatial biases tend to be explained by either differences in hemispheric processing (Bowers & Heilman, 1980; Bradshaw et al., 1987; Bryden, 1966; Cohen et al., 2000; Davis & Bowers, 2004; M. J. White, 1969), or prioritisation in the direction of reading (Chokron & De Agostini, 2000; Sylvie Chokron & Michel Imbert, 1993; Holcombe et al., 2017; Rinaldi et al., 2014; Sakhuja et al., 1996; Śmigasiewicz et al., 2010; Spalek & Hammad, 2005; Jyotsna Vaid & Maharaj Singh, 1989). Goodbourn and Holcombe favoured a reading direction account in the case of their second-target deficit, largely on the basis that hemispheric differences could not explain the strong lower field deficit observed in the vertical arrayed condition. The effect of reading direction on the second-target deficit is the focus of Chapter 3 of this thesis.

The dual RSVP paradigm used by Goodbourn and Holcombe allowed them to make further claims about the processing stage at which the second-target deficit occurred. Crucially, each RSVP stream contained each letter once. This meant that it was possible to calculate where in the stream the reported letter had occurred relative to the target. To operationalise this, Goodbourn and Holcombe created a distribution of serial position errors (SPEs) for letters reported from each stream for each participant. Reporting the target has an SPE of 0. If instead the participant reports the item immediately before the target, this has an SPE of -1, and if the participant reports the item immediately after the target, this has an SPE of +1 and so on. One way that a second-target deficit could arise is if participants sampled from the prioritised stream first, and then from the deficient stream. If this had occurred, the serial position errors for the left stream should be earlier than the serial position errors for the right stream. In fact, serial position errors did not significantly differ between streams, suggesting that sampling occurred for both streams at the same time on average.

In the absence of sequential sampling, Goodbourn and Holcombe suggest that the second-target deficit reflects a post-sampling process that has a limited capacity. Prioritisation of one of the items at the capacity limit creates the large difference in performance between two of the streams. Goodbourn and Holcombe contemplate both parallel tokenisation and bottleneck models that could account for the observed spatial biases. Chapter 6 of this thesis describes these models in more detail, and investigates Goodbourn and Holcombe's claim that a serial bottleneck is more likely to explain the second-target deficit than a parallel account.

## 1.5 Spatial Biases in the Reading Process

### 1.5.1 Capacity limits in reading

Goodbourn and Holcombe found evidence of a second-target deficit in a laboratory task that was obviously different to the type of visual processing tasks that one might encounter in everyday life. However, their explanation — that the second-target deficit reflects a capacity limit in late stage processing of simultaneously presented items — suggests that this research could potentially have relevance for a range of tasks that require multiple objects to be identified from visual scenes, such as locating a car in a busy parking lot, or a particular person in a photo containing multiple faces.

One task that is a particularly strong candidate for being affected by the proposed capacity limit is reading. Fluent reading requires a large number of objects to be identified in the correct order to comprehend meaning from the text. In addition to the direct association between the letter stimuli used by Goodbourn and Holcombe, and reading, Goodbourn and Holcombe posited that the simultaneous targets in their dual RSVP experiments were prioritised at the capacity limited stage in the same left to right, top to bottom order as words must be processed when reading. The extent of capacity limits in reading, and in particular, whether multiple words are processed at one time, remains a key difference between prominent models of eye-movements in reading (Reichle, Vanyukov, Laurent, & Warren, 2008). Experiments aimed at resolving this debate have typically tested predictions of these models relating to the patterns of fixations and saccades as participants read long passages of text (Cutter, Drieghe, & Liversedge, 2017; Dare & Shillcock, 2013; Drieghe, Pollatsek, Juhasz, & Rayner, 2010; Drieghe, Rayner, & Pollatsek, 2007; R. Engbert, Nuthmann, Richter, & Kliegl, 2005; K. Rayner, Juhasz, & Brown, 2007; Risse, Hohenstein, Kliegl, & Engbert, 2014). Chapter 5 of this thesis investigates whether the dual RSVP paradigm contemplated in this thesis may also provide insight this debate.

### 1.5.2 Text processed at each eye movement

Skilled adult readers typically move their eyes across the page in a series of fixations (landings) and saccades (jumps). Almost all information that is used in the reading process is extracted during the fixations (Matin, 1974), which last around 200-250 ms fixations for an adult reader, with saccades serving as a means to get the eyes to the next landing point. Visual constraints limit processing on each fixation. Acuity is best for characters that are extracted by the fovea (the area closest to the point of fixation) and is diminished for characters in the parafovea (the ring directly around the fovea), and in the periphery (the area outside the parafovea).

Experiments that manipulate the content of parafoveal and peripheral words (such as the gaze-contingent moving window technique set out in McConkie & Rayner (1975) and Rayner (2014), and the boundary paradigm set out in Rayner (1975)), have established that readers do extract some information from the parafovea. The region from which readers access information is termed the perceptual span, which is usually 3 to 4 character spaces to the left of fixation to about 14-15 character spaces to the right of fixation for skilled adult readers of alphabetic text like English (McConkie & Rayner, 1975). However, some studies have found that word encoding is unlikely to extend more than 7-8 characters to the right of fixation, with the more extreme characters thought to provide only low spatial frequency information about letter shape and word length (Keith Rayner, Well, Pollatsek, & Bertera, 1982; N. R. Underwood & McConkie, 1985). The asymmetry in the perceptual span demonstrates that this limitation is not simply a reflection of limitations in visual acuity (which are symmetric), but rather, is likely to reflect a limitation in attention that is influenced by experience reading a particular script. Consistent with this, the perceptual span is smaller for beginner readers (Häikiö, Bertram, Hyönä, & Niemi, 2009; Keith Rayner, 1986) and dyslexic readers (Keith Rayner, Murphy, Henderson, & Pollatsek, 1989), and critically for this thesis, is also sensitive to characteristics of the writing system (Chen & Tang, 1998; Inhoff & Liu, 1998), including the direction of reading, with readers of Hebrew (read right to left) showing a perceptual span that extends further to the left than the right (Pollatsek, Bolozky, Well, & Rayner, 1981).

Further evidence that at least partial lexical processing occurs for parafoveal words comes from studies that show that access to parafoveal information can infer a *preview* benefit, which reduces the duration of subsequent fixations to the location of the parafoveal word (for example, see Reingold, Reichle, Glaholt, & Sheridan, 2012). Several studies have demonstrated that benefits accrue not only from the preview of identical words, but also from the preview of orthographically and phonologically related words (see Schotter, Angele, & Rayner, 2012 for a review), and controversially, preview of semantically related words (Schotter, 2013; Veldre & Andrews, 2016a, 2016b, 2018).

### 1.5.3 Serial and parallel models of reading

After several decades of intensive research, many models of reading have been proposed. Here, I outline E-Z Reader (Alexander Pollatsek, Erik D Reichle, & Keith Rayner, 2006; Reichle, Pollatsek, Fisher, & Rayner, 1998; Reichle, Rayner, & Pollatsek, 2003), and SWIFT (Ralf Engbert, Longtin, & Kliegl, 2002; Kliegl & Engbert, 2003), which are models of eye-movement control in reading and provide a clearly specified account of the relationship between the perceptual, attentional and lexical processes that contribute to reading.

E-Z Reader (see figure 3) is described as a *serial attention shift* model, which reflects the central assumption of the model that lexical processing occurs for one word at a time. Lexical processing incorporates two stages. The first, *L1* (called the 'familiarity check' in early conceptions of E-Z Reader), provides an early index that lexical retrieval is likely to be successful, which informs the programming of eye-movements. The second, *L2*, provides full lexical access to word representations stored in long-term memory that are required to integrate information from the text with existing semantic knowledge. When L2 processing is complete, attention moves to the next word, where L1 and L2 begin again. Eye-movements are also programmed in two stages. *M1* is a labile stage which can be cancelled in response to the outcomes of ongoing lexical processing. *M2* is a non-labile stage which cannot be cancelled. The most recent version of E-Z Reader has also incorporated two additional stages *(A and I)*, which relate to stages involved with shifting attention to the next word, and post-lexical integration. A central assumption of the E-Z Reader model is that attention can shift to a word before an eye-movement is made to it. This means that lexical processing can occur for a word before that word is fixated, which allows the model to account for preview benefits while still maintaining the strict assumption that lexical processing occurs for one word at a time. The two stages of eye-movement programming (M1 and M2) allow the model to account for situations in which the word to the right of the fixated word is identified before an eye-movement has been made to that word, making it efficient for the eyes to 'skip' over this word. The E-Z Reader model shares some features with the serial bottleneck account that Goodbourn and Holcombe used to explain the deficits in their dual RSVP experiments. In particular, as well as the limitation that only one item is processed at a time, both accounts argue that this serial stage is subsequent to an earlier parallel stage. However, while E-Z reader assumes that this stage, which they label stage "V" is limited to parallel processing of low spatial frequency information for the purposes of determining the location of subsequent fixations, Goodbourn and Holcombe speculate that early representations of the letters themselves are likely to be activated in parallel. As such, the E-Z reader model contemplates an earlier convergence to serial processing than would be predicted by the serial bottleneck account set out in Goodbourn and Holcombe (2015).

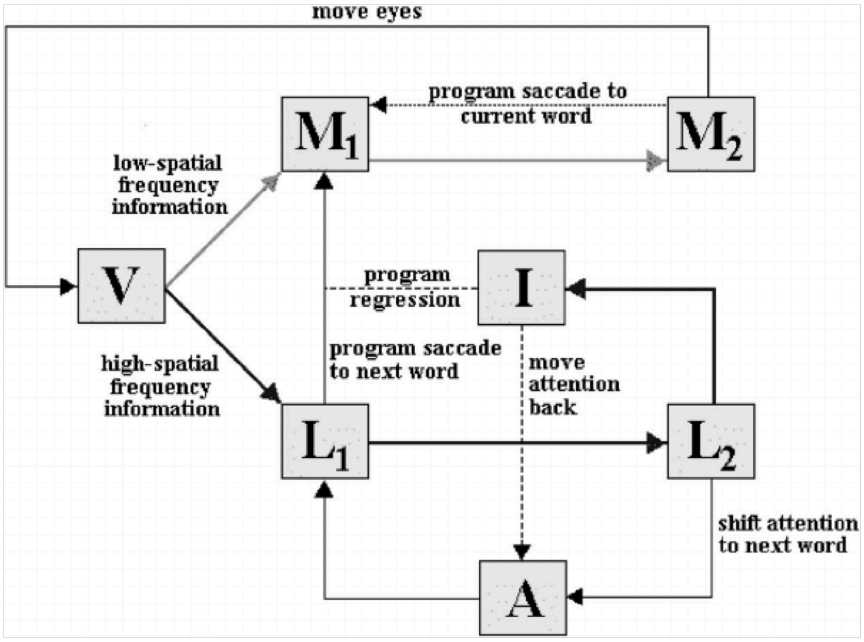

*Figure 3:* Schematic of E-Z Reader (Alexander Pollatsek et al., 2006; Reichle et al., 1998; Reichle et al., 2003). Stages of processing depicted in the model are: (V) preattentive visual processing; (L1) familiarity check; (L2) Lexical Access; (M1) labile saccadic programming; (M2) non-labile saccadic programming; (A) Attentional shift; and (I) lexical integration. Adapted from "Using E-Z Reader to Simulate Eye Movements in Nonreading Tasks: A Unified Framework for Understanding the Eye-Mind Link" by Reichle, E. D., Pollatsek, A, and Rayner, K. (2012), Psychological Review, 119(1), 155-185. Copyright: © 2012 by the American Psychological Association.

SWIFT (figure 4) is described as a *gradient of attention guidance* model. In contrast with the one-word limit associated with E-Z Reader, SWIFT assumes that lexical processing occurs for up to four words in parallel. The amount of resources that are devoted to processing each word is influenced by a range of factors that includes the position of the word relative to fixation. Other things being equal, the fixated word (n) receives the most resources, followed by the words immediately to the left (n-1) and right of fixation (n+1), with the second word to the right of fixation receiving the least resources (n+2). While this distribution provides a small processing bias towards earlier words in the four word sequence, proponents of E-Z Reader highlight that this is not sufficient to ensure words are processed in a strict left to right order, which they argue is necessary to comprehend meaning from text (A. Pollatsek, E. D. Reichle, & K. Rayner, 2006).

Unlike E-Z Reader, which assumes that eye-movements are determined by lexical processes, SWIFT assumes that eye-movements are automatically generated but are sometimes delayed for difficult words.

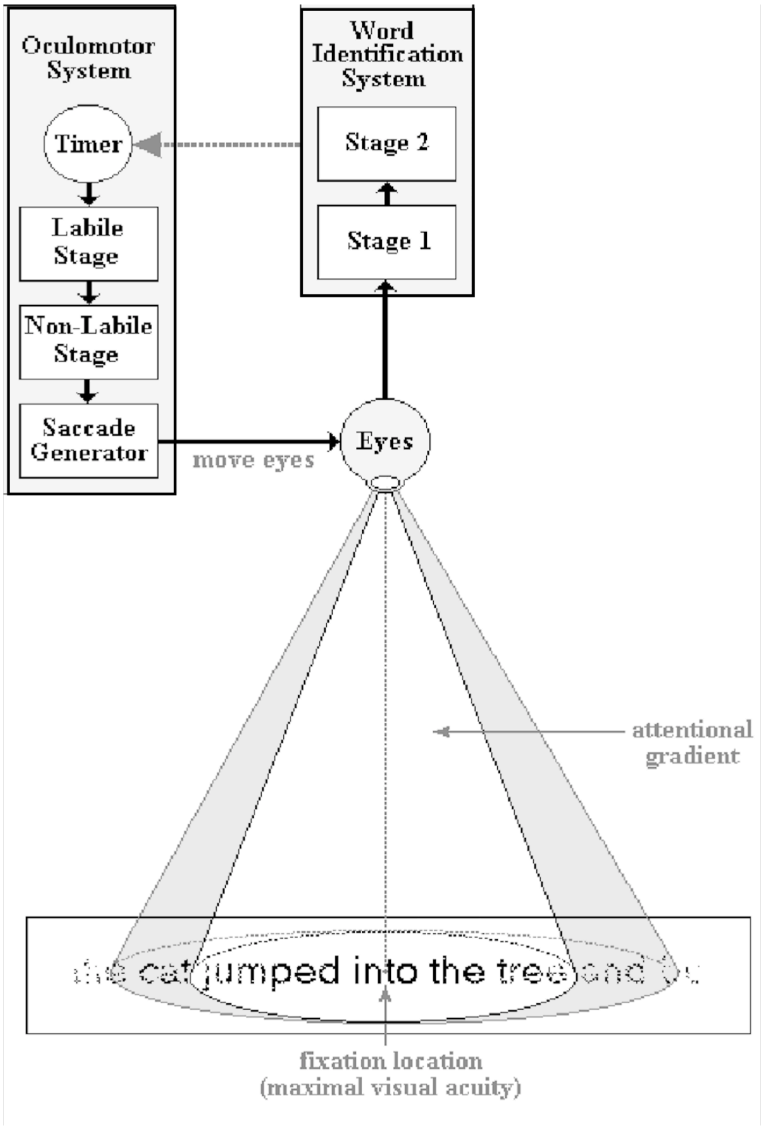

*Figure 4:* Schematic of SWIFT model (R. Engbert et al., 2005). Adapted from "The EZ Reader model of eye-movement control in reading: Comparisons to other models" by Reichle, E. D., Rayner, K, and Pollatsek, A. (2003), Behavioral and brain sciences, 26(4), 445-476. Copyright: © 2003 by the Cambridge University Press.

## 1.6 Goals and Approach

### 1.6.1 Thesis goals

The visual system has a limited capacity to process information extracted at the retina, and sometimes fails to process items that are clearly presented within an observer's field of vision. In this thesis, I investigate a particular failure of awareness that occurs when two target letters embedded in dynamic streams of distractors are briefly presented at the same time in different spatial locations. This paradigm shows remarkable consistency in the spatial pattern of errors that participants make, with studies using streams of English letters consistently finding a deficit in reporting the item in the right stream. It has been suggested that this may reflect a functional strategy used by the brain to prioritise information at a key processing bottleneck.

This investigation has three main goals:

(1) The first is to understand the processes that determine which item is prioritised at the capacity limit. Right visual field deficits across a number of tasks tend to be explained by one of two mechanisms. The first is cerebral lateralisation of resources for spatial attentional, and the second is a learned asymmetry that develops through habitually reading in the same direction. Chapter 3 directly investigates this by testing whether the deficit is sensitive to readers' experience in reading in different directions and the script in which it is presented — cultural influences that would indicate that the deficit is at least partially learned. Chapter 5 also contributes to this goal by investigating whether the spatial bias is eliminated when the

two streams are presented in the same hemifield, which would indicate that the spatial bias is a result of information in the left and right visual fields being processing in different hemifields.

(2) The second is to investigate the nature of the processing responsible for the capacity limit. Chapter 4 investigates a claim that the spatial biases observed in dual stream RSVP experiments are derived from prioritisation of one of the items at a bottleneck. Chapter 6 then draws on an observation that studies with targets at different times show right deficits that are empirically similar to the right stream deficits that have been found when targets are presented at the same time. This Chapter compares the spatial bias in trials with targets at the same time, and at different times, with an eye to exploring whether a single neural mechanism can explain the bias in both cases. It also investigates whether the recent *RAGNAROC* model, which was developed to explain the attentional blink phenomenon, might also explain deficits in dual stream experiments.

(3) The third is to investigate the links between these phenomena and the normal reading process. The main motivation for investigating reading comes from the suggestion in Goodbourn and Holcombe, followed up in Chapter 3, that prioritisation at the capacity limit is sensitive to the direction of reading and so may have a functional role in the process of reading. Chapter 5 investigates whether the spatial bias concerns a stage that processes letters or words, and also discusses the interaction of the capacity limit with cerebral lateralisation. Across several chapters, neural mechanisms that may explain the capacity limit are considered in relation to models of reading.

### 1.6.2 Thesis approach

To achieve these goals, this thesis presents a series of experiments that build on the dual RSVP methodology used by Goodbourn and Holcombe (2015). Over a number of experiments, Goodbourn and Holcombe documented robust spatial biases in accuracy, which were attributed to prioritisation at a capacity limit in visual processing. The experiments in this thesis manipulate aspects of the dual RSVP methodology (such as the items in the streams (Chapters 3 and 5); the locations of the streams (Chapter 5); and the timing of the targets (Chapter 6), to investigate the effect on the size and direction of the spatial bias, and test predictions from Goodbourn and Holcombe's account of the bias.

Following the analysis methods used by Goodbourn and Holcombe, spatial biases are determined using a mixture modelling technique in Chapter 3 and a related rule of thumb in Chapters 5 and 6. Bayesian data analysis techniques are also applied throughout this thesis. These methods are described in more detail in Chapter 2, which describes the approach used to investigate aspects of the capacity limit within this thesis in more detail.

# Chapter 2: Investigating Capacity Limits using Spatial Biases

## 2.1 Chapter Synopsis

As discussed in Chapter 1, spatial biases have been recorded across a number of different paradigms and are usually attributed to either differences between the cerebral hemispheres, or experience reading in a particular direction. The present thesis investigates a particular spatial bias documented in a recent set of dual RSVP experiments in which two targets embedded in dual RSVP streams are presented at the same time, which has been attributed to prioritisation at a serial bottleneck at a late stage of visual processing (Goodbourn and Holcombe, 2015). While the dual RSVP paradigm used in these experiments is more complex than many other methods that have been used to measure spatial biases, it provides an indication of both the accuracy of visual processes and the time at which visual information is extracted. The addition of timing information makes this method well suited to investigating the neural processes that give rise to the bias. This Chapter details the approach used throughout this thesis to measure spatial biases using dual RSVP and related stimuli, and the analytical techniques used to test hypotheses about the neural processes that give rise to these spatial biases.

## 2.2 Main Analytical Techniques Used

### 2.2.1 Mixture modelling

A key advantage of the dual RSVP methodology used by Goodbourn and Holcombe (2015) is that it provides information about both the accuracy and timing of responses. Importantly, accuracy and timing of responses are not measured directly, but are instead constructed from a measure of the serial position errors associated with participant's responses. The serial position of an error refers to the number of items between when the target appeared and when the letter that the participant responded appeared. If a participant correctly reports the target, this is coded as a serial position error of 0, whereas if the participant reports the item immediately before the target, this is coded as a serial position error of -1, and if the participant reports the item that appeared immediately after the target, this is coded as a serial position error of +1. By multiplying the serial position error by the stimulus onset asynchrony, it is also possible to determine the lead or lag time in processing a target. For example, if the stimulus onset asynchrony is 100 ms, a serial position error of +2 indicates that the participant is reporting a target that was presented between 100 and 200 ms after the target offset.

Serial position errors for each participant in a particular condition can be plotted in a frequency histogram, such as that shown in figure 5a. Typically, serial position error histograms reveal two different forms of responses that participants tend to make in dual RSVP experiments, which are identified on the diagram. *Target-related responses* reflects responses in which the participant selects items that appeared at a similar time to the target. This includes correct responses, as well as responses in which participants make small temporal errors. Responses with SPEs that occur a few items before or after the target occur frequently in dual RSVP paradigms, and are indicated by the peak in the SPE histogram. Holcombe and colleagues (2017) speculated that these temporal errors may occur as a result of the cue (circle) binding to the wrong letter in the stream. By their account, letters from the RSVP stream activates multiple letter representations at once that are briefly buffered. The cue generates its own neural representation, which must be bound to an active letter representation. Usually this is the target, but occasionally the cue is bound to a non-target letter representation. While target related responses need not be strictly ‘correct’ (in that the participant need not accurately identify the letter within the target), they indicate that the participant has engaged processing resources as a result of the cue. *Guessed responses* reflect times when the participant did not attend to the target and so was forced to guess the response. When a participant guesses a response, the selected letter could occur at any position in the RSVP stream. As such, guessed responses are indicated in the SPE histogram by a pseudo-uniform component. Note that this uniform component may also include responses where the participant did attend to the letter, but either could not recognise it or made a memory error. These responses result in the same uniform SPE profile as guessed responses and so are indistinguishable in the mixture modelling process.

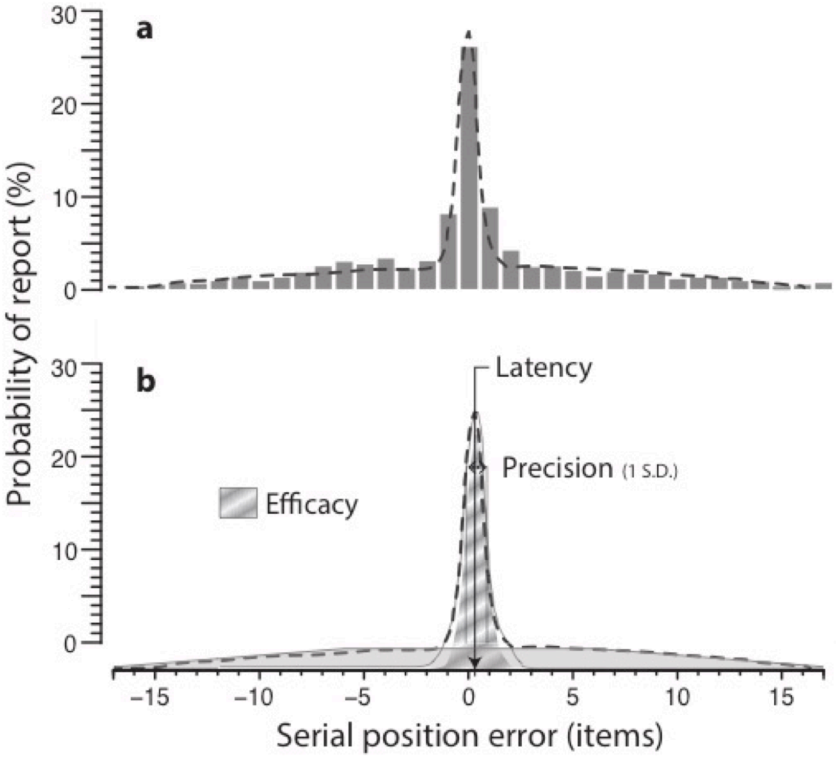

*Figure 5.* Example of mixture modeling distributions. Each letter reported by the participant corresponds to a serial position error. (a) The histogram shows a distribution for a typical participant in one stream for one condition. The dashed line showing the best-fitting mixture model, whose components are shown in panel b. (b) The overall mixture distribution (dashed line) is made up of two component distributions. The area of the Gaussian component (cross-hatched) is the efficacy, its mean the latency, and its standard deviation the precision. The pseudo-uniform (guessing) distribution is shown in light grey.

The mixture modelling technique assumes that all responses fit into either the target-related or guessed responses categories. Target related responses are assumed to be drawn from a Gaussian distribution, and guess trials are assumed to be drawn from a uniform distribution that is tapered at its extrema to reflect the fact that extreme positive SPEs are only possible when the target occurs early in the stream and extreme negative SPEs are only possible when the target occurs late in the stream. Maximum likelihood estimation is then used to fit the

Gaussian-uniform mixture to the empirical SPE distribution for each participant, condition and stream. The maximum likelihood procedure used in this thesis estimates 3 parameters of these distributions, which are shown in figure 5b: *Efficacy* represents the proportion of target related trials (the Gaussian proportion); *latency* represents the average SPE for target-related trials (the mean of the Gaussian); and *precision* is the dispersion of SPEs around the average (the standard deviation of the Gaussian). Parameters are based on estimates from 100 repetitions, with randomised starting values for each parameters. The Gaussian distribution fit the data well, with most the serial position errors of most participants being strongly peaked (the distribution in figure 5 provides an indication of a typical distribution). The mixture modelling procedure was conducted for each participant, for each condition, for each trial. Spatial biases were calculated by subtracting the efficacy in the right trial from efficacy in the left trial. Mixture modelling is applied in Chapter 3.

The experiments in Chapters 5 and 6 also use dual RSVP to measure differences in spatial biases, but present each item in the stream for a longer duration to accommodate more difficult items in the stream, or more difficulty processing targets. The maximum likelihood technique used to estimate the parameters of the Gaussian distribution in Chapter 3 do not work as well with the slower stimulus due to the fact that each item is presented for longer, and so a given temporal error is likely to span fewer items. This means that the Guassian component of the serial position error distribution may cover only a few discrete serial position error units, making it difficult to fit a continuous distribution. As such, mixture modelling techniques are not used in these Chapters. Instead, these Chapters assume that responses within 2 serial positions of the target (SPE +/- 2) are target related, and responses outside this band are guessed. Efficacy is then calculated as the proportion of total trials that are target related. This rule of thumb produces estimates of efficacy that are similar to those produced by mixture modelling. However, it is likely that the method will falsely classify some trials as target related when they were guessed (for example, when a participant guesses a response that happens to be within two serial positions of the target), and some trials as guessed when they were target-related (for example, if the cue is bound to an item more than 2 serial positions from the target). In Chapter 5, the efficacy measure determined by the rule of thumb method is converted to a spatial bias measure by subtracting efficacy in the left field from efficacy in the right field. However, in Chapter 6, the dependent variable is T2|T1, which is calculated as the proportion of efficacious results for the second item for those trials where there has been an efficacious result for T1. This is described further in that Chapter.

### 2.2.2 Bayesian data analysis

The spatial biases extracted though the methods described above are ultimately used to test theories about the causes and consequences of capacity limits in visual processing. Bayes Factors are used to test hypotheses throughout this thesis. Chapters 3, and 6 use the Bayesian paired samples t-tests outlined by Rouder, Speckman, Sun, Morey, and Iverson (2009) and by Wetzels, Raaijmakers, Jakab, and Wagenmakers (2009), Chapter 6 also uses Bayesian ANOVA outlined by outlined by Rouder, Morey, Speckman and Province (2012) and Chapter 4 uses Bayesian ANCOVA as outlined by Rouder and Morey (2012). All tests are implemented in JASP (JASP Team, 2017). Bayes factors compare the likelihood of the data under the experimental and null hypotheses. A Bayes factor of one indicates that the data are equally likely under either hypothesis, whereas a Bayes factor of (for example) three in favour of the null hypothesis ($BF_{01} = 3$) indicates that the data are three times more likely under the null hypothesis than the alternative. In contrast, $BF_{10} = 3$ (note the reversal in the order of the subscripts) means that the data are three times more likely under the alternative hypothesis.

Bayesian methods are increasingly used to test hypotheses in cognitive psychology.

For the analyses in this thesis, Bayesian methods offer two key advantages over classical statistical methods. First, for many tests conducted as part of the thesis, there was not a strong basis for estimating effect size before the commencing the experiment. Had classical methods been used, it would have been necessary to test an overly large sample to ensure the experiments were well-powered. Bayesian methods allow sample size to be determined according to a stopping rule rather than by nominating the sample size before running participants, and so avoids the need to continue to sample participants when evidence is sufficient to support confident findings in relation to stated hypotheses. This was particularly valuable for the experiment using Arabic reading participants in Chapter 3, where recruiting was particularly costly. Second, Bayesian methods can quantify support for hypotheses of no difference, which is utilised in Chapters 3, 5 and 6. Classical statistics do not have the same ability to support a null hypothesis — they may only reject the null, or fail to reject the null. Importantly, failure to reject the null hypothesis in *classical* statistics should not be taken as evidence that the null hypothesis is true, whereas Bayesian statistics can inform such inferences (Gallistel, 2009).

Bayesian methods are sensitive to assumptions about the prior distributions which weight the probability of the data under the alternative hypothesis. I have taken the approach of using default priors from JASP analysis software. These priors are designed to be relatively uninformative about the prior likelihood of a particular distribution of results, and their use ensures that the choice of prior is independent of the motivations of the analyst to achieve a particular result. The default Bayes factor model assumes that effect sizes under the alternative hypothesis follow a folded Cauchy (0,1) distribution.

## 2.5 Additional Procedures

### 2.5.1 Preregistration

To clearly distinguish the pre-planned from the post-hoc (Pierce, 1878), hypotheses and data analysis plans were preregistered on the Open Science Framework and can be accessed at (https://osf.io/search/?q=Ransley&filter=registration&page=1). The analyses presented in this thesis contain several departures from the preregistrations, which are noted in the text.

### 2.5.2 Handedness

For all experiments, participants completed the Revised Edinburgh Handedness Inventory (Williams, 2010) to determine whether they were left or right handed. Scores on the EHI-R range from -400 (complete left-handedness) to +400 (complete right-handedness). For the purposes of this thesis, responses above +200 were considered to be right handed.

### 2.5.3 Eye-tracking protocols

Experiments presented in Chapters 5 and 6 all monitored gaze position to ensure that participants maintained central fixation. During these experiments, participants were seated 57 cm from the monitor, with their face in a chin-rest. The position of the eyes was monitored using an Eyelink 1000, which was calibrated several times throughout the experiment. The experimenter began each trial by confirming that the eyes were positioned centrally.

Eye position was monitored for the duration of the letter streams. Trials were removed when the eye-tracking data indicated that the eyes had strayed more that 1 deg from the fixation point at any point during the trial sequence. If participants made several eye-movements in a row, the experimenter informed them of this.

# Chapter 3: Arabic

## 3.1 Preface to Chapter 3

The contents of this chapter are a minor revision of the following publication, including an online supplement to the article:

Ransley, K., Goodbourn, P. T., Nguyen, E. H. L., Moustafa, A. A., & Holcombe, A. O. (2018). Reading direction influences lateral biases in letter processing. Journal of experimental psychology. Learning, memory, and cognition. doi: 10.1037/xlm0000540

## 3.2 Chapter Synopsis

Humans have a limited capacity to identify concurrent, briefly presented targets. Recent experiments using concurrent rapid serial visual presentation (RSVP) of letters in horizontally displaced streams have documented a deficit specific to the stream in the right visual field. The cause of this deficit might be either prioritisation of the left item based on participants' experience reading from left to right, or a right-hemisphere advantage specific to dual stimulation. Here we test the reading-experience hypothesis by using participants who have experience reading both a language written left-to-right (English) and one written right-to-left (Arabic). When tested with English letters, these participants showed a deficit, of a similar magnitude to that found previously, for reporting the item on the right. However, when the stimuli were Arabic letters the deficit disappeared. This suggests that reading direction plays a large role in the second-target deficit. The pattern of participants' errors suggests where in the processing stream reading experience affects stimulus processing: Specifically, the error pattern suggests that the limited-capacity stage responsible for the deficit corresponds to a post-sampling process such as consolidation into short-term memory.

## 3.3 Introduction

Our capacity to process simultaneous and briefly presented stimuli is limited. To investigate this, Goodbourn and Holcombe (2015) presented RSVP (rapid serial visual presentation) streams of English letters to English readers, with one letter circled to indicate it was the target to be reported. Participants could identify a single target embedded in either of two concurrent streams, but would often miss a target if two (one in each stream) were presented at the same time. This second-target deficit suggests that the requirement to identify multiple concurrent targets may breach a capacity limit in visual processing. By investigating this capacity limit, we can learn about the brain mechanisms that come into play when multiple parts of the visual scene must rapidly be processed.

The pattern of errors in the results of Goodbourn and Holcombe (2015) provided some insights into the nature of the capacity limit that causes the second-target deficit. When the streams were presented with one on each side of fixation, participants were better at reporting the item on the left. Their error pattern suggested, however, that the letters on the left were not sampled before the letters on the right. When participants made errors, they often reported a letter that had appeared a few items before or after the cue, rather than the cued letter itself. If the targets were sampled from left to right, participants would be expected to usually report earlier items from the left stream than from the right stream. In fact, the letters reported from the left stream were presented no later, on average, than letters reported from the right stream. Goodbourn and Holcombe suggested that the letters were sampled independently and often simultaneously, but subsequently the left target letter was prioritised for processing at a higher-level bottleneck. While Goodbourn & Holcombe did not specify the stage at which the bottleneck occurs, their results are consistent with the pattern of deficits predicted by recent theories of consolidation into visual working memory (for example, Ricker & Hardman, 2017). According to this model, viewing a stimulus activates fragile sensory memory traces that are lost if they are not consolidated into more durable working memory traces. Consolidation can only occur if attention dwells on the internal sensory memory trace. Such limits on the ability to consolidate two items into memory are well known for items presented at different times (for example, the attentional blink phenomenon); however, Ricker and Hardman argue that even when stimuli are presented concurrently, they may be consolidated one at a time, and so are subject to the same temporal processing limitations. Thus, the second-target deficit may occur as a result of the temporal delay in processing the second of two simultaneously presented items.

Goodbourn and Holcombe speculated that the order in which the concurrent targets in their dual-RSVP task are processed (at a post-sampling stage such as working memory consolidation) reflects the left-to-right processing used when reading English text. This was consistent with the right visual field disadvantage they observed. However, such disadvantages in reporting items in the right visual field in conditions of dual stimulation are traditionally explained not by implied reading order, but rather by differences between the two cerebral hemispheres (Boles, 1990).

Recently researchers have begun to investigate whether it is reading direction that causes the visual-field asymmetries that are traditionally attributed to hemispheric differences. Specifically, researchers have compared visual-field task asymmetries for readers of right-to-left scripts with those who read left-to-right scripts. In most published studies, left biases in readers of languages written from right to left have been reported to be either reversed to yield a comparable right bias (and aesthetic preference: Chokron & De Agostini, 2000; for example, line bisection: S. Chokron & M. Imbert, 1993; Rinaldi et al., 2014; inhibition of return: Spalek & Hammad, 2005), or diminished relative to left to right readers (preferred viewing location: Deutsch & Rayner, 1999; for example, luminance judgements: Friedrich & Elias, 2014; and perception of facial affect: J. Vaid & M. Singh, 1989). A few studies have found that left biases were preserved in right-to-left readers (for example, see Nicholls & Roberts, 2002). Overall, this body of research provides good evidence that reading direction plays a role in at least some spatial biases. However, to the best of our knowledge, none of the studies to date has been able to distinguish whether native reading order affects prioritisation at the sampling stage, or instead at later processing stages. Moreover, almost all of these studies have assessed the effect of reading direction on tasks that do not use letters or words, thus it is unclear what these studies can tell us about how the visual system negotiates the bottlenecks of letter or word processing. An exception to this is the study of Śmigasiewicz and colleagues (2010), which compared biases of readers of German (read left to right), Chinese (read top to bottom) and Hebrew (read right to left) on a task that required participants to report two targets (each presented at a different time) from two horizontally displaced RSVP streams of letters. Śmigasiewicz and colleagues found left biases in all participants regardless of whether the stimulus was presented in their native language or in a latin alphabet. However, the bias was reduced in Chinese and Hebrew readers relative to German readers when the stimulus was presented in the reader's native language. While Śmigasiewicz and colleagues use two RSVP streams in a similar configuration to the RSVP streams used by Goodbourn and Holcombe (2015), the two experiments differ in the timing of the targets (successive in Smigasiewicz et al; simultaneous in Goodbourn and Holcombe). Successive targets may trigger a shift of attention that mimics the shift of attention required to progress along a line of text when reading. Such a shift would create a systematic difference in the time at which the items were sampled which could account for spatial biases in this context. In contrast, using simultaneous targets, Goodbourn and Holcombe found that items in the left and right streams were sampled independently and often simultaneously, and so spatial biases in this context were attributed to post-sampling stages of processing. Given that the spatial biases observed across the two experiments may occur at different stages of processing, it is not clear that reading direction would affect the biases observed by Goodbourn and Holcombe in the same way as it does for Śmigasiewicz and colleagues.

The present experiment investigated whether the second-target deficit studied by Goodbourn and Holcombe (2015) is shaped by reading direction and examined the processing stage at which the deficit occurs. To examine the effect of reading direction, we used participants who had both right to left (in Arabic) reading experience and also left to right (in English) experience in order to decouple lateral biases due to hemispheric differences from biases due to reading direction. The stimuli in one block of trials were presented in English and in the other block of trials were presented in Arabic. The stimuli were nearly identical to the dual-RSVP streams used by Goodbourn and Holcombe with the exception that Arabic letters were used in the Arabic condition. The participants were told that on most trials, two circles would simultaneously appear, one around each stream, and they were to report the cued letters. As in Goodbourn and Holcombe, the second-target deficit was indicated by the difference between the proportion of accurately reported trials for the left and right streams. If the right-side deficit previously observed in the dual-target condition in left-to-right readers is related to the reading direction associated with the script, it should reduce or reverse when bilinguals are tested with Arabic letters. Thus, our primary hypothesis is that the second-target deficit (expressed here as a right deficit) should be greater in the English condition than the Arabic condition. To investigate the stage of processing at which the deficit occurs, we observed the position in the stream of the letters reported by the participant relative to the target letter (in both Arabic and English trials). If the deficit reflects a delay in sampling items from one of the streams, we would expect participants to report earlier-presented items in the better-reported stream, and later-presented items in the more poorly reported stream. This would be expected in both languages (i.e., earlier left items than right items for English; and earlier right items than left for Arabic). However, if the deficit reflects a post-sampling process—as Goodbourn and Holcombe suggested—we would not expect the position of responses relative to targets to differ between streams in either language. To clearly distinguish the pre-planned from the post-hoc (Pierce, 1878), we preregistered our data analysis plan (https://osf.io/s9n2d/), which was designed to assess whether participants' left bias differed between the Arabic and English conditions.

## 3.4 Method

### 3.4.1 Participants

Seventeen adult participants (5 male, 12 female) with substantial experience reading both Arabic and English were recruited by word of mouth and from the first-year undergraduate participant pools of the University of Sydney and Western Sydney University. First-year psychology students received course credit for participating, while other participants were paid $30. All participants were naïve to the purpose of the study. Language experience was assessed by performance on reading-speed tests in Arabic and English based on the International Reading Speed Texts (Trauzettel-Klosinski & Dietz, 2012).  Each test is normed on monolingual native speakers. We anticipated that native-level competence in both languages would be uncommon in our sample, so we opted to omit only those participants who read at more than four standard deviations slower than the test norm in either language. One participant met this criterion (for the Arabic test), and was omitted from subsequent analysis. Note that this is a deviation from our preregistered data analysis plan, which stated that participants would be omitted if they read more than three standard deviations slower than the test norm. Applying this criterion would have severely compromised our sample size, with a further eight participants subject to omission based on their reading level in either English (5 participants) or Arabic (3 participants). On balance, we decided that retaining these participants was preferred given our aim was simply to recruit participants with strong competence habitually reading in the correct direction, which is likely to occur prior to achieving native-level competence. Had we instead omitted these 8 participants, the results would have been similar to those reported in our results section, but with Bayes Factors closer to one (i.e., the same conclusions, but with less strong support).

Reading speed in English ranged from 113 to 270 wpm. The mean of 171 wpm (SD = 45 wpm) was around two standard deviations lower than the test's adult norm, 228 wpm (SD = 30 wpm). Reading speed in Arabic ranged from 68 wpm to 199 wpm. The mean of 134 wpm (SD = 46 wpm) was close to the adult norm of 138 wpm (SD = 20 wpm). All participants had learnt to read Arabic in childhood, and were currently either working or studying in an English-speaking environment.

The final sample size reflected a preregistered (https://osf.io/s9n2d/) Bayesian stopping rule: that participant recruitment and testing would continue until the evidence favoured the primary hypothesis or the null hypothesis by a factor of five to one or more. This level was passed well before testing concluded (see 'Results') because in practice, the time-consuming mixture modeling and Bayes factor computation was completed every few days rather than after every participant. Thus, 17 participants had completed the experiment at the time that the Bayes factor was first known to have exceeded the criterion.

Based on the Revised Edinburgh Handedness Inventory (EHI-R Williams, 2010), all participants were right-handed except one, who was left-handed. All analyses were also run without the left-handed participant, and the same pattern of results was found.

### 3.4.2 Apparatus

Stimuli were generated using MATLAB R2014b with Psychtoolbox-3 (Brainard, 1997; Pelli, 1997; Pelli, Burns, Farell, & Moore-Page, 2006) on a MacBook Pro, and displayed on either a Samsung S27A950D LCD monitor or an EIZO FG2421 LCD monitor. Both monitors had a resolution of 1600 × 900 pixels and a nominal refresh rate of 60 Hz. Participants were seated in a dark room with their head supported on a chin-rest at a 57cm viewing distance from the monitor. Oral responses for the reading speed test were recorded using a Sony ICD-PX440 Digital recorder. Start and finishing times for the reading speed test were extracted by scanning through the audio file. For the RSVP task, participants wore headphones that delivered an auditory tone to signal the beginning of each trial. Responses for the RSVP task were made using a mouse placed to the participant's right-hand side.

### 3.4.3 Procedure

Participants completed one block in Arabic and one block in English, with the order of the blocks counterbalanced across participants. Within each block, participants completed a reading-speed test immediately followed by a dual-RSVP task. Participants were required to take a five-minute break between the two language sessions.

Reading-speed test. Individual paragraphs from the English and Arabic editions of the International Reading Speed Tests or IReST (Trauzettel-Klosinski & Dietz, 2012) were presented on the computer in white against a black background. The English font was Verdana, and the Arabic font was Geeza Pro. The letter height was 3° of visual angle.

Paragraphs 3 and 5 were used from both the English and the Arabic editions of the IReST (the two extracted from the Arabic edition were direct translations of the two extracted from the English edition). The allocation of paragraph (i.e., paragraph 3 or paragraph 5) to language was counter-balanced across participants, ensuring that no participant read the same paragraph in both languages.

Participants made a mouse click to begin the reading-speed test, after which the stimulus was presented immediately. Reading speed was calculated as the number of words read per minute, not including omitted or incorrectly read words.

Dual-RSVP task. Stimuli were white lowercase letters, presented against a black background. Each participant completed one block of trials with English letters and one block of trials with Arabic letters. The letters appeared in Courier New font in both language conditions. A white fixation circle of 0.25° diameter was located at the centre of the screen. One letter streams was centred 6.0° directly to the left of fixation, and the other was centred 6.0° directly to the right of fixation. Each stream consisted of a serial presentation of 18 different letters in a random order (Figure 6). For the English trials c, f, j, n, q, u, v and y were excluded to reduce confusability among letters; for the Arabic trials, ظ, ض, ذ, ث, ت, ر, ف, س, ح and ه were excluded. For the English letters, the maximum height was 1.9° (measured using letter f) and the maximum width was 1.5° (measured using letter m). For the Arabic letters, the maximum height was 1.9° (measured using letter ل) and the maximum width was 1.6° (measured using letter ش).

Participants were instructed to fixate on the central white dot for the duration of the trial. An auditory tone and two white rings at the locations of the streams (both of 250 ms duration) indicated that a trial was about to commence. The first item appeared 1 s later.

Each letter in a stream was presented for 83 ms followed by a 33 ms blank interval (8.6 items per second). The serial position of the target letters was between the 7th and 12th inclusive and was randomly chosen on each trial. Each target letter was cued by a ring that enclosed it. The rings were white, of 0.1° thickness, subtended 5°, and were presented for the same duration as the letter.

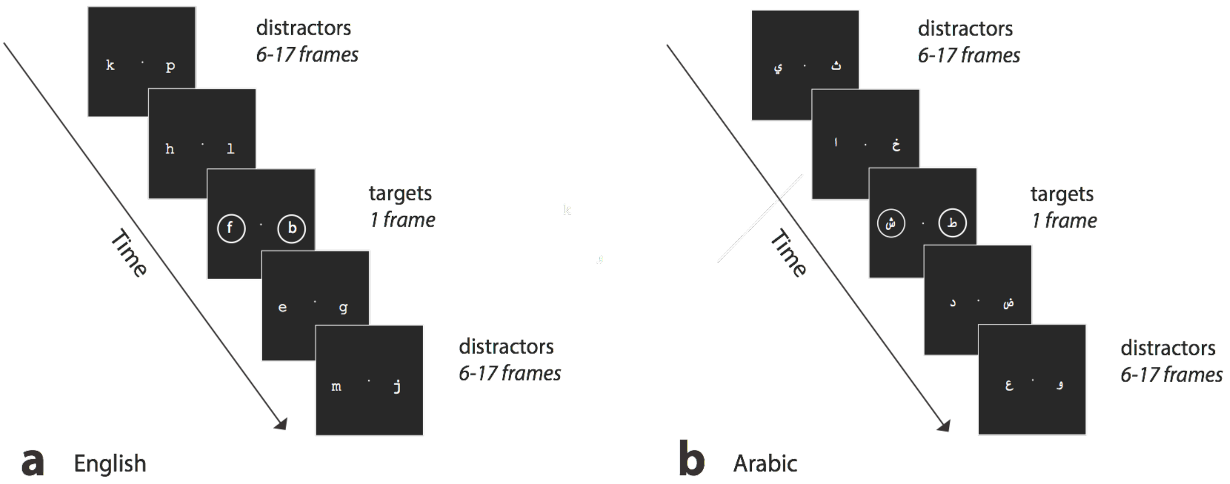

*Figure 6:* Schematic of the stimulus used in the experiment. (a) English condition. (b) Arabic condition.

Participants completed 24 practice trials before commencing the dual-RSVP task in each language. The dual-RSVP task contained 140 trials per language, so participants completed 280 trials in total. In 100 of the 140 trials, targets were presented simultaneously in both streams. In the remaining 40 trials, streams were presented on both sides but only one stream was cued (in 20 trials this was the left stream and in 20 trials it was the right stream). The order of the trials was randomly determined. In this condition, previous experiments found similar levels of performance for the left and right streams (Goodbourn & Holcombe, 2015). The purpose of these single-target trials was to assess whether participants were fixating centrally (see ‘Analysis’ below).

A response screen appeared 500 ms after offset of the final letters. This comprised 18-letter vertical arrays on the left and right side of the screen, presented in alphabetical order from top to bottom. One array was active at a time, with the inactive array dimmed. The array that was the first to become active was chosen randomly on each trial. Participants selected the target letter from the active array using the mouse. The selected letter then appeared at the corresponding stream location. Participants were free to reselect until they confirmed their answer with a mouse click, after which the second array became active. This procedure was approved by the University of Sydney Human Research Ethics Committee.

## 3.5 Analysis

### 3.5.1 Mixture modeling

The dependent variables in our analysis were estimated using a mixture model similar to that used by Goodbourn and Holcombe (2015). This procedure differs from more traditional RSVP analyses in that it provides an estimate of the proportion of trials that reflect successful perception and processing of the ringed letter or a temporally neighbouring letter (i.e., attending to the ring, identifying a letter from around the time of the ring, and consolidating that letter into short-term memory), rather than simply counting those trials in which participants reported the letter in the ring (for comparison, we also report a conventional accuracy analysis in the ‘Efficacy’ component of our Results section). A key advantage of mixture modeling over analysis of accuracy is that it also provides some information about the temporal characteristics of successful processing.

The estimate of the proportion of trials that reflect successful perception and processing is based on the distribution of serial position errors. Because all letters in the response array are presented on each trial, the letter reported by the participant always corresponds to some serial position in the stream. The difference between the serial position of the reported letter and target letter is the serial position error, and the distribution of these errors is plotted as a histogram (as shown in figure 7). On some proportion of trials, participants do not know the target letter and must guess. These guesses, aggregated across trials, form a near-uniform distribution of serial position errors. This guessing distribution (which may also include visual or other errors) contributes one part of the overall distribution of serial position errors. On the remainder of trials, participant reports appear to be drawn from an approximately Gaussian distribution of serial positions (Goodbourn & Holcombe, 2015; Martini, 2013) centred either on or close to the target letter. Thus, when participants do not report the target letter, often they report a letter that appeared one or a few items before or after the target letter.

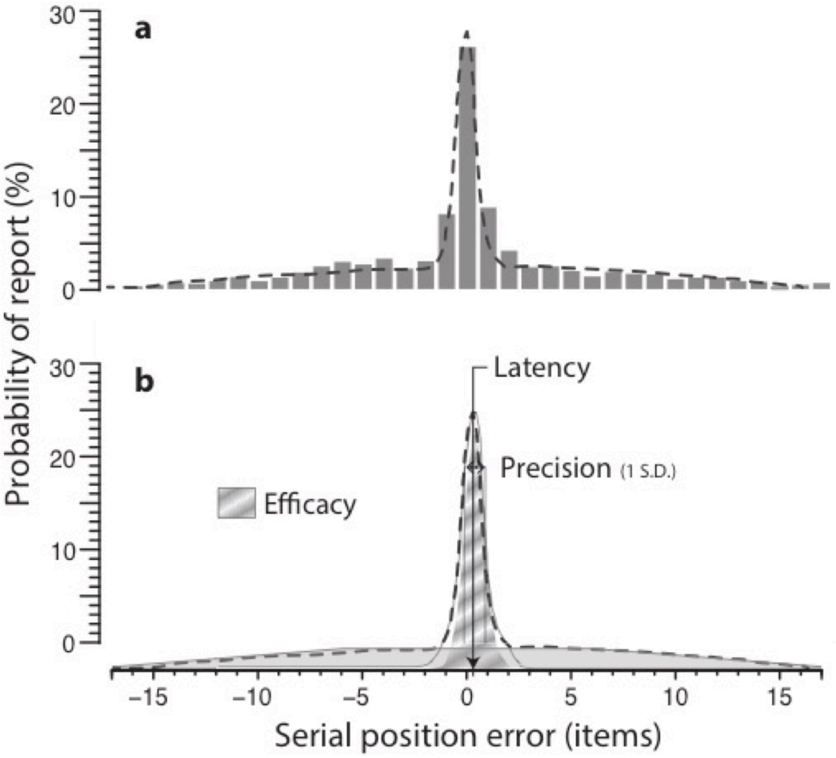

*Figure 7:* Example of mixture modeling distributions. Each letter reported by the participant corresponds to a serial position error. (a) The histogram shows a distribution for a typical participant in one stream for one condition. The dashed line showing the best-fitting mixture

model, whose components are shown in panel b. (b) The overall mixture distribution (dashed line) is made up of two component distributions. The area of the Gaussian component (cross-hatched) is the efficacy, its mean the latency, and its standard deviation the precision. The pseudo-uniform (guessing) distribution is shown in light grey.

The mixture modeling technique uses a likelihood-maximisation procedure, repeated 100 times with different randomised starting values, to estimate the parameters of the Gaussian and guessing distributions that together make up the overall distribution of serial position errors. These parameters correspond to the three parameters that are used to test our hypotheses. Efficacy indicates the proportion of trials corresponding to the Gaussian part of the overall distribution. That is, the proportion of trials in which participants successfully report a letter around the time of the target (non-guessing trials). The difference in efficacy between the left and the right streams indicates the size and direction of the second-target deficit (see 'Bayesian data analysis') and is the dependent variable in tests of our primary hypothesis. Latency is the mean, or the location of the peak, of the Gaussian component. It indicates the time relative to the target at which the distribution of non-guessing responses is centred. Finally, precision is the standard deviation of the Gaussian; a measure of the temporal spread of non-guessing responses. The findings for latency and precision help us to infer the stage of processing at which the second-target deficit occurs. Specifically, a deficit at the sampling stage would be consistent with a difference in latency or precision between the left and right streams. In contrast, a deficit at a later stage, as Goodbourn and Holcombe suggested, would be consistent with latency and precision being the same in the left and right streams.

### 3.5.2 Single target trials

Forty single-target trials were included to assess whether participants were fixating centrally. If participants' responses on dual-target trials resulted from fixating at either side of the central fixation point, this would also affect spatial biases in the single-target trials. We specified the following procedure in our preregistration for measuring spatial bias in the single-target condition. First, responses were counted as accurate if the serial position error was between −2 and 2 inclusive (mixture modeling was not used because of the relatively few trials available in the single-target conditions). For each participant, the proportion of these responses was then calculated and a z-test carried out in each language condition to evaluate the difference between the proportion of accurate responses on the left and right sides. A difference between left and right responses on the single target trials that was significant at the $\alpha = 0.01$ level, in either language, was the criterion for omission on the basis of asymmetric fixation. No participants met this criterion. (Results for individual participants are available at https://osf.io/yptmq/).

Bayesian data analysis. The second-target deficit observed in Goodbourn and Holcombe (2015) was specific to efficacy; no difference was found between left and right streams for latency or precision. Accordingly, our primary (and preregistered) hypothesis was that the right deficit in efficacy (left stream efficacy minus right stream efficacy) will be greater when the stimulus is presented in English than in Arabic. A secondary hypothesis was that latency and precision would not differ between streams in either language.

We analysed data using the default Bayesian paired samples t-tests outlined by Rouder, Speckman, Sun, Morey, and Iverson (2009) and by Wetzels, Raaijmakers, Jakab, and Wagenmakers (2009), and implemented in JASP (JASP Team, 2017). A Bayes factor of one indicates that the data are equally likely under either hypothesis, whereas a Bayes factor of (for example) three in favour of the null hypothesis ($BF_{01} = 3$) indicates that the data are three times more likely under the null hypothesis than the alternative. In contrast, $BF_{10} = 3$ (note the reversal in the order of the subscripts) means that the data are three times more likely under the alternative hypothesis. The default Bayes factor model we used assumes that effect sizes under the alternative hypothesis follow a folded Cauchy (0,1) distribution. One-tailed tests were used for the efficacy analysis to reflect the directionality of our hypothesis, and two-sided tests were used for the analysis of latency and precision.

Our decision to use Bayesian t-tests to analyse our results (see the preregistration at https://osf.io/s9n2d/) provided two advantages over frequentist tests. Firstly, we did not have a strong basis for estimating effect size before we had run the experiment, and so had we used frequentist methods, we would have needed an overly large sample to ensure our experiment was well-powered. Bayesian methods allow sample size to be determined according to a stopping rule rather than by nominating the sample size before running participants, and so avoids the need to continue to sample participants when evidence is sufficient to support confident findings in relation to stated hypotheses. Secondly, Bayesian methods can quantify support for hypotheses of no difference, which we apply here in our analysis of the stage of processing at which the deficit occurs.

For all analyses, we have run equivalent tests using traditional frequentists methods and can confirm that the findings from our Bayesian data analysis are the same as those that would be obtained using a $p < .05$ criterion.

### 3.5.3 Reading experience

Our data (including results of the reading speed tests) may contribute to future efforts to understand the link between second-target deficits and the amount of experience a participant has had reading in a certain direction. While our sample size is not sufficient to provide a well-powered analysis of these effects, we have included a preliminary analysis in an attachment to this Chapter in the hope that this may aid in future research.

## 3.6 Results

### 3.6.1 Second-target deficit

#### *3.6.1.1 Efficacy*

Efficacy in the left and right streams for each language condition is shown in Figure 8. The second-target deficit is calculated as efficacy in the left stream minus efficacy in the right side. A positive value indicates a right-side deficit, and a negative value a left-side deficit. As predicted, the mean right deficit in the English condition ($M = 0.22$, $SE = 0.06$) was larger than that of the Arabic condition ($M = -0.08$, $SE = 0.07$). Bayesian t-tests comparing the difference in the right deficit in efficacy in the English and Arabic conditions produce a Bayes factor of $BF_{10} = 33.8$ (Figure 9a), indicating that the observed data are nearly 34 times more likely to be observed under a hypothesis that the right deficit is greater in the English condition than under the null hypothesis. This is strong evidence for our primary hypothesis. For a sense of how a Bayes factor this size relates to p-values, consider that the maximum possible Bayes factor that can be obtained when $p = .05$ is 6.8 (https://alexanderetz.com/2016/06/19/understanding-bayes-how-to-cheat-to-get-the-maximum-bayes-factor-for-a-given-p-value/). As shown in Figure 9b, the Bayes factor here is robust to reasonable variation of the width of the prior distribution on the effect size of the primary hypothesis. Overall efficacy was similar in the English ($M = 0.54$, $SD = 0.16$) and Arabic ($M = 0.50$, $SD = 0.17$) conditions, with Bayesian t-tests favouring no difference between the two languages ($BF_{01} = 2.12$).

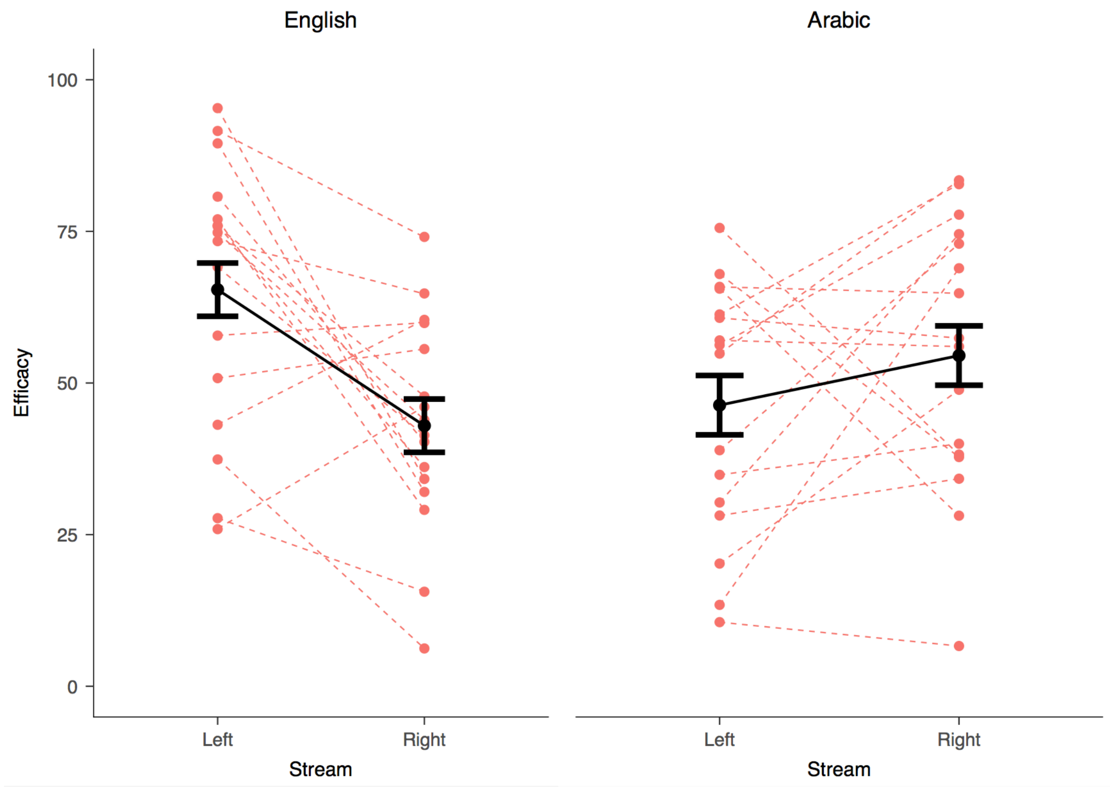

*Figure 8:* Efficacy in left and right streams for each language condition. Participants showed a left advantage in the English condition, and but not in the Arabic condition. Pale dots indicate data points for individual participants, joined by dashed lines.

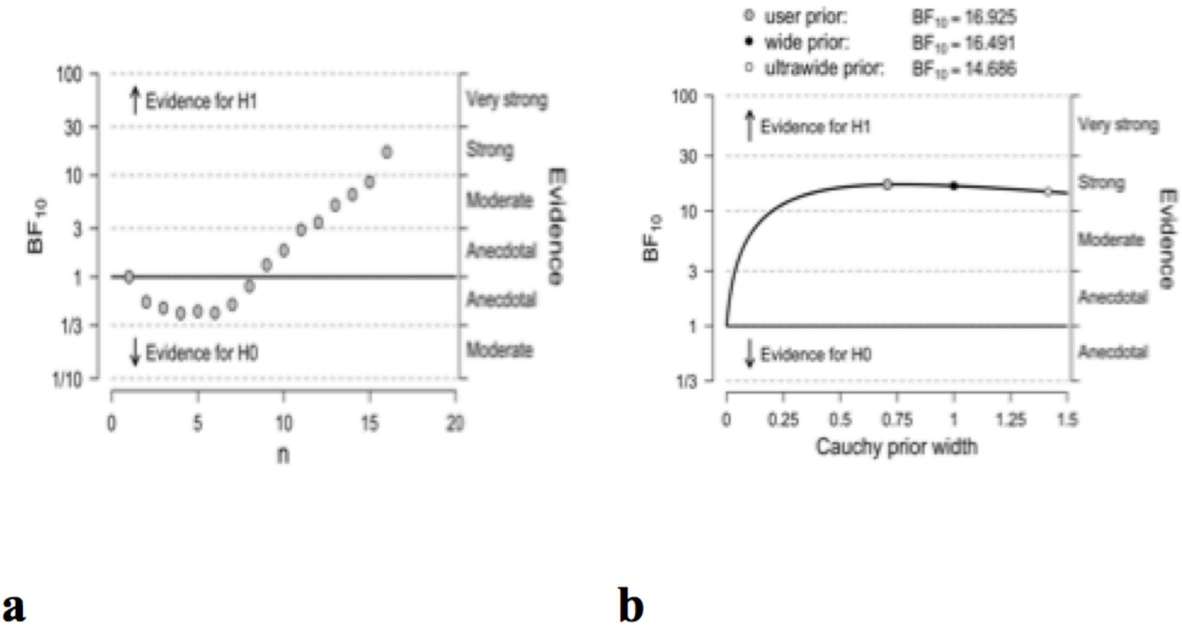

*Figure 9:* Bayesian analysis of efficacy results. (a) Development of Bayes factors with

increasing sample size for the comparison of left bias in efficacy between English and Arabic conditions. The conditions for stopping (set out in our preregistered data analysis plan) were reached after 16 participants. (b) As a robustness check, a plot of the Bayes factor as a function of the scale parameter r of the Cauchy prior for effect size under the alternative hypothesis. Figure adapted from plots produced by JASP (jasp-stats.org).

The data of the English condition strongly support a large right deficit ($BF_{10} = 34$). The efficacy is 22 percentage points higher for the left stream (M = .65, SD = .22) than for the right stream (M= .43, SD = .18). For the Arabic condition, a small left deficit was observed (efficacy was 0.08 percentage points higher for the right stream), but the Bayesian t-test indicates that the evidence marginally favours the null hypothesis of no difference between left (M = .46, SD = .21) and right (M = .54, SD = .22) streams ($BF_{01} = 1.26$).

Similar results are obtained using a rule of thumb instead of mixture modeling to estimate the second-target deficit. Under this method, a response is considered to be a non-guessing response if it appeared in the stream fewer than two serial positions from the target. The mean right deficit from this method in the English condition (M = 0.15, SE = 0.05) was again larger than that of the Arabic condition (M = −0.07, SE = 0.05). A one sided Bayesian t-test comparing the difference in the right deficit in the English and Arabic conditions produces a Bayes factor of $BF_{10} = 23.9$, indicating that the observed data are almost 24 times more likely to be observed under a hypothesis that the right deficit is greater in the English condition than under the null hypothesis. When the language conditions are considered separately, there is a large right deficit for English ($BF_{10} = 13.6$), and Bayesian t-tests negligibly favour a hypothesis that performance is the same for left and right streams in the Arabic condition ($BF_{01} = 1.03$). Note that results from the rule-of-thumb analysis may include both false positives (when a participant guesses an item that is proximal to the target), and false negatives (when a participant makes an informed response that is more than two serial positions from the target).

### 3.6.2 Stage of processing

#### *3.6.2.1 Latency*

A latency value of zero would mean the serial position error distribution is centred on the target interval (the time from when the target appears to when the next item appears). Mixture modeling estimated the latencies as being slightly after the centre of the cue interval (average across conditions, M = 23 ms). Bayes factors from two-tailed t-tests indicate that the data are three to four times more likely under the null hypothesis of no difference between left and right streams than under the hypothesis of difference between the left and right streams for the English condition (left: M = 20, SE = 9; right: M = 14, SE = 14; $BF_{01}$ = 3.6) and about equally likely under the null hypothesis as under a hypothesis that the left and right streams differ for the Arabic condition (left: M = 38, SE = 13; right, M = 20, SE = 6; $BF_{01}$ = 1.2).

#### *3.6.2.2 Precision*

Precision is a measure of the temporal spread (1 standard deviation) around the cue of the letters reported. In conjunction with the positive but small latencies observed (see Latency, above), the precision estimates of about 80 ms indicate that items both before and after the target are reported in response to the cue. As was found for latency, Bayes factors indicate that the observed data are around three times more probable under the null hypothesis than under the hypothesis of difference between the left and right sides, for both the English (left: M = 94, SE = 11; right: M = 81, SE = 9; $BF_{01}$ = 2.7) and Arabic (left: M = 87, SE = 14; right:

M = 72, SE = 5; $BF_{01}$ = 2.7) conditions. The values observed for precision, between 70 and 95 ms, are similar to those found previously for RSVP tasks (Cellini et al., 2015; Goodbourn & Holcombe, 2015; Alex O Holcombe, 2009; Holcombe et al., 2017; Martini, 2013).

### 3.6.3 Summary of results

We observed a difference in efficacy between streams, but did not observe a difference in the latency or precision of responses in any condition. There was strong evidence that the bias in efficacy was different for English compared to Arabic letters. In the English condition, efficacy was greater in the left stream, while in the Arabic condition the evidence did not favour a bias (the numerical trend was for a right bias).

## 3.7 General Discussion

Goodbourn and Holcombe (2015) used participants thought to predominantly read from left to right (they did not ask their participants about their language experience), and documented a disadvantage for reporting letters (presented in English) appearing on the right side. Here, using participants with experience reading Arabic as well as English, we also find a right disadvantage for the English stimuli. This right disadvantage was eliminated for the Arabic stimuli. Evidently, the visual processes responsible for the right disadvantage are strongly affected by implied reading direction.

The Arabic condition eliminated the usual right deficit in efficacy, but it did not completely reverse; that is, efficacy on the left was only slightly lower than efficacy on the right. A comparable pattern has also been found in some previous studies of right-to-left reading (Friedrich & Elias, 2014; Holcombe et al., 2017; Jyotsna Vaid & Maharaj Singh, 1989), which tend to explain the lack of an equivalent left disadvantage in right-to-left conditions as either: (1) a result of participants having less experience reading right to left than left to right; or (2) an advantage for processing items from the left visual field derived from (non-cultural) differences between the cerebral hemispheres. The results from our reading-speed tests indicate that on average, our participants read at a speed that was close to the monolingual norm when reading in Arabic, but were two standard deviations below the norm when reading in English. There is thus no sign that our participants have less lifetime experience with Arabic. However, there is evidence that one's current linguistic environment may interact with the effect of reading direction on spatial biases in some tasks (Maass & Russo, 2003; Sieroff & Haehnel-Benoliel, 2015), and so it may be that the asymmetry reflects the fact that our experiment was performed in a predominantly English-speaking country. Testing the dual RSVP paradigm on a bilingual (Arabic- and English-speaking) population in a predominantly Arabic-reading country would be useful to elucidate the effect of linguistic environment, and further dissociate the effects of reading experience from differences between the cerebral hemispheres.

Could differences between Arabic and English other than implied reading direction have contributed to the lack of bias in the Arabic condition? A previous study has documented that Arabic letters are more complex, and are identified less efficiently, than English letters (Pelli et al., 2006). However, we do not think that differences in complexity or efficiency of identification are likely to have affected the pattern of biases observed in the Arabic and English conditions. Firstly, differences in complexity or efficiency are likely to affect performance in both left and right streams. While this would affect the size of the second-target deficit if the level of performance in one stream was at floor, we do not think that this is the case given that mean efficacy was above 0.4 in each stream in each language. Moreover, both the range and pattern of results that we observe is similar to that found in dual-RSVP experiments comparing English letters in their canonical position with English letters in various non-canonical orientations (Holcombe et al., 2017), where letter complexity was matched. The consistency across studies suggests that both are likely to be driven by the same reading-direction-related mechanism.

Our mixture modeling error analysis sheds light on the stage of processing responsible for the observed biases. Consistent with past work (Goodbourn & Holcombe, 2015; Holcombe et al., 2017), latency—the time, relative to the cue, on which the reports from the stream were centred—did not differ markedly between the two streams in either language condition. Precision—the span of time from which participants sampled letters—was similarly unaffected. However, the effect of language on the left–right efficacy difference was large. Why should the location of the stream affect efficacy of responses, but not latency or precision? We consider that this dissociation likely indicates that that latency and precision are determined by one stage of processing, and efficacy by another. Goodbourn and Holcombe suggested that orthographic representations of the letters are at an early stage activated in parallel (giving rise to latency and precision parameters that are independent of the location of the stream), and then briefly buffered before reaching a bottleneck at a later stage (giving rise to the spatial bias in efficacy).

The dissociation between early- and late-stage processing contemplated here is consistent with the dissociation between sensory memory (activated for multiple items in parallel) and visual working memory (activated for multiple items serially) that has featured in models of consolidation for many years (for example, Coltheart, 1972), and also with the well-supported two-stage models long used to explain data from single-stream paradigms (Chun & Potter, 1995; Jolicoeur, 1999; Wyble et al., 2015). Recent research into the time course of visual working memory consolidation using stimuli presented in a sequence suggests that consolidation is subject to an ‘attentional blink’ whereby attentional capture of the first target temporarily prevents processing of subsequent targets (Ricker & Hardman, 2017). The right-side deficit observed by Goodbourn and Holcombe may thus be viewed as a spatial corollary of the attentional blink, where the processing of one of the items prevents high-level processing of the other of the other, leaving the fragile sensory memory trace vulnerable to decay before the attention necessary for consolidation can be allocated.

The present results are consistent with this theory. The large effect of language suggests items are prioritised for consolidation according to reading direction. Thus, in the English condition, priority is given to the item on the left. This style of processing would presumably provide an advantage in reading, where word order is necessary for comprehension. Indeed, some prominent models of reading (for example, the E-Z reader model in Reichle et al., 2003) suggest that words are recognised one at a time in the order of reading, and that this is the primary mechanism for establishing word order.

The present task is of a type for which visual-field differences traditionally would be attributed to hemispheric differences in the brain. The surprisingly large influence of implied reading order indicates its potential for informing theories of reading, and here we have made a start by showing that temporal binding of the unprioritised side remains unperturbed despite a large concomitant overall difference in performance. Future studies should use entire words rather than individual letters and investigate the role of temporal binding in natural reading.

## 3.8 Appendix 1 to Chapter 3 - Reading Experience Supplement

### 3.8.1 Reading Direction Influences Lateral Biases in Letter Processing: Does the amount of reading experience affect spatial biases in dual RSVP?

As set out in our preregistration (https://osf.io/hkgps/), the primary aim of the study was to use participants with experience reading English and Arabic to investigate whether the reading direction implied by the stimulus would affect the spatial bias in a task where participants must report two simultaneously presented letters. A secondary aim was to begin to explore how the amount of experience participants had reading in each direction would affect the spatial bias observed for each participant in each language. To progress our secondary aim, we observed the correlation in our dataset between total lifetime experience (as indicated by performance on a reading-speed test) and spatial bias in the dual RSVP task. However, large sample sizes are typically required to support a well-powered test of correlational hypotheses (Schönbrodt & Perugini, 2013). Given this analysis relates only to a secondary aim, we elected not to increase our sample size to the level required to meet this standard (see our preregistration for more information). Instead, we elected to run our analysis on a more limited sample in the hope that preliminary findings can help drive future research.

We also examine whether very recent (over the course of the experiment) experience affected the spatial bias. First, we investigate whether participants who completed the English condition first have a greater left bias in that condition than those who completed it immediately after the Arabic condition. The latter group performed the English phase immediately after reading Arabic, whereas the former group is likely to have performed the English phase after travelling through an English-speaking environment to get to the laboratory. Second, we investigate whether experience acquired over the course of the experiment affected results by testing whether the hypothesised bias in each language (left for English, right for Arabic) is greater for the second half of trials in each block than for the first half of trials in the block.

### 3.8.2 Lifetime reading experience

Lifetime reading experience was indicated by performance on the International Reading Speed Texts in Arabic and English (Trauzettel-Klosinski & Dietz, 2012). Reading speed is well established as an indicator of reading experience in a particular language (Wells, Christiansen, Race, Acheson, & MacDonald, 2009). The reading-speed test was carried out according to the protocol set out in the test booklet, with the exception that the test paragraphs were presented on the computer monitor, rather than in the booklet (further details of the reading-test stimuli are in the main article). Reading speed was measured in words read per minute (wpm), which was calculated by dividing the total time in minutes taken to read the paragraph by the number of words in the paragraph, less any words that were missed or read incorrectly.

Reading speed in English ranged from 113 to 270 wpm. The mean of 171 wpm (SD = 44.6 wpm) was around two standard deviations lower than the adult norm for the test of 228 wpm, (SD = 30 wpm), which may reflect the fact that the test was normed on a sample of native English speakers. Participants who read the English paragraph faster showed a non-significant trend for a greater left bias on the dual RSVP task when it was presented in English than the slower readers in English. The associated Pearson's r correlation statistic of 0.40 was about equally likely under a null hypothesis that there was no correlation as under a hypothesis that reading speed was a correlated with the magnitude of the left bias in English ($BF_{10} = 1.2$). More data would be needed to support a definitive inference.

Reading speed in Arabic ranged from 69 wpm to 207 wpm. The mean of 139 wpm (SD = 47.9 wpm) was close to the adult norm of 138 wpm (SD = 20 wpm). The rate at which participants read the Arabic paragraph was only very weakly negatively correlated with the left bias in the RSVP task (that is, faster readers in Arabic tended to be slightly more right biased: Pearson's r = −0.05).  Such a small correlation would be 3 times more likely under a model where reading speed and performance on the task were unrelated than under a model where they were correlated ($BF_{01} = 3.2$).

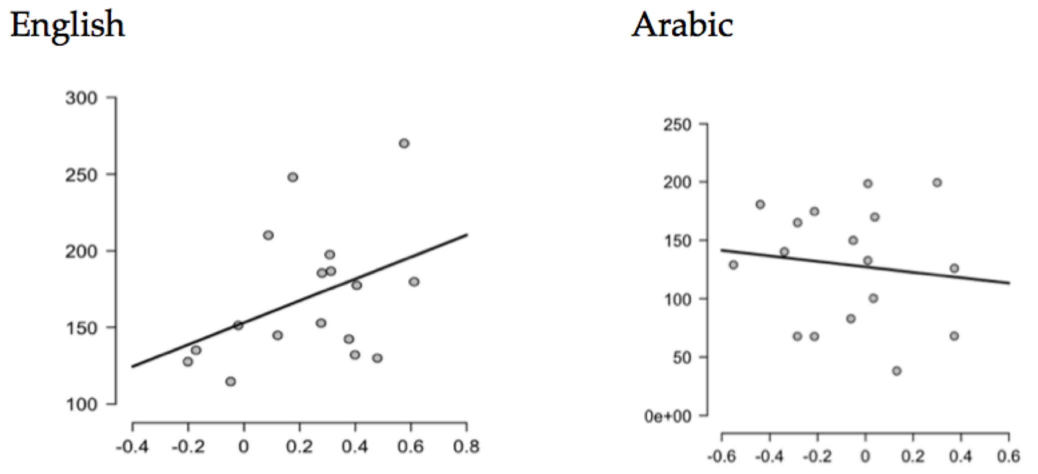

*Figure 10.* Scatter plot with line of best fit showing the correlation between reading speed (vertical axis) and the left bias in the RSVP task (horizontal axis) for the English (left chart) and Arabic (right chart) language conditions. Dots represent individual participants.

We also included reading speed as a covariate in Bayesian repeated-measures ANCOVAs (Rouder, Morey, Speckman, & Province, 2012) using the default priors in JASP (JASP Team, 2017). The English and Arabic results were analysed separately. The purpose of this analysis was to test whether the effect of stream (left or right) in each language was affected by lifetime reading experience. The analysis reinforced the previous finding that efficacy in English differed between the left and right streams ($BF_{10} = 44.3$). However, the evidence was very weak that the reading-experience covariate improved the model: A model without the English reading-speed covariate explained spatial bias in the English dual RSVP task almost as well as a model with the reading speed covariate ($BF_{10} = 1.2$). For the Arabic condition, the ANCOVA without reading speed as a covariate found weak evidence for the null hypothesis of no left or right bias (BF01 = 1.6), and this conclusion became marginally stronger with Arabic reading speed as a covariate (BF01 = 2.2).

Overall, these results are inconclusive about whether the amount of reading experience affects the spatial biases. A properly powered study may elucidate these results further.

### 3.8.3 Recent experience

#### *3.8.3.1 Within-block learning*

The English and Arabic parts of the experiment were performed in separate blocks comprising the reading-speed test followed by 20 practice trials and 140 trials of the dual-RSVP task. In each block, all instructions and stimuli were presented in the relevant language, and so throughout each block participants were reading text written exclusively in the relevant direction for that language. If recent reading experience contributes to the spatial bias in the dual-RSVP task, we might expect participants to show a greater bias in trials later in the block than those early in the block.

To test this, we used two-sided Bayesian paired sampled t-tests to compare the spatial bias in efficacy for trials completed in the first half of a block with those in the second half of a block. Bayes factors indicate that the data are close to four times more likely under the null hypothesis of no difference between the first and last half of trials than under the hypothesis of difference for both the English condition (first half: M = 0.19, SE = 0.08; last half: M = 0.20, SE = 0.06; $BF_{01}$ = 3.8) and the Arabic condition (first half: M = −0.07, SE = 0.07; last half: M = −0.08, SE = 0.07; $BF_{01}$ = 3.8). Thus, it appears unlikely that the reading that occurred during the experiment affected the spatial bias.

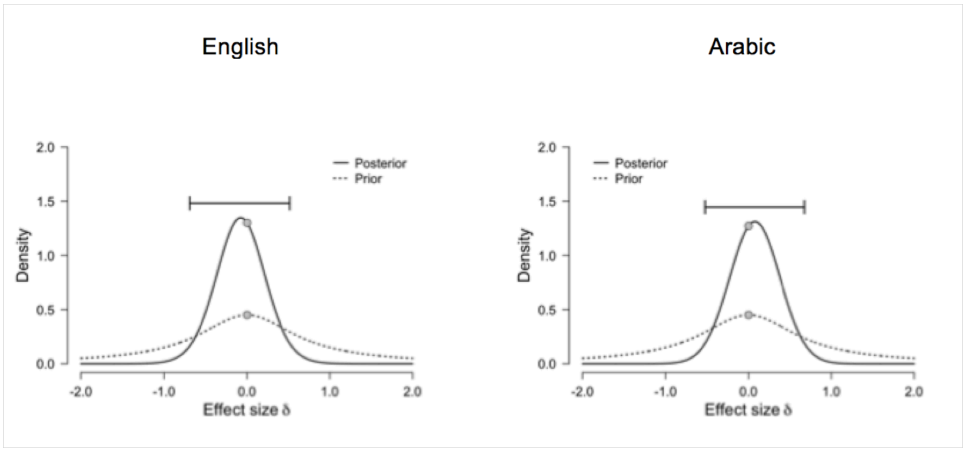

*Figure 11.* Bayesian analysis of within-block learning, showing the posterior distribution of effect size under a two-sided prior distribution (Rouder et al., 2009).

#### 3.8.3.2 *Order of language blocks*

The order in which participants completed the language conditions was counterbalanced across participants. The experiment was conducted in a predominantly English-speaking country, and most of the participants were students at English-speaking universities. As such, it is likely that for most participants, their encounters with written text immediately prior to participating in the experiment will have been with English. If this very recent experience reading left to right contributes to the spatial bias in the RSVP task, we might expect participants who did the English component first to have a larger left bias in English than those who did the English condition after the Arabic condition.

In fact, participants who did the English component first had a slightly smaller left advantage than those who did the English component last, though a Bayesian t-test comparing the two groups indicates that the data are twice as likely under a hypothesis of no difference than of difference (English first: M = 0.17, SE = 0.07; English last: M = 0.26, SE = 0.10; $BF_{01}$ = 2.0). Similarly, the order or the language conditions did not appear to affect the spatial bias in the Arabic condition (English first: M = −0.09, SE = 0.05; English last: M =

−0.08, SE = 0.12; $BF_{01}$= 2.4). While these Bayes factors are small, they support the trend in the previous analysis that there appears to be no effect of recent experience.

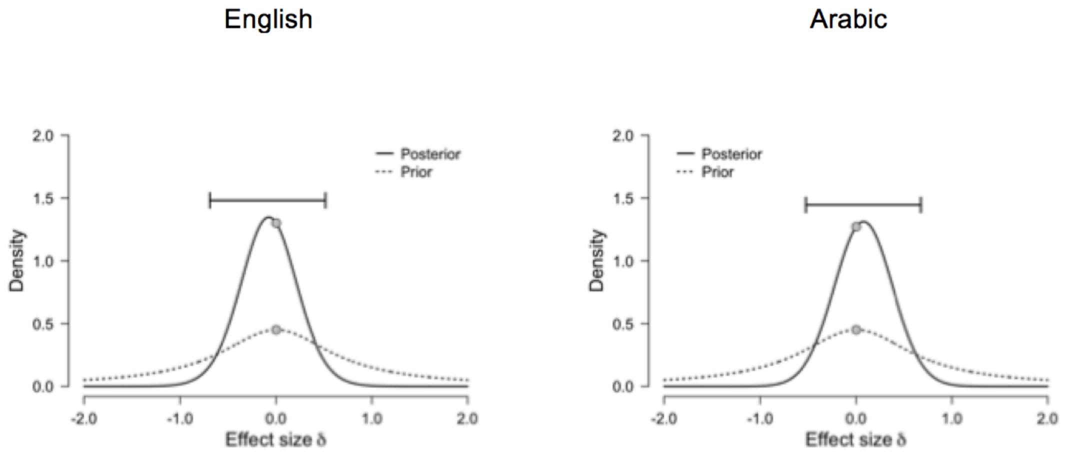

*Figure 12.* Bayesian analysis of the order of language blocks, showing the posterior distribution of effect size under a two-sided prior distribution (Rouder et al., 2009).

### 3.8.4 Discussion

Because all of the Bayes factors relating to the effect of lifetime reading experience are relatively small ($BF_{01}$ ranged between 1.03 and 3.0), more evidence is needed to determine whether or not recent reading experience, or amount of lifetime experience (beyond that needed for competence in the language) affects spatial bias. This evidence may marginally favour an inference that differences in reading experience beyond basic competence had no effect on results. However, the very low Bayes Factors leave open the possibility that an imbalance in the amount of lifetime reading experience participants have in English and Arabic is why the left bias observed in the English condition of the dual-RSVP task was not matched by a similarly large right bias in the Arabic condition. A more powerful study would be needed to confidently discriminate between this and other potential explanations for the imbalance in biases, such as a concurrent effect of hemispheric specialisation acting in the opposite direction to the language effect.

The analyses of recent effects provided more (although still inconclusive) evidence, with tests of both the effects of within-block variation and the order of language blocks weakly supporting the absence of an effect of recent experience on spatial bias. The individual Bayes Factors were inconclusive ($BF_{01}$ ranged between 2.2 and 4.0) but the trends were consistent across both analyses, and posterior distributions indicate that if there is an effect it is likely to be small. We note that these tests assessed the effect of recent experience in only two limited ways: experience accumulated in the first half of each block, and experience that participants are likely to have accumulated in some period immediately before the experiment. It may be that spatial bias is sensitive to experience accumulated over a different period (for example, seconds or minutes) or occurs near-instantly in response to the particular stimulus. Such effects could not be readily assessed from the present experiment. All participants had in excess of 10 minutes' immediate experience reading stimuli in a particular language (through the reading test and practice trials) before any spatial bias results were recorded, and so any adjustment that occurred within this period was not measured. Studies that switch reading direction more frequently within the experiment may be better able to determine the time course of adjustment to the inferred spatial pattern of the stimulus.

## 3.9 Appendix 2 to Chapter 3 – Factors other than hemispheric processing asymmetry that can influence visual field differences

Across many papers, researchers have debated whether various visual field differences occur as a result of experience reading in a particular direction, or processing differences related to hemispheric specialisation. Recent research has, however, identified a number of other factors that may contribute to visual field differences. One is the informational content of the stimuli. Hsiao and Cheng (2013) and Hsiao (2011) compared visual field differences observed when Chinese characters were presented in the left and right visual fields. They found that when the right side of the stimulus carried a greater informational content, participants were faster at reporting items presented in the left visual field, and when the left side of the stimulus carried greater informational content the participants were faster at reporting items presented to the right visual field. Here, the informational content was defined according to the location of the phonetic component in Chinese logographs (orthographic complexity did not have an effect), suggesting that the effect not a function of low level visual processing. In addition, Hsiao and Lan (2013) found that for tasks using words from different artificial lexicons presented to the left and right visual fields, lexicons with more similar words produced a greater right visual field advantage than lexicons with fewer similar words. While these studies differed from the present study in that they used either artificial words or Chinese logographs, rather than letter units, they demonstrate that visual field differences may be sensitive to many aspects of a writing system. Further experiments would be needed to ascertain whether these factors contribute to visual field differences observed between English and Arabic conditions in the present Chapter.

# Chapter 4: Partial report

## 4.1 Chapter Synopsis

Humans have a limited capacity to identify concurrent briefly-presented targets. Recent experiments using concurrent rapid serial visual presentation (RSVP) of letters have found a deficit in reporting the right-most of two simultaneously presented targets which is thought to occur as a result of a delay in processing one item at a capacity limited stage of processing. Here, we investigate this claim using a stimulus where two words are briefly presented at the same time (not embedded in an RSVP stream), and the location of one of the words is subsequently cued. We manipulate the delay in processing the target item by sometimes providing early target information that should allow participants to reprioritise processing to that item, and sometimes providing this information after a 1 s delay. We observed a right visual field advantage, that was not affected by whether participants were told which word to report immediately, or after a 200 ms delay. These experiments provide insight into the conditions in which hemispheric differences rather than reading-related prioritisation drives visual field differences, and may have implications for our understanding of visual processes that operate when one must identify and remember multiple stimuli, such as when reading.

## 4.2 Introduction

Goodbourn and Holcombe (2015) claimed that the spatial bias observed in reporting simultaneous targets from dual RSVP streams reflects a capacity limit at a post-sampling stage of processing. They further speculated that this capacity limit may be a serial bottleneck at which multiple items are resolved in the direction of reading. In the previous chapter, I investigated their claim that the left advantage reflects prioritisation in the direction of reading. Here, I investigate their claim that prioritisation occurs at a serial bottleneck that occurs at a post-sampling stage of processing.

### 4.2.1 A serial bottleneck

The bottleneck account preferred by Goodbourn and Holcombe (2015) attributes the spatial bias to the fact that type representations for multiple items can be activated in parallel, but must be tokenised if they are to be reported at the end of the trial (see figure 13). Critically, their account assumes that only one item can be tokenised at a time. When two type representations are activated at once, tokenisation will occur immediately for one representation and will be delayed for the other. Neural activity pertaining to non-tokenised items can be sustained for a brief interval, meaning that on many trials, participants can tokenise the second item after the first. However, occasionally the neural activity for the delayed item decays before tokenisation occurs, preventing conscious access (and thus accurate reporting) of that item.

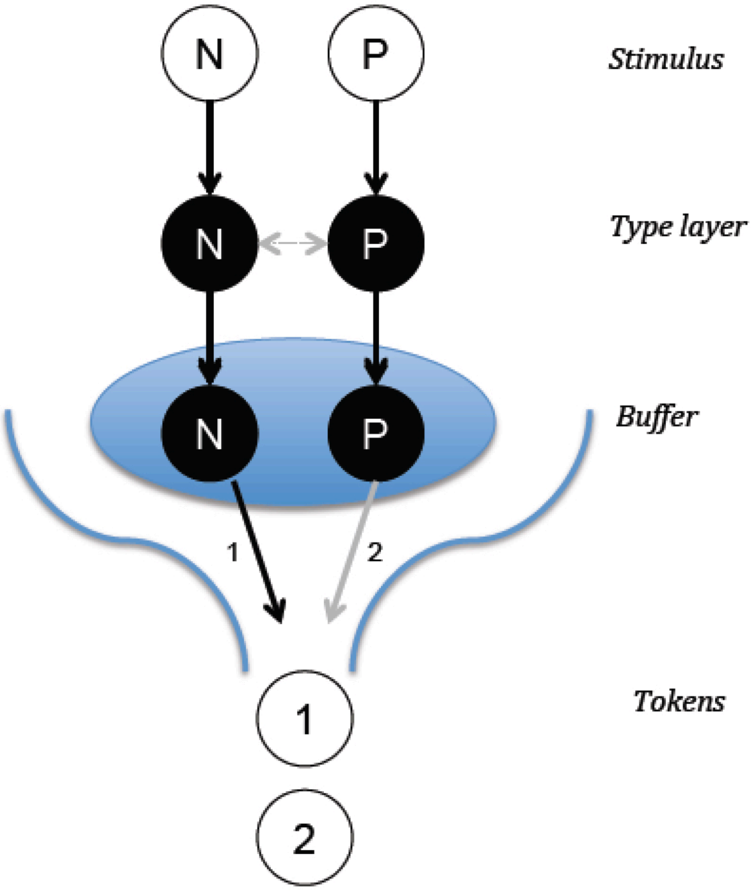

*Figure 13:* Serial bottleneck account. Dual targets simultaneously activate corresponding type nodes. These weakly inhibit each other, but with no item receiving an advantage. They proceed to the buffer, where activation can be maintained for a limited amount of time. Items are tokenised one at a time, with priority for tokenisation determined by the direction of reading.

Four aspects of their results support this account. Firstly, their mixture modelling technique allowed them to observe temporal aspects of the stimuli reported. The latency parameter, used in their study to indicate the average timing of reported letter relative to the cue, indicated that items reported from the left stream appeared at approximately the same time as items reported from the right stream. If type representations were formed one at a time, we would expect the items reported from the non-prioritised side to occur on average later than the items reported from the preferred side. The dissociation between the relative timing of each stream and the relative likelihood of error suggested two distinct processing stages. That is, one stage in which items are sampled simultaneously, and another stage in which items are tokenised one at a time.

Secondly, Goodbourn and Holcombe (2015) found that, when the stimuli contained two streams, but only a single target was presented, performance did not depend on whether the target was in the left stream or the right stream. This is in contrast with the large left side advantage in the dual target condition. The fact that the deficit was specific to the dual target condition is consistent with a serial bottleneck account, which assumes that the bottleneck can accommodate one target and so prioritisation is not required in single task conditions. If the spatial bias instead occurred as a result of hemispheric differences — because the left item had exclusive access to superior processing resources in the right hemisphere — it should have also resulted in a bias in the single target condition, which was not the case. However, Boles (1990) argues that a deficit that is specific to dual target conditions could still be consistent with a hemispheric account if targets on the right were transferred to the left hemisphere for processing when there was a single target, but not when there were two targets. This could occur if the transfer depended on the relevant resources of the left hemisphere not being currently engaged in processing a right visual field target. Goodbourn and Holcombe acknowledge that Boles' account could explain why the bias was not present in the single target condition, but argue evidence against the bias being driven by differences in hemispheres on the basis that a spatial bias also occurred when both streams were presented in the same hemisphere, in a vertical configuration.

Thirdly, Goodbourn and Holcombe (2015) found that the efficacy of items in the prioritised stream of a dual target condition is similar to that when only one target is presented. It appears that all of the burden of processing two targets (rather than one) falls on the second target, rather than being distributed between both targets. This is consistent with a model whereby immediate tokenisation of the first item ensures that this item can be reported. Consistently delaying the second item reduces performance specifically in this stream.

Finally, the strength of the spatial bias that Goodbourn and Holcombe (2015) observed was relatively constant regardless of the locations of the two streams. That is, the left advantage for two horizontally arranged streams was very similar in size to the top stream advantage for two vertically arranged streams. They also observed a left bias of a similar magnitude in both a main diagonal condition (top left/bottom right); and the anti-diagonal condition (bottom left/top right), despite the fact that the main diagonal pits two favoured aspects of location with two non-favoured aspects, while the anti-diagonal has a favoured and non-favoured aspect in each stream. This similarity is easily explained under a serial model, because the relative position of the streams determines only which stream receives the advantage, and not the strength of that advantage.

### 4.2.2 Alternative mechanisms that can cause capacity limits

While the serial bottleneck account contemplated by Goodbourn and Holcombe (2015) fits well with their data, it runs counter to the recent trend in attentional blink research to explain limitations in processing multiple targets by a competitive mechanism that facilitates the formation of distinct episodes in visual working memory (Wyble, Bowman, & Nieuwenstein, 2009; Wyble et al., 2011). In these models, the failure to process a second target is not caused by a bottleneck in processing, but rather by the fact that processing a target triggers inhibitory links that suppress the processing of other targets. The inhibition is argued to serve the purpose of enhancing the temporal distinctiveness of the items, and so contribute to the formation of coherent object representations in visual working memory by increasing the likelihood that temporally similar items are grouped together, and temporally distinct items are not (Swan & Wyble, 2014). The shift towards such parallel models recognises the fact that such accounts arguably provide a better basis for explaining both the lag 1 sparing and spreading of sparing phenomena, which run counter to the one-item-at-a-time capacity limit associated with the serial bottleneck account.

While theories advanced in an attempt to explain the attentional blink research have tended to focus on mechanisms that suppress information occurring at a different time to the target, related ‘parallel activation’ models suggest that, while multiple targets that appear at the same time can be processed in parallel, there may also be inhibitory links between different locations that cause competition between targets when presented at the same time (Bay & Wyble, 2014; Tan & Wyble, 2015). So far, the experiments that have fed into the development of such models have not measured spatial biases, and so these models do not incorporate a mechanism that could account for the fact that the deficit tends to occur on the right side (at least, when the stimuli are English letters). However, Goodbourn and Holcombe (2015) speculate that if the inhibitory linkages favoured a particular spatial location, this may cause one item to have a competitive advantage over the other and so may be better represented in visual working memory, and thus explain the reporting advantage for one stream.

A major challenge to parallel activation models is the fact that biases between the streams were of a similar sizes regardless of where the two streams were located (including when streams were in main and anti-diagonal arrangements). In a parallel activation model, the size of the bias would be expected to vary depending on how ‘favourable’ a location is relative to the location of the other item. Goodbourn and Holcombe (2015) acknowledge that the similarly sized biases could occur by coincidence, but suggest that it is more likely that the location of the streams determines which item receives an advantage, but not the strength of that advantage, which is consistent with their serial bottleneck model.

### 4.2.3 Testing the serial bottleneck account

The serial bottleneck model favoured by Goodbourn and Holcombe (2015) contends that failure to encode the second item occurs because the type representation for that item decays before consolidation into working memory can occur. This reasoning is exemplified in a series of seminal studies of iconic memory decay by Sperling (1960). Sperling's methodology is described in detail below as it forms the basis for experiments presented in this Chapter to investigate whether decay occurs for the right-most of two simultaneously presented items.

Sperling (1960) manipulated the time between offset and consolidation using a partial report methodology. A 4 × 4 array of letters was presented for 50 ms. After the stimulus offset, participants were required to report either all of the items (the whole report condition), or items in a randomly selected row or column which was indicated by a tone (the partial report condition). Crucially, the tone indicating which item to report in the partial report condition was presented after the offset of stimulus (Sperling included conditions that are exceptions to this, but these are not important here). This procedure was repeated over many trials, so that many different samples of a participant's performance could be obtained at different probed locations, thus providing the basis for estimating of the total information that was available to the participant on average at the time of the tone. Sperling's experiments indicated that participants could generally report no more than 4.5 letters on average in the whole report condition. However, when performance for the whole array was estimated from the partial report conditions, participants could report an average of 9.1 letters immediately after the stimulus offset, indicating that people had access to about twice as much information at the time of the tone than they could report in full-report conditions, presumably because in the time taken to report the first few items, the representations for other items would decay. In a subsequent experiment, Sperling explicitly addressed the time to consolidation by manipulating the partial report condition such that the tone indicating which letters to report occurred at one of six intervals (ranging from 0.10 sec before, to 1 sec after) from the tone offset. Here, Sperling demonstrated that performance decreased with increased time between the stimulus offset and the tone, which is consistent with the effects of delayed consolidation into memory as predicted by the serial bottleneck account.

Sperling (1960) reported that participants were generally more accurate at reporting letters from the top row than the bottom row, which is consistent with the spatial bias found by Goodbourn and Holcombe when the two streams were presented in a vertical configuration. While Sperling did not elaborate on the reason for this, it could reflect the same prioritisation in the direction of reading that is posited as the basis for spatial biases reported in dual RSVP experiments. That is, in the absence of information about which letters from the array to process, participants may initially begin processing the item in the prioritised location. If the tone indicates that this location is indeed the one that participants need to report, they continue to process these items. In contrast, if the tone indicates that a different location must be reported, they must reprioritise, and begin processing a different item. As such, prioritisation can be seen as giving them a ‘head start’ that aids their overall ability to report the stimuli.

### 4.2.4 The present paradigm

The serial bottleneck account favoured by Goodbourn and Holcombe (2015) implies that the poorer ability to report the right-most of simultaneous targets embedded in RSVP streams occurs because consolidation for that item is typically delayed while the left item is processed. Performance for the right item is thought to be sensitive to the delay because, prior to consolidation, neural representations are fragile and decay over time. Once activity falls below a critical threshold, the representation is lost.

Here, we used a partial report paradigm similar to that used by Sperling (1960) to investigate whether spatial biases observed when two items are presented at the same time are sensitive to delays in consolidation. Two post-masked words were presented simultaneously for a short amount of time: one on the left and one on the right. A cue was then presented under the location of one of the words (randomly determined). Participants verbally reported the word that had appeared at the cued location. The delay in consolidation was manipulated by revealing the location of the item to be reported promptly after the offset of the post-mask, or after a 1 second delay. As the words are not visible when the cue is presented, participants must draw on stored information in order to make an accurate report.

While the intention is to provide insights into the capacity limits that cause the spatial bias reported by Goodbourn and Holcombe (2015), the paradigm here differs from their dual RSVP paradigm in three important regards. First, the two items are not embedded in RSVP streams. Second, the stimulus uses words and not letters. Finally, participants say their response, rather than selecting the item from an array of letters. These changes were introduced to ensure that the partial report methodology could be meaningfully applied to a two item paradigm. Words are more practical than letters in this paradigm, which requires either unfeasibly fast presentation rates, or substantial degradation of the stimulus to avoid ceiling performance when for letter stimuli. The vocal response follows from the decision to use words. A line up response is suitable for letters because there are only 26 possible responses. While a line up could have been constructed from a limited selection of words (one being the target), this would have increased the probability that participants could attend to one or two letters (rather than read the whole word) and deduce a correct answer. A spoken response reduces the potential for such guessing strategies. It is expected that simultaneous presentation of English words will produce the same left bias that has been previously observed for letters. However, we note that some previous research has found better performance for linguistic stimuli in the right visual field, which is attributed to lateralisation of language processing areas to the left hemisphere. This may reduce the size of the left bias, though the effect would be expected to be constant across all delay conditions.

If information is processed from left to right, we would expect the items on the left to be better reported in the long delay condition than items on the right. This bias is predicted to be reduced in the short delay condition, where early information about which item is the target may allow participants to reprioritise processing resources to the target before the fragile representation has decayed. Such reprioritisation will be indicated by a stronger left-side bias (number correct on the left side minus the number correct on the right side) that is greater in the long-delay condition than in the short delay condition.

## 4.3 Experiment 1

In Experiment 1, participants' ability to correctly report a target word from a display of two briefly presented words was compared when the participant received early and late advice about which word was the target. The purpose of the experiment was to investigate the claim made in Goodbourn and Holcombe (2015) that spatial biases in reporting two simultaneous targets embedded in RSVP streams reflects a delay in processing one of the stimuli. Early information should allow participants to prioritise processing of the right word, reducing the potential for decay.

### 4.3.1 Method

#### *4.3.1.1 Participants*

Thirty-five adult participants were recruited from the University of Sydney first year participant pool. This is three more than was nominated in the Data Analysis Plan. The excess occurred due to the retention rate for recruited participants being better than anticipated. Participants were required to be native speakers of English.

Most observers were right handed according to the Edinburgh Handedness Inventory, but five participants were left handed or ambidextrous. The pattern of results was compared for the different handedness groups and found to be similar. The results presented here combine results from left and right handed participants. However, a separate analysis which excludes the left handed and ambidextrous participants can be accessed here (https://osf.io/y652g/). Limiting the sample to right handed participants generates the same main findings with slightly lower Bayes factors.

#### *4.3.1.2 Apparatus*

Stimuli were generated using Psychopy version 1.82.01 (J. Peirce et al., 2011; J. W. Peirce, 2009) on a MacBook Pro, and displayed on a Diamond Pro 2070 SB CRT monitor. The monitor had a resolution of 1600 × 900 pixels and a nominal refresh rate of 60 Hz. Participants were seated in a dark room with their head supported on a chin-rest at a 57cm viewing distance from the monitor. Participants commenced each trial by pressing a key on a standard keyboard. Responses were recorded using a microphone.

#### *4.3.1.3 Stimuli*

Stimuli contained lower-case four-letter English words (see figure 14). The words were drawn in white against a black background using the font Arial. A white fixation circle of 0.25° diameter was located at the centre of the screen. Targets were centred 1.25° from the fixation point. The maximum word height was 0.50° and the maximum width was 1.61° (measured using the word 'whom').

Words for the experiment were selected from a subset of four-letter items in the SUBTLEX database (Van Heuven et al, 2014) within a mid range frequency band of 4.1 to 5.65 according to the Zipf scale, which is equivalent to approximately 13 to 446 per million words. Words were omitted if they were proper nouns, plurals, highly emotive, unsavoury (judged subjectively by the author) or contained multiple syllables. Words were always presented in the same 'pairs', with the constraint that no letter appeared twice in the word pair, and the difference in frequency between the two words in the pair was never more than 0.01 according to the Zipf scale (.001 per million words). All participants saw the same word pairs, however the spatial position of the words was swapped for half the participants (for example, half the participants saw "beam" on the left and "trip" on the right, and the other half saw "trip" on the left and "beam" on the right. Words were presented for either 35 or 50 ms, followed by a 200 ms mask consisting of symbols (#%$&), with the order of symbols randomly determined on each trial. The distribution of words to duration and speed conditions was also counterbalanced across the experiment.

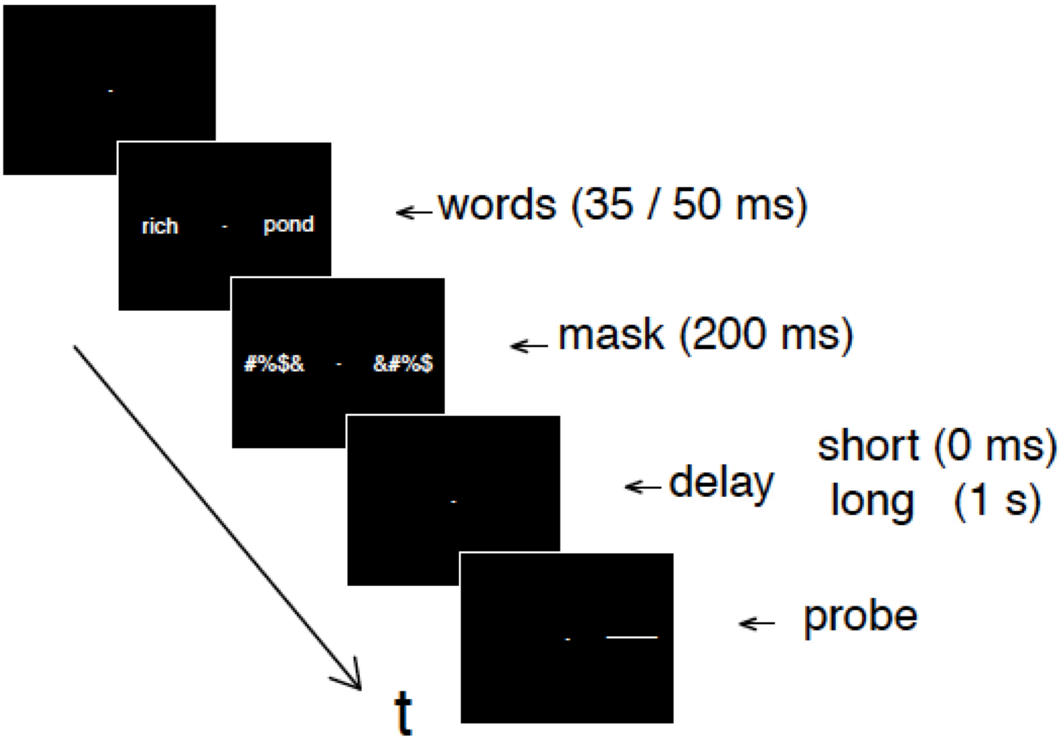

*Figure 14:* Schematic of the partial report stimulus.

#### *4.3.1.4 Procedure*

Each participant performed 100 trials in each of four conditions (brief presentation, brief-delay; long presentation, brief-delay; brief presentation, long-delay; long presentation, long-delay), which were presented in blocks with the order of blocks counterbalanced across participants.

Participant's verbal responses were keyed in by the experimenter. Responses on 1663 trials (8.4% across the whole experiment) were not discernible. 437 of these trials were eliminated from the sample either because the high-pitched tone indicating the start of the trial was not recorded, or because the scorer could hear that a response had been made, but not tell whether it was correct or not. The remaining 1226 trials of these trials were marked incorrect, either because a response was not given within four seconds, or because the response was clearly different from the target, but could not be accurately interpreted.

After completing the partial report task, participants completed the Author Recognition Test (ART) (Stanovich & West, 1989), which has been found to be a valid indicator of reading experience (Moore & Gordon, 2015). The test involves viewing a list of 50 names and discriminating authors from foils. Participants gain a point for every item they select that is an author, and lose a point for every item they select that is not an author.

### 4.3.2 Analysis

Planned hypotheses and data analyses were preregistered according to Open Science Framework protocols and can be accessed here (https://osf.io/kw9n3/).

The experiment used two different presentation rates (brief = 35 ms; long = 50 ms). This manipulation was included to provide options in the event that the experiment was too hard or too easy for some participants. The preregistration noted that in the event that no participants performed above 90 per cent or below 10 per cent for both stream in all of the conditions in the experiment, data would be averaged across trials with brief and long presentation rates, which was carried out. As further evidence for the lack of effect of presentation duration, a Bayesian ANOVA confirmed that while performance in the slow condition tended to be better than performance in the fast condition ($BF_{10} > 1$ million), it did not interact with the effect of stream ($BF_{01} = 4.81$), the length of the delay ($BF_{01} = 5.68$), or the combination of these effects ($BF_{01} = 3.69$). As such, the remainder of the analysis combined data for fast and slow presentation trials.

The preregistered confirmatory hypothesis was that the spatial bias would favour the left more when the probe indicating which item to report was presented after a long delay than after a short delay. Support for this hypothesis required only that the long delay condition be relatively more left biased (or less right biased) than the short condition. It is not necessary that either condition have an absolute left bias; the hypothesis could still be supported if there was right bias in both conditions, but this was relatively smaller in the long delay condition.

To test this hypothesis, two one-tailed Bayesian paired samples t-tests (described below) will be used to compare the spatial bias in the long and short delay condition. The dependent variables for the t-tests are spatial bias, which will be calculated by subtracting the percentage correct in the left stream from the percentage correct in the right stream. A positive bias score would indicate a left side advantage (that is, a right side deficit), whereas a negative bias score would indicate a right side advantage (that is, a left side deficit). In the first (and primary) t-test, spatial biases are averaged for each participant, in each condition. In the second (and secondary) t-test, spatial biases are averaged for each different item, in each condition. The null hypothesis will be rejected if both t-tests produce Bayes factors greater than 5 (though Bayes Factors less than this still provide some information about the likely effect, albeit with less confidence). Assessment of between-items and between-participants analyses is a common practice historically in psycholinguistic research, and is used to make inferences about whether effects are generalisable to other items. While many psycholinguistic analyses now use linear mixed effects models for analyses of items and subjects, the simpler analysis presented here has been shown in simulation studies to involve only a small loss of power (Barr, Levy, Scheepers, & Tily, 2013), and is more easily implemented in the Bayesian framework that I have consistently applied throughout this thesis.

Two further analyses will be conducted. The first (not pre-registered) investigates whether the streams show the predicted right stream deficit by separately evaluating spatial biases in the long delay and short delay conditions using one-tailed, one-sample t-tests. Separate tests will be presented for spatial biases averaged across participants, and items.

The second analysis (preregistered as an exploratory hypothesis) investigates whether there are any effects of reading experience (as estimated by the Author Recognition Test) on the magnitude of left bias. In a departure from the preregistration (which states that these will be analysed using multiple regression), this hypothesis will be tested using a Bayesian ANCOVA.

### 4.3.3 Results

The spatial biases were similar in the long- and short-delay conditions when averaged across participants or items (figures 15 and figure 16). This contrasts with the effect that would be predicted if the spatial bias reflected a delay in consolidation, with Bayesian t-tests indicating that the data were substantially less likely under the experimental hypothesis that the left bias would be greater when the delay was long, than under the alternative hypothesis that the left bias would be at least as great when the delay was short (BF01participants = 9.52; BF01items = 24.40).

Contrary to the strong right deficits found in the dual RSVP studies with letters as stimuli, the data here showed a strong left deficit for both the short-delay (BF01participants = 22.15; BF183.3items) and long-delay (BF01participants = 48.19; BF01items = 190.2) conditions.

A Bayesian ANCOVA was equivocal as to whether reading experience (as estimated by the Author Recognition Test) had an effect on the magnitude of left bias ($BF_{01}$ = 2.05) but found that any effect was unlikely to interact with the length of the delay ($BF_{01}$ = 7.128).

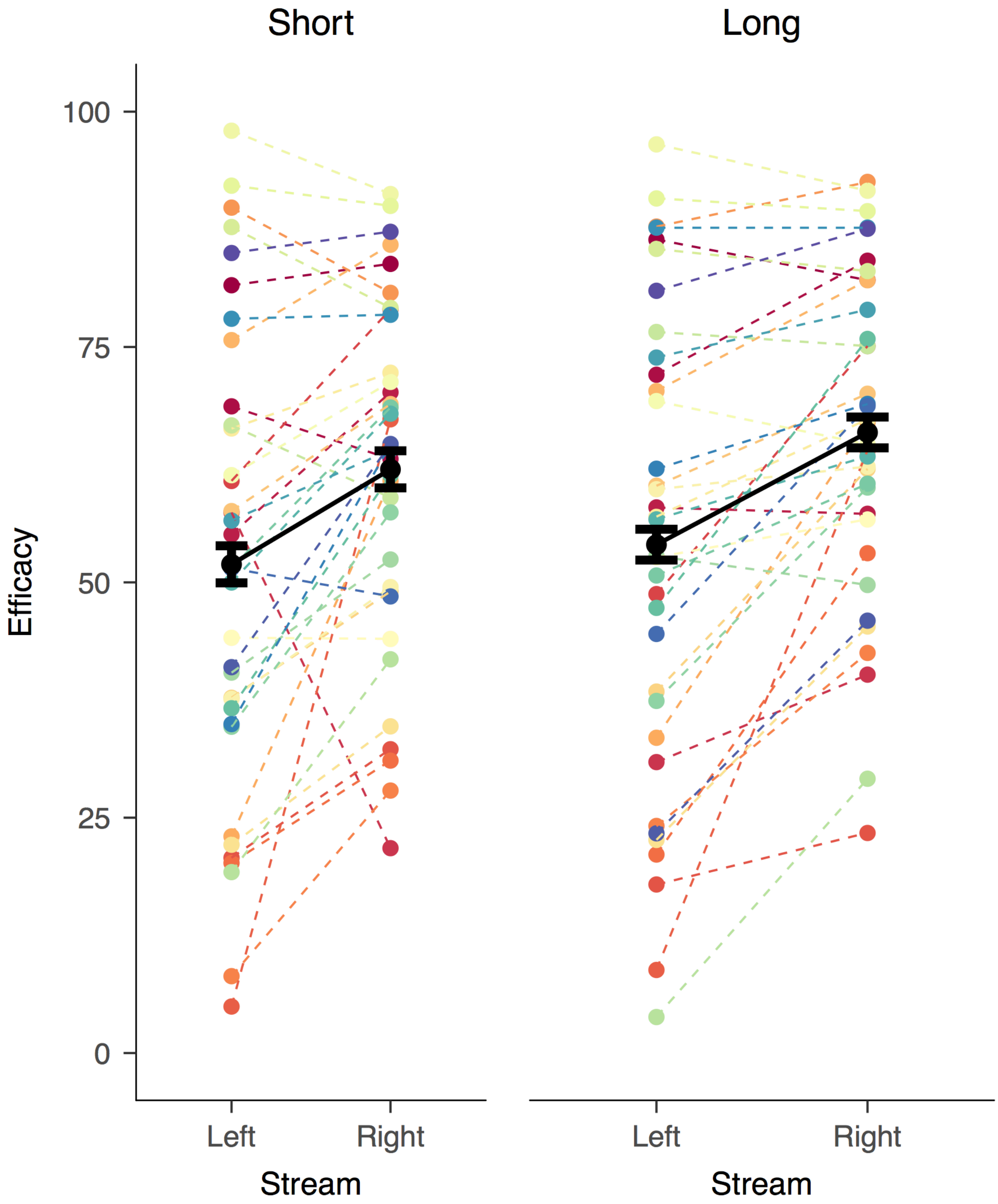

*Figure 15:* Efficacy by participant for short and long delay conditions. Coloured dots are results for individual participants. Black dots (with error bars) are results averaged over participants.

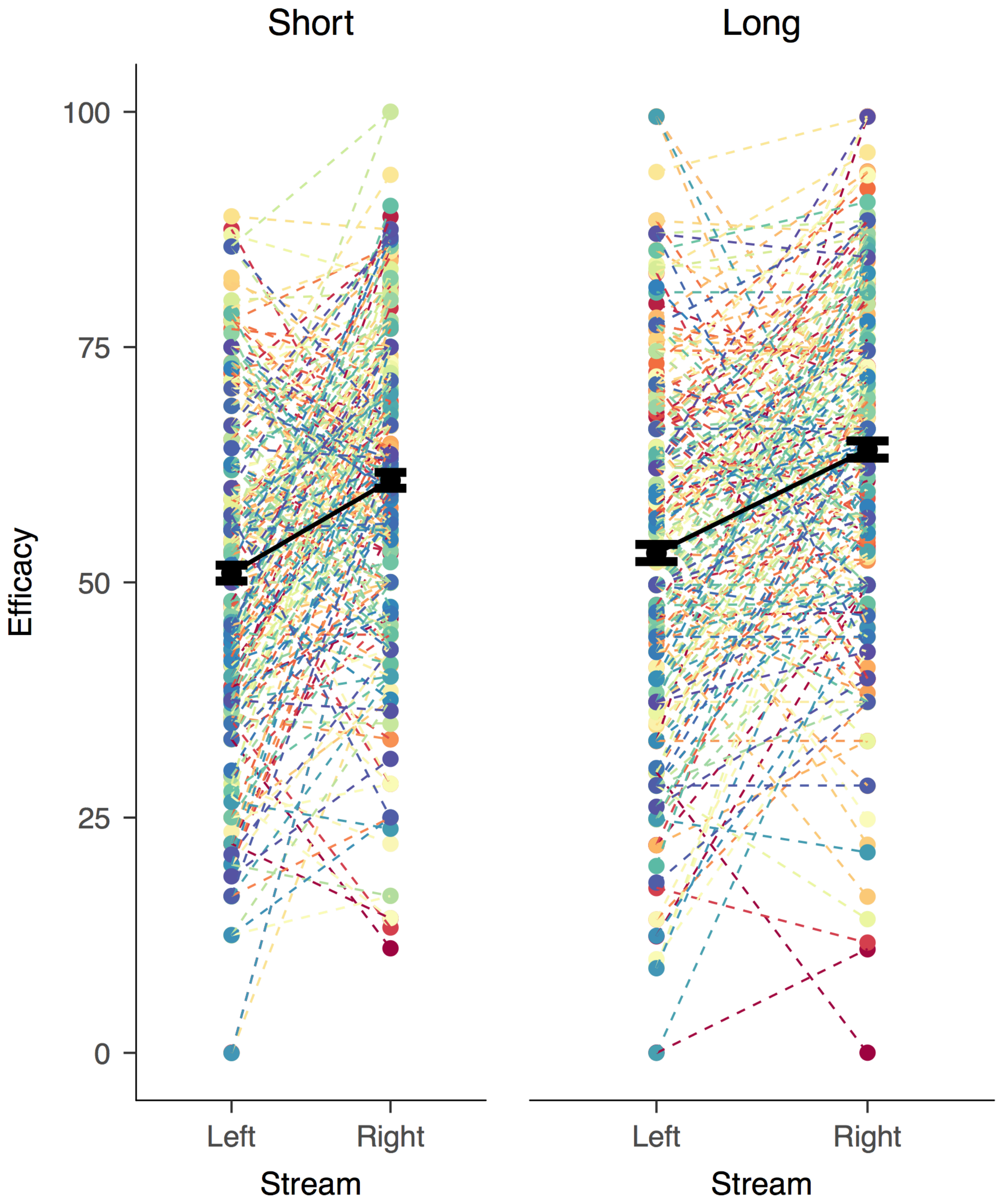

*Figure 16:* Efficacy by item for short and long delay conditions. Coloured dots are results for individual items. Black dots (with error bars) are results averaged over participants.

### 4.3.4 Discussion of Experiment 1

In line with the findings of Goodbourn and Holcombe (2015), it had been predicted that the relative advantage for the left stream would be greater when there was a long delay between the offset of the stimulus and the onset of the cue indicating which word to report. In fact, the Bayesian analysis clearly favoured the alternative hypothesis that the relative advantage for the left stream was at least as large when there was a short delay between the offset of the stimulus and the onset of the cue. It appears that the spatial bias in the present experiment reflected a process that differed in at least some regard from that contemplated by Goodbourn and Holcombe in response to the spatial biases documented through their dual RSVP experiments.

The fact that the deficit was on the left side for both short and long delay conditions was also not predicted by the model suggested by Goodbourn and Holcombe and is likely to reflect differences between the stimuli used in the two experiments. In particular, Goodbourn and Holcombe used letters embedded in RSVP streams, but here the stimulus is a single presentation of a pair of words followed by masks. Several previous psycholinguistic experiments using words in different experimental paradigms have also found left stream deficits for words and have attributed these to the lateralisation of language processes in the brain, a factor that is likely to be responsible for the results observed here. Chapter 5 of this thesis, which seeks to illuminate the differences between capacity limits on words and letters in the dual RSVP paradigm, discusses the previous literature in detail.

Another potential explanation for the lack of a delay effect is that the key manipulation in the present experiment — delaying the cue indicating which stream to report — may not have effectively manipulated the delay in consolidation associated with each of the streams. In our experiment, the shortest duration between the offset of the word and the onset of the cue was 200 ms (the duration of the intervening mask). Perhaps this was simply not short enough to avoid decay of one of the targets? Experiment 2 addresses this by reducing the duration of the mask by 165 ms, so that the duration of the mask is 35 ms. This will provide an earlier indication of the target in the brief delay condition and so increase the likelihood that the target can be prioritised before decaying regardless of its spatial position. It also includes a condition where a single word is presented on either the left or right side, to assess whether the left deficit for words is specific to simultaneous presentation.

## 4.4 Experiment 2

Experiment 2 presents the same stimuli as Experiment 1, but with a shorter mask duration. It also introduces a single target condition in which participants must report one word that is presented either to the left or the right of fixation. The purpose of this experiment is to investigate whether the failure to find an effect of delay in experiment 1 was because the delay was not short enough to avoid decay in the right-side targets. The addition of the single target condition was included to provide insight into whether the observed spatial biases are specifically associated with processing two targets.

### 4.4.1 Method

The method was the same as for Experiment 1, with three exceptions. The first is that the post-stimulus mask was presented for only 35 ms, rather than 200 ms as in Experiment 1. The second is that an additional condition was included in which a single word was presented in either visual field. Participants were able to report the word as soon as it was presented. The three trial conditions (long delay, short delay and single target) were blocked and the order of the blocks was counterbalanced across participants. The third is that all items were presented for a duration of 17 ms. The previous method of using two different presentation rates was abandoned because experiment 1 had found less variation in performance across participants than originally expected.

### 4.4.2 Analysis

As with Experiment 1, the primary hypothesis is that the spatial bias would favour the left more when the probe indicating which item to report was presented after a long delay than after a short delay. This is again tested using one-tailed Bayesian within subjects t-tests.

An additional hypothesis is that when participants are asked to report a word that is presented in isolation, they will show a smaller left bias than when they are required to report one target from a set of two words that are presented simultaneously. This is consistent with evidence that bilateral stimulus presentations are associated with larger spatial biases (Boles, 1990). As stated in the preregistration, this will be tested using an additional one-tailed Bayesian within subjects t-test comparing the left bias in the single target condition with the left bias in the dual target long delay condition. The long delay condition was chosen here because it is considered most likely to show an effect of prioritisation in the direction of reading. The short delay condition was designed to override reading direction prioritisation, making it potentially more similar to the single target condition.

Finally, consistent with Experiment 1, spatial biases in each condition will be separately evaluated using one-tailed, one-sample t-tests.

### 4.4.3 Results

In Experiment 2, advice indicating which word was the target was presented 165 ms earlier than in Experiment 1. Even with the earlier advice, spatial biases were similar in the short- and long-delay conditions when averaged across participants or items (figures 17 and 18), with Bayesian t-tests still indicating that the data were slightly less likely under the experimental hypothesis that the left bias would be greater when the delay was long, than under the alternative hypothesis that the left bias would be at least as great when the delay was short (BF01participants = 2.73; BF 01items = 1.86). While the earlier advice about the target did not produce results that were consistent with the predictions of the delayed consolidation account posited by Goodbourn and Holcombe (2015), it was closer to the predicted result (that is, a more leftward spatial bias when in the long condition relative to the short direction) than was obtained in the first experiment. The analysis was equivocal as to whether the difference between the left deficit in the single target condition and the dual target long delay condition reflected a true difference between conditions or was due to chance when analysed by participant ($BF_{01}$ = 1.23) though there appeared to be an effect when analysed by item ($BF_{01}$ = 9.20) which may reflect an influence of lexical qualities of the stimulus such as word frequency.

When the conditions were evaluated separately, one-tailed t-tests indicate left deficits in all conditions, with the greatest deficit in the single target condition (M = 13.58, SD = 15.96, $BF_{10}$ = 1061.84), followed by the short delay condition (M= 10.78, SD = 4.30, $BF_{10}$ = 2.72) and the long delay condition (M= 8.68, SD = 23.21, $BF_{10}$ = 1.471.

Contrary to Experiment 1, a Bayesian ANCOVA found a large effect of reading experience (as estimated by the Author Recognition Test) on the magnitude of left bias ($BF_{10}$ = 156.44) and found that this interacted with the performance in the different conditions ($BF_{10}$ = 22.76). From the scatter plots, it appears that there may indeed be a positive relationship between performance on the Author Recognition Test and the magnitude of the left bias for each condition (figure 19). However, the sample size that would be needed to perform robust correlational analyses is likely to be well beyond that used in this study (Schönbrodt & Perugini, 2013). Given that this is a secondary hypothesis, we have elected not to increase our sample size to a level necessary to conduct this analysis.

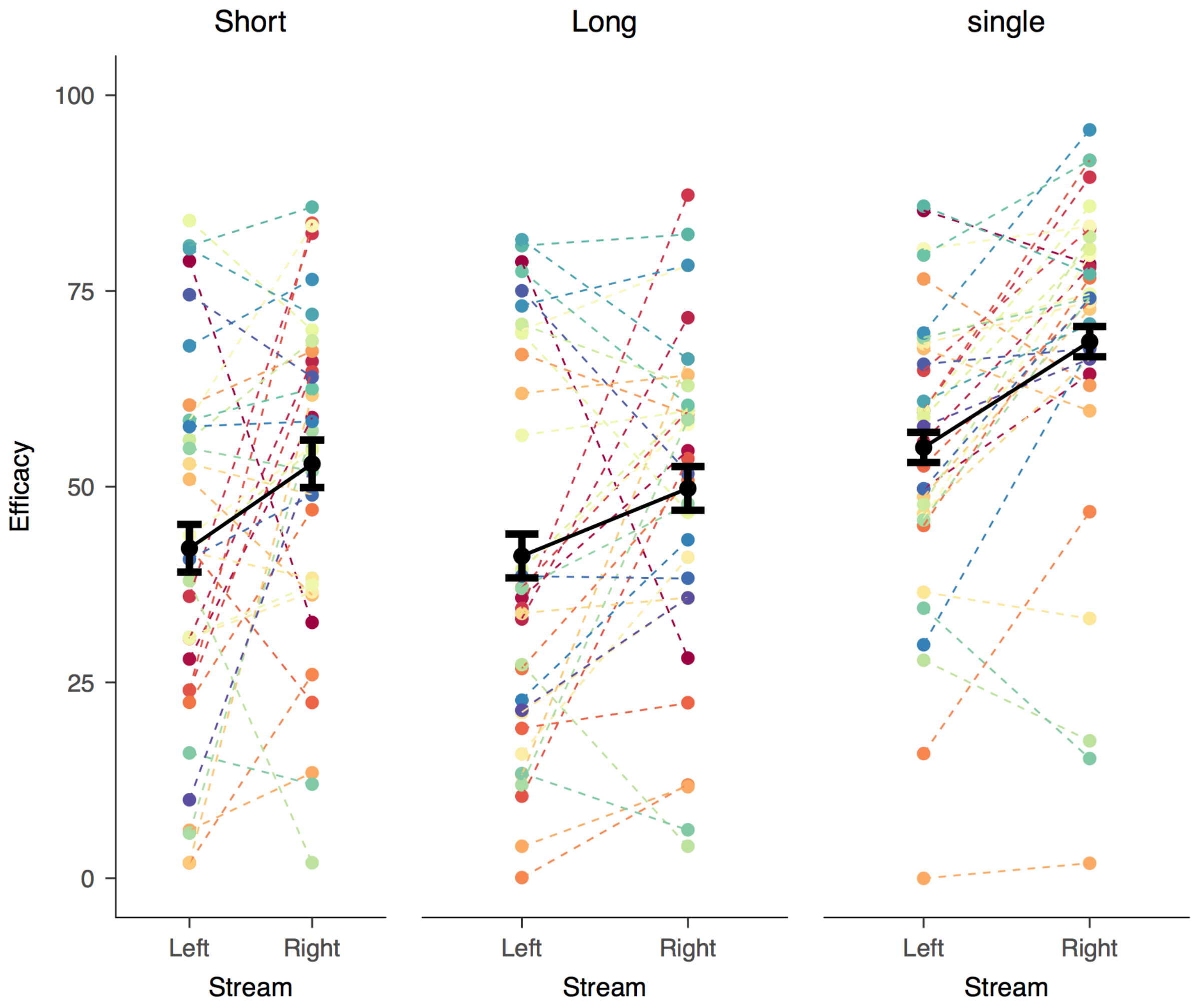

*Figure 17*: Efficacy by participant for short and long delay conditions and the single target confition. Coloured dots are results for individual participants. Black dots (with error bars) are results averaged over participants.

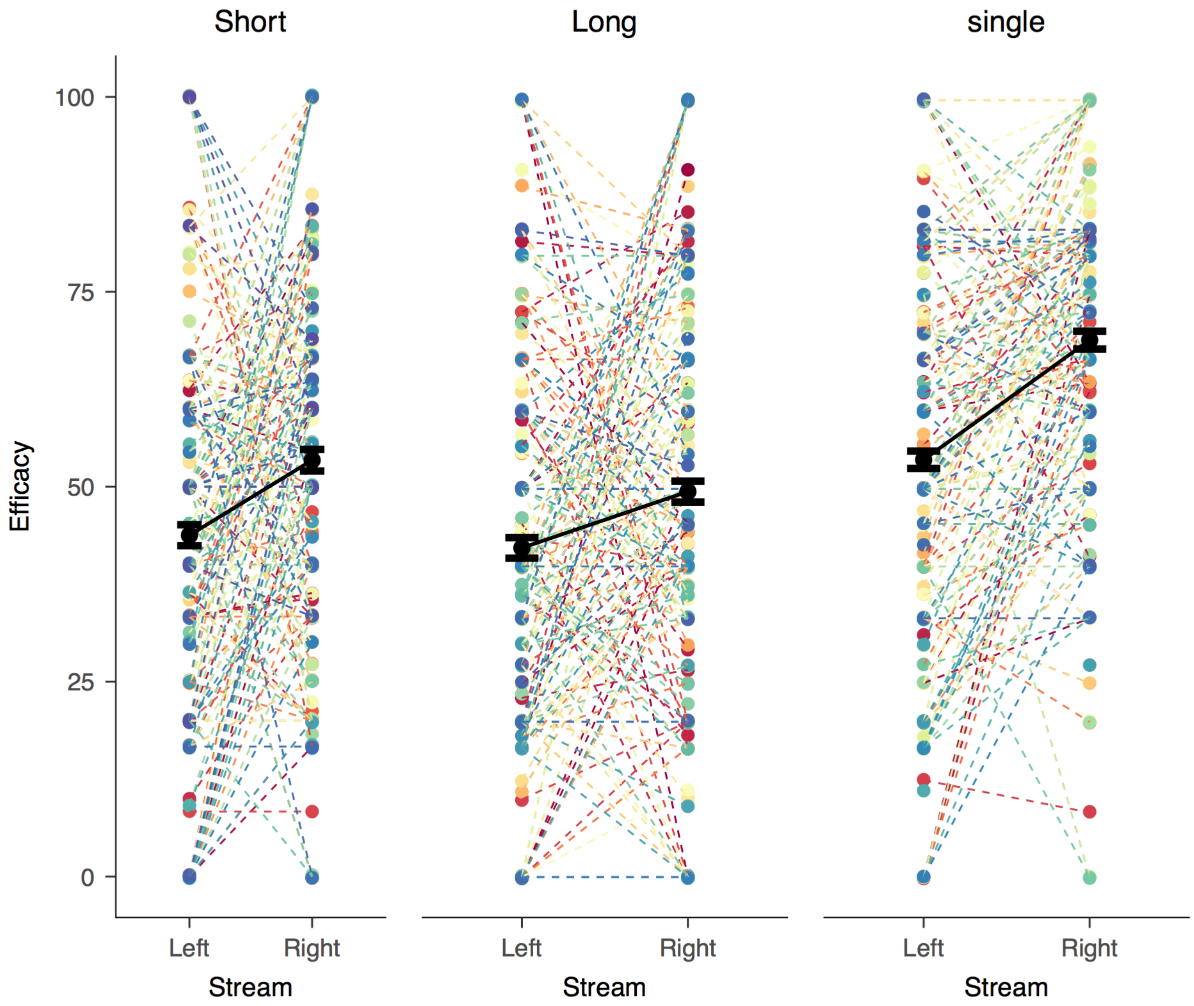

*Figure 18:* Efficacy by item for short and long delay conditions and the single target condition. Coloured dots are results for individual items. Black dots (with error bars) are results averaged over items.

*Figure 19:* Scatter diagram of score on the Author Recognition Test and the left bias.

### 4.4.4 Discussion of Experiment 2

Experiment 2 investigated whether the spatial bias associated with reporting one of two simultaneously presented targets could be diminished by providing early advice about which item was the target. Like Experiment 1, the results failed to show the predicted effect that the long delay condition would be relatively more left biased than the short delay condition. Moreover, there was again a left deficit in all conditions. This was numerically greater in the single target condition, though Bayesian t-tests did not support an interpretation that these were different. Notwithstanding this, spatial biases are often negated in single target experiments (Boles, 1990), and it is unusual to find even a slightly higher bias in a single target condition than in a dual target condition.

In contrast to Experiment 1, performance on the Author Recognition Test appeared to be associated with a greater left bias on the dual RSVP task. This was unexpected given the similarity between the two experiments and the fact that experiment one found that the Author Recognition Test was not associated with bias on that dual RSVP task. One difference between the two experiments that may have contributed to the effect was the introduction of the single target condition. However, the scatter plots appear to show a positive relationship for all three conditions, which would be unlikely to be the case if the results were solely driven by the single target condition. That said, notwithstanding the strong Bayes factor of the main effect of reading experience on the left bias, correlational analyses usually require larger sample sizes than are used here. This, in addition to the fact that the effect was different across the two experiments, suggests some caution should be attached to any interpretation of the results. In many ways, the overall insight from the analysis of the Author Recognition Test is similar to that from analysis of reading experience in Arabic and English presented in Chapter 3: While these results leave open the possibility that the right deficit may indeed be influenced by reading experience, a dedicated study with a much larger sample size would be needed to be confident of this.

## 4.5 General Discussion

Goodbourn and Holcombe (2015) argued that the spatial bias observed in their dual RSVP experiment was likely to reflect a delay in processing the right-most of two targets at a post-sampling stage of processing due to a bias induced by habitual reading direction. The present experiment investigated this claim by requiring participants to report one of two briefly presented words, and manipulating when they were told which word to report. If Goodbourn and Holcombe's claim is correct, early cueing of report order may allow participants to override the usual left side prioritisation, and so avoid the delay in processing the right word. This should lead to a smaller deficit than when the cue to report order is provided later, by which stage the word on the right may have already decayed. Neither experiment 1, which provided the cue indicating which word to report 200 ms after the offset of the word, nor experiment 2, which provided the report cue 35 ms after offset, found a spatial bias in the short delay condition that was convincingly smaller than when participants were told which word to report much later. As such, the evidence provided here does not corroborate the serial bottleneck account that has been used to explain the spatial biases in dual RSVP experiments.

While the lack of an effect of the cue delay may indicate that the capacity limit causing the second-target deficit takes a form other than a serial bottleneck, it is also possible that participants were not able to effectively use the information in the short delay condition to prioritise to the target word when it was on the right side. For example, in both long and short delay conditions, the initial presentation of the words may trigger processing for the left item before participants are cued about which item to report. To make use of the information revealing which item to report, participants must disengage from processing one item, and redeploy processing to the other. While Sperling (1960) convincingly demonstrated that participants could make use of a cue to the location of target objects when required to report a large array of letters, it is possible that disengagement is more difficult for words than letters. Supporting this, words have been associated with strong unconscious processing tendencies as demonstrated through the inability to inhibit word reading when performing Stroop tasks (Coltheart, Woollams, Kinoshita, & Perry, 1999; Stroop, 1935). Furthermore, items in Sperling's experiment were not post-masked, and so items may have persisted in iconic memory. This may have allowed participants more time to disengage and redeploy attention in response to the post-cue. The ability for participants to disengage from processing an item, and the implications of this for serial and parallel theories of the second-target deficit, are discussed in more detail in Chapter 6.

In contrast to the large right deficits that were found in Goodbourn and Holcombe's (2015) experiment with dual RSVP experiments with letters, and the English letters condition of the dual RSVP experiment in the previous chapter, the present experiments find large left deficits in all conditions. The different results appear most likely to reflect a processing advantage for linguistic stimuli in the left hemisphere (to which items in the right visual field are initially directed) that was triggered by using words and not letters. An influence of hemispheres has long been used to explain right visual field advantages found for word naming and lexical decision in other paradigms (Bryden, 1966; Cohen et al., 2000; Davis & Bowers, 2004; M. J. White, 1969), and the present task is likely to engage similar linguistic processing stages. Even so, the fact that using words rather than letters would produce such different results remains somewhat surprising given that these right advantages found in other paradigms have sometimes also been found for letters as well as words (Bryden, 1966; Mishkin & Forgays, 1952).

Moreover, the prioritisation mechanism thought to be responsible for the bias in dual RSVP experiments with letters appear to be linked to reading direction (Holcombe et al., 2017; Ransley, Goodbourn, Nguyen, Moustafa, & Holcombe, 2018). Many models of reading are based on a hierarchical process where letters are identified first, then bigrams, and ultimately words (Vinkier et al, 2007). Most do not incorporate a mechanism for prioritising letters within a word because it is assumed that the letters are processed in parallel (and Adelman, Marquis, & Sabatos-DeVito, 2010; see Rumelhart & McClelland, 1982). Thus, a strong possibility is that the prioritisation mechanism contemplated by Goodbourn and Holcombe (2015) is typically engaged at a stage of processing that occurs after letter units have been grouped together to form word representations — that is, the two letters in the second-target deficit experiments may be functionally treated as words because they are widely spaced. This possibility is specifically investigated in the next chapter. A left advantage that has been found for letters that are being treated as words would also be expected to occur for actual words, which again suggests that the prioritisation at the capacity limit should have the influence on spatial biases in the present experiment when the stimuli are words as it did in dual RSVP studies with letters as stimuli.

One way to explain the deviation in results without invoking a prioritisation mechanism that operates differently for letters or words is to attribute the left deficit in the present experiment to a different stage of processing than that of the capacity limit. Supporting this is the fact that the left deficit was no bigger in the dual target (long delay) condition than in the single target condition (in fact, it was numerically smaller). Spatial biases that are larger for a single target than for multiple simultaneously presented targets are relatively uncommon in investigations of visual field effects, which usually find biases that are two to three times smaller in single target conditions (Boles, 1979, 1983; McKeever, 1971). Such biases are attributed to a greater ability to transfer neural representations to the favoured hemisphere when there is not an object in the contralateral visual field (Boles, 1990). The fact that the right deficit found in the dual RSVP experiments was not also observed here may indicate that although the right deficit also occurs for words in the dual target condition of the present experiment, it is more than offset by a left deficit at a different processing stage. If this is the case, it supports an interpretation that the spatial biases in the present experiment are a reflection of both prioritisation at a capacity limit that applies to words and letters, and a larger effect of hemispheric differences that is selective for words.

Does the fact that the experiments failed to find the predicted right deficit explain why they also failed to show the predicted effect of the cue delay on the size of the bias? The answer to this depends on the nature of any interaction between hemispheric factors and prioritisation at the bottleneck. It is conceivable that the left hemisphere advantage for language may make it more likely that both items would be processed at the capacity limited stage (for example, by making the neural representation of the right item more robust) and so reduce the likelihood that delaying the cue would cause non-prioritised items to decay. This issue has important implications for understanding the processes underlying the capacity limited stage, and is discussed at length in the following Chapter.

Finally, while the delay manipulation in the partial report paradigm did not support the serial bottleneck account, the present experiment demonstrates that robust spatial biases can be observed using a stimulus presentation methodology that is simpler than dual RSVP streams and more closely resembles how psycholinguistic research is typically done. While this methodology yielded results that are equivocal about the temporal aspects of processing which form the basis of Goodbourn and Holcombe's (2015) claim that items are sampled in parallel, it again demonstrated that spatial position influences the ability to report targets, which is central to their theory about the second-target deficit. With RSVP streams, there are, unfortunately, complications associated with presenting complex items, such as non-words, letter strings, and complex non-linguistic items. The present experiment thus adds to the range of paradigms that can be usefully applied to these stimuli. Ultimately, such manipulations may be useful in understanding the stages of processing that are affected by the capacity limit.

# Chapter 5: Dual RSVP with Words

## 5.1 Chapter Synopsis

When two letters embedded in dual RSVP streams are presented concurrently and briefly, participants typically show a spatial bias, performing much worse for one of the streams than for the other. The capacity limit that prevents accurate report of both letters has been linked to implied reading order (left to right in English, yielding a right-side deficit in most participants). Does this capacity limit occur at a stage at which individual letters are processed, or where representations of words have been formed? Here we investigate this by comparing deficits found when the two stimuli are letters with those found when the two stimuli are words. Presenting the streams in a horizontal configuration yielded the previously documented right-side deficit for English letters, but a left-side deficit for the English words. This is consistent with a left hemisphere advantage that is specific to word recognition. When hemispheric factors were controlled by presenting the streams in a vertical configuration, a lower-stream deficit was observed for both letters and words. The similar deficits for words and letters when hemispheric factors are controlled are consistent with previous suggestions that implied reading order affects priority of processing for a capacity limit. These findings further suggest that this capacity limit occurs after letters are combined to form words.

## 5.2 Introduction

The experiment discussed in Chapter 3 used concurrent RSVP of letters and documented that the direction in which a script is typically read affects which of two horizontally-displaced streams is prioritised — in English, the letters of the left stream are better reported but this is not the case in Arabic. This suggests that the prioritisation process may reflect a capacity limit that plays a role in natural reading. Reading is a complex task, and involves multiple processing stages at which visual features, letters, and ultimately words are identified. Determining the stage at which the capacity limit occurs is important for understanding the role of the capacity limit in natural reading.

Goodbourn and Holcombe (2015) found a deficit in reporting the right-most of two simultaneously presented letters. While this superficially suggests that the capacity limit occurs in the process of identifying the letters of a word, it may also be that spacing between the letters causes the visual system to process the letter stimuli as if they were short words. If this is the case, second-target deficit experiments with words ought to generate the same spatial biases as Goodbourn and Holcombe found with letters. In fact, the experiments presented in the previous chapter found very different spatial biases in a paradigm that required participants to identify simultaneously presented words, rather than letters, which may suggest that the capacity limit observed by Goodbourn and Holcombe occurs before letter representations have been grouped to form words. However, those experiments did not use a dual RSVP presentation, and instead presented two words simultaneously in a static display. This makes it difficult to determine whether the failure to achieve the right target deficit previously reported from dual RSVP of letters was the result of the stimuli being words, or alternatively, was related to other aspects of stimulus presentation such as the static display. The experiments in the present Chapter return to the dual RSVP paradigm to provide a more detailed examination of the factors that influence spatial biases with letters and words, with a view to revealing the relative roles of reading direction prioritisation and hemispheric factors during reading.

### 5.2.1 Evidence for prioritisation of letters in the direction of reading

If the second-target deficit reflects a capacity limit associated with combining letters to form words, the left to right prioritisation associated with the second-target deficit would indicate an advantage in processing the left-most letters of a word. A number papers show evidence of letter position effects in experiments with single words as stimuli. Both Ashenbrenner, Balota, Weigand, Scaltritti, & Besner (2017) and Scaltritti & Balota (2013) found first letter position effects in a paradigm where participants are briefly shown a masked word, and then asked to select the target from two alternatives: one that is identical to the target, and one that differs by only one letter. In both cases, participants made fewer errors when the two alternatives differed by their first letter, but had a reasonably even distribution of errors across other letter positions. Similarly, Lindell & Nicholls (2003) reported first letter position effects in a paradigm in which an exogenous cue preceded the presentation of a word in either the left or right visual field. To examine letter position effects, they manipulated whether the cue was directed to the beginning of the word, the middle of the word or the end of the word. They found that cuing the beginning of the word improved performance relative to cuing the middle or end of the word, but that this difference occurred only for words presented to the left visual field - when words were instead presented to the right visual field, performance was independent of the position of the cue. Further evidence for prioritised processing of the first letter of a word comes from the phonological Stroop effect, which shows that participants can name the colour of a word faster when the word has a phoneme in common with the colour name, and that this effect is greater when the shared phoneme is at the start of the word than at the end (Coltheart et al., 1999).

While the studies described above suggest left prioritisation of letters, the observed effects appear to be limited to an advantage that relates to the beginning of the word, whereas a serial bottleneck predicts a gradient from beginning to end. Of the four studies citing letter position effects, three (Aschenbrenner et al., 2017; and Lindell & Nicholls, 2003; Scaltritti & Balota, 2013) found that performance was roughly the same at the middle and the end of the word, and the fourth (Coltheart et al., 1999) only compared the beginning and end of the word, and so could not test this. Some researchers have argued that such a first-letter bias may develop to take advantage of the fact that the beginning of words are more informative than the middle or end of words (Brysbaert, Vitu, & Schroyens, 1996). However, given that the dual RSVP experiments have been limited to two streams, a first letter effect could explain the right target deficit reported by these studies.

Notwithstanding this limited evidence for first-letter effects, most mainstream models of reading assume that letter representations activate corresponding lexical entries in parallel (R. Engbert et al., 2005; Alexander Pollatsek et al., 2006; Reichle et al., 1998; Reichle et al., 2003). There is evidence to support this assumption. For example, in a seminal work, LaBerge (1983) asked participants to either categorise a letter or categorise a word. On some trials, a probe was inserted in one of the letter positions, and participants had to respond as fast as possible to the probe. When participants were performing the letters task, the reaction time to the probe formed a "V" shaped function with respect to the position of the probe (reaction time was shortest for the middle letters). However, when participants were performing the words task, the reaction time was reasonably flat across all letter positions. This is consistent with there being a parallel process for words whereby attention is equally distributed across all of the letter positions. More recently, Adelman, Marquis, and Sabatos-DeVito (2010) measured the threshold presentation duration for which a forward- and backward- masked target word could be correctly discriminated from a word that differed by one letter. If participants were encoding letters sequentially, the threshold would be expected to be greater for words that had different letters in later positions than earlier positions. However, the observed threshold did not differ according to the position of the different letter. Again, these results seem to back up the typical assumption that letters within a word are processed in parallel.

### 5.2.2 Evidence for prioritisation of words in the direction of reading

If the second-target deficit instead reflects a capacity limit that occurs when combining words to form sentences, the left to right prioritisation associated with the second-target deficit would indicate an advantage in processing the left-most word in a sentence. The order in which words are processed has been subject to extensive investigation using methodologies that monitor the pattern of eye-movements participants make while reading passages of text (see Keith Rayner, 2009 for a review). These studies measure the location and duration of each fixation, and make inferences about which words are being processed from models of reading that seek to explain patterns of eye-movement data. As discussed in more detail in Chapter 1, the two major models of eye-movement control in reading agree that multiple words can be processed within a fixation, but disagree on whether this is achieved by processing multiple words concurrently or by processing one, then shifting attention to allow processing of the next word. However, most models incorporate some form of reading direction prioritisation, which either affects which word is processed in a serial sequence (Reichle et al., 2003), or the distribution of processing resources across multiple words (R. Engbert et al., 2005). Importantly, neither model contemplates how that left-to-right process would be implemented in a situation where participants fixate between two words, as occurs in both dual RSVP experiments (for example, the experiment in Chapter 3), and the partial report experiment discussed in the Chapter 4. As such, while many models of eye-movements in reading contain a mechanism for prioritising a subset of words, is not clear that they would necessarily predict prioritisation of the left item in a dual RSVP or partial report display.

One recent study by White, Palmer and Boynton (2018) investigated prioritisation of words in two experiments in which words were presented simultaneously to the left and right hemifields. In one experiment, target words were embedded in RSVP streams similar to those used by Goodbourn and Holcombe (2015), and in the other, target words were briefly presented and masked, using a similar display to that used in the partial report paradigm used in Chapter 4. However, in contrast to these other dual item experiments, which always encouraged a strategy of attending to both locations, White, Palmer and Boynton (2018) compared a condition in which participants were told before the trial to attend to one location (either left or right), with one in which participants were told to attend to both locations. On each trial, the task was to judge either the colour or semantic category of the target(s) in the location(s) that they attended to. They found that in the dual target condition participants could judge colour accurately for both targets, but were generally only able to accurately judge semantic category accurately for one of the two targets, which was interpreted as strong evidence for serial processing. In contrast to the right visual field deficit observed by Goodbourn and Holcombe (2015), White and colleagues' participants were better at reporting the item on the right. This suggests that participants were more likely to prioritise that item, and were able to identify the colour of the non-prioritised item, but had little to no ability to process it to a lexical or semantic level.

### 5.2.3 Hemispheric differences may contribute to the spatial biases

In addition to reading direction effects, a difference between processing targets on the left and right could also result from differences in how the two cerebral hemispheres process stimuli (Boles, 1990). Both spatial attention and language production are thought to be lateralised, with imaging studies confirming that these functions typically reside in different hemispheres — for most right-handers, language production is lateralised to the left hemisphere (Knecht et al., 2000; Pujol, Deus, Losilla, & Capdevila, 1999) and spatial attention is lateralised to the right hemisphere (Kinsbourne, 1987; Zago et al., 2017). Functional magnetic resonance imaging experiments have found evidence that reading *words* shares the same pattern of hemispheric bias as language production (Van der Haegen, Cai, & Brysbaert, 2012), however, reading *letters* tends to produce similar activation in each hemisphere, suggesting that letter recognition units may be distributed across both hemispheres (Vinckier et al., 2007). Notwithstanding this, classic behavioural experiments using *unilateral* presentations have typically found more accurate recognition of items presented in the right visual field, regardless of whether the items are letters or words (Vinckier et al., 2007). The left lateralisation of language centres has also been posited as an explanation of the right visual field advantages typically found in experiments using *bilaterally* presented words (Davis & Bowers, 2004; Hunter & Brysbaert, 2008).

In contrast with the right visual field advantages typically found in studies with unilaterally presented letters or words, and bilaterally presented words, the few published experiments that have investigated visual field effects using bilaterally presented letters or non-word letter strings have tended to find left visual field advantages (Bryden, 1960, 1966; Harcum, 1964; Heron, 1957), favouring explanations based on reading direction. This is consistent with the findings of our previous dual RSVP experiments that implied reading direction had a large influence on the size of the second-target deficit (Holcombe et al., 2017 and see also Chapter 3 of this thesis). However, the dual RSVP paradigm has not yet been applied to word stimuli. Given that experiments using bilaterally presented words as stimuli tend to yield different spatial biases to experiments that use bilaterally presented letter strings as stimuli, it is possible that different processes contribute to spatial biases in dual RSVP with words and letters.

### 5.2.4 The present study

The present study investigates whether the capacity limit documented in previous dual RSVP studies reflects a stage at which individual letters are processed, or whether the limit occurs after nearby letters have been grouped together, as is done to create word representations. This is achieved by comparing the deficits observed in the dual stream RSVP paradigm when the two stimuli are letters with those found when the two stimuli are words. Experiment 1 applied the horizontal dual stream configuration used in Experiment 1 of Goodbourn and Holcombe (2015), but manipulated the content of the RSVP streams (letters in one condition, words in the other). If the capacity limit applies after letters have been combined to form representations of words, a right deficit should be observed for both words and letters. Alternatively, if the capacity limit applies to letters, there would be no reason to expect the same pattern of results for letters and words.

To determine whether the spatial biases observed for the horizontal configurations of Experiment 1 are influenced by differences in hemispheric specialisation between letters and words, Experiment 2 removes hemispheric differences as a factor by presenting the two streams in a vertical (up/down) configuration. On half the trials, both streams are presented in the left hemifield, and in the other half of trials, both streams are presented in the right hemifield. Test are conducted to determine whether the deficit is similar for letters and words. Previous work has found that when two letter streams are presented in a vertical configuration, participants are worse at reporting targets in the lower stream (Goodbourn & Holcombe, 2015; Holcombe et al., 2017). This lower-stream deficit was eliminated when all the letters in the two streams were rotated such that they faced upward, supporting the theory that the usual upper-stream advantage reflects implied reading direction (Holcombe et al., 2017).

The second (vertical configuration) experiment also uses a visual field manipulation to test whether participants show an advantage in reporting words and letters from the right visual field. Although this has been shown repeatedly for individual words and letters, there is less literature on simultaneous presentation of two stimuli in one hemifield, and as demonstrated in Chapter 3, bilateral presentation of normally oriented English letters results in a *left* advantage for letters. Experiment 2 will investigate whether any such advantage applies to both letters and words. It will also investigate a claim made in previous literature that language processing is weighted towards serial mechanisms in the right hemisphere, and parallel mechanisms in the left hemisphere (Ellis, Young, & Anderson, 1988; Lindell & Nicholls, 2003; Whitney & Lavidor, 2004).

To clearly distinguish the pre-planned from the post-hoc (Pierce, 1878), we preregistered our data analysis plans for Experiment 1 (https://osf.io/jknmx/) and Experiment 2 (https://osf.io/jpy58/). For both experiments, the primary focus of the analyses was to assess whether the second-target deficit differed when the stimuli were words compared with when they were letters. We also planned to calculate Bayes factors, as they can help quantify evidence for a result of no difference between conditions.

## 5.3 Experiment 1

### 5.3.1 Method

#### *5.3.1.1 Participants*

Participants were recruited from the first-year subject pool at the University of Sydney and received course credit for participating. Twenty-four participants (11 male, 13 female) completed the experiment. Data from one participant was omitted from the analysis because she reported that she had misunderstood the instruction about which item to report first. According to the Revised Edinburgh Handedness Inventory (Williams, 2010), all participants were right-handed except two, who were left-handed. Data for the left-handed participants were omitted.

#### *5.3.1.2 Apparatus*

Stimuli were generated using Psychopy (J. Peirce et al., 2011; J. W. Peirce, 2009) on a MacBook Pro, and displayed on a Diamond Pro 2070 SB CRT monitor. The monitor had a resolution of 1600 × 900 pixels and a refresh rate of 85 Hz. Participants were seated in a dark room with their head supported on a chin-rest 57 cm from the monitor. Participants commenced each trial by pressing a key on a standard keyboard.

Eye movements were monitored using an Eyelink 1000 eyetracker in order to remove trials on which a participant did not maintain central fixation.

#### *5.3.1.3 Stimuli*

The two RSVP streams presented on every trial consisted of lower-case letters in one condition, and lower-case four-letter English words in the other (see figure 20). The letters or words were drawn with Arial font, in white against a black background. A white fixation circle of 0.25° diameter was located at the centre of the screen. One letter stream was positioned so that the centre of the word was 6.0° directly to the left of fixation, and the other was positioned so that the centre of the word was 6.0° directly to the right of fixation. The height of the tallest letter was 1.9° (measured using letter *f*) and the width of the widest was 1.5° (measured using letter *m*). The width of the widest word was 4.52° (measured using the word *name)*. In the letters condition, on each trial, for each of the two streams, 18 letters were randomly selected (without replacement) from the 26 letters of the alphabet. In the words condition, on each trial, in each stream 18 four-letter words were presented. Words were selected from a subset of the SUBTLEX database (Van Heuven, Mandera, Keuleers, & Brysbaert, 2014) with words omitted if they were proper nouns, highly emotive, unsavoury (judged subjectively by the author) or contained multiple syllables. Selection was made according to an algorithm implemented in R, which can be accessed at (https://osf.io/cznfy/). This algorithm was designed to balance the need to avoid frequent repetition of the same words over the course of the experiment with the desire to avoid too large a variation of frequency among the words of a trial. Meeting these objectives was challenging given that the dual RSVP stimulus requires 36 words per trial, resulting in a total of 3,456 word presentations across the whole experiment. After trialling several potential sampling criteria, we elected to used 324 words in total, and ensured that a word would never appear twice in the same trial, and could appear at most 8 times over the course of the experiment. Words were constrained to a mid-range frequency band. On the Zipf scale developed by van Heuven and colleagues (2014) the lower frequency cut-off was 4 (which corresponds to 10 per million words) and the upper frequency cut off was 5.2 (which corresponds to 158 per million words).

In addition to restricting the frequency range of the words used in the entire experiment, we further restricted the frequency range of words that could be presented in a single trial. This was intended to limit the influence of word frequency (which would contribute to the error variance in the statistical tests) on differences in responding between the left and right streams. Six frequency bands were created, each with 54 words. Within each band the Zipf range was no more than 0.2. This corresponds with a range of 5 per million words for the lowest band, and a range of 50 per million words for the highest frequency band. It was not possible to have bands that each had the same frequency range when measured in words per million due to the distribution of words in the SUBTLEX database, and the need to ensure that each band the required number of words.

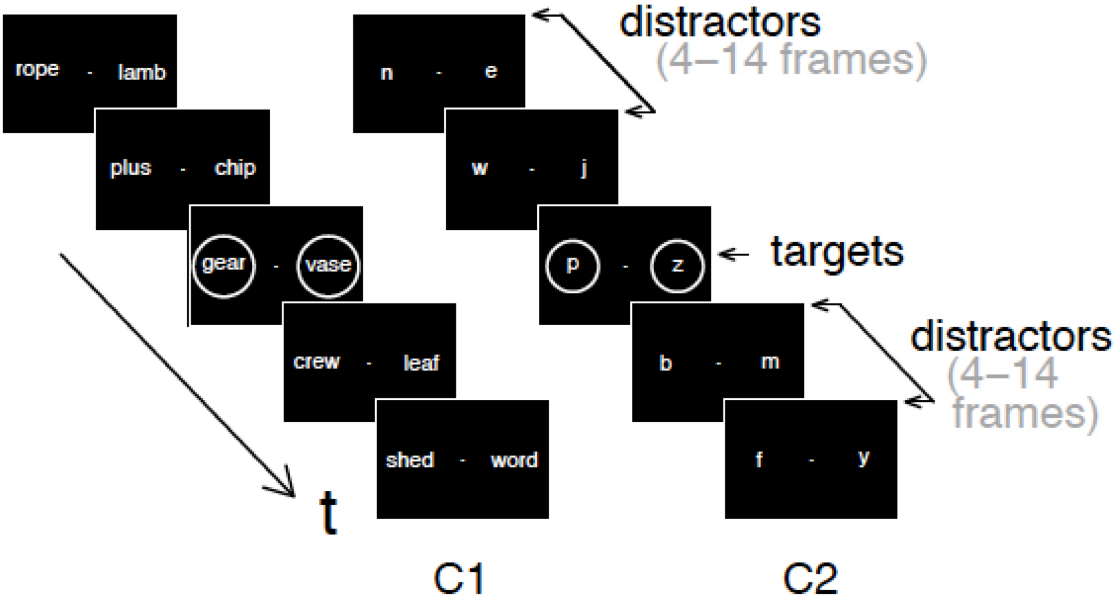

*Figure 20:* Stimulus used in experiment 1. C1: words condition. C2: letters condition.

#### 5.3.1.4 Procedure

Participants completed a 96-trial letters block and a 96-trial words block, with the order of the blocks counterbalanced across participants. One participant performed 11 fewer trials in the words condition due to a computer malfunction. Participants completed four practice trials before commencing the dual-RSVP task in each condition. The whole procedure took approximately one hour.

Participants were instructed to fixate on the central white dot for the duration of each trial. An auditory tone and two white rings at the locations of the streams (both of 250 ms duration) indicated that a trial was about to commence. The first item appeared 1 s later. Each item in a stream was presented for 130 ms followed by a 40 ms blank interval. The serial position of the target items was between the 5th and 14th inclusive and was randomly chosen on each trial. Each target item was cued by a ring that enclosed it. The rings were white, of 0.1° thickness, subtended 5°, and were presented for the same duration as the letter (130 ms).

A response screen appeared immediately after offset of the final items. This comprised a line which appeared under the position of one of the streams (randomly determined). The line indicated which stream (left or right) the participant was required to report first. Participants responded by saying the word that had appeared in the stream indicated by the line. They then pressed a key, and the line would move to the other side, prompting them to say the target word from the other stream. An experimenter seated in the room typed the participants' responses. If the word the participant responded had a homophone, participants were prompted to spell the word. Some participants occasionally stated that they had 'no idea' what the target was. On the first instance this occurred, participants were told that it was best to guess if they could. If they persisted in saying they had no idea, the response was recorded as incorrect.

This procedure was approved by the University of Sydney Human Research Ethics Committee.

### 5.3.2 Analysis

As prescribed in our preregistered data analysis plan, trials were removed from the analysis when participants made an eye movement of more than one degree from the fixation point. A total of 180 trials (4 per cent of total) met this criterion. A participant would be omitted if he/she made eye movements on more than 35 per cent of trials. No participant met this criterion.

Previous studies using RSVP stimuli have documented two types of errors that participants typically make in reporting the target. The first type of error (guessed responses) occurs when participants make a response that does not appear to be related to the target at all, presumably indicating that the participant failed to attend to the target. The second type (target related responses) occurs when the item that the participant reported appeared in close temporal proximity to the target — typically immediately before or immediately after. Previous work that implemented a mixture modelling technique to determine the proportion of ‘miss’ trials relative to other trials for each participant found that these errors occurred more frequently than would be expected by chance, suggesting that they arise when the ring around the target is attended, but bound to a temporally proximal item rather than the target itself (Goodbourn & Holcombe, 2015). Given that such 'binding errors' are likely to reflect successful perception and processing of the ringed letter or a temporally neighbouring letter (i.e., attending to the ring, identifying a letter from around the time of the ring, and consolidating that letter into short-term memory), we followed Goodbourn and Holcombe’s approach of treating probable binding errors as ‘correct’ responses. However, mixture modelling techniques were not appropriate in the current experiments due to slower speed of the stimulus needed for participants to successfully perform the dual RSVP task with words. Thus, we used a rule of thumb, similar to that introduced by Vul, Nieuwenstein, & Kanwisher (2008), of counting an item as correct when the reported item was either the target or one of the two items presented immediately before or after the target. This metric was used to determine the proportion correct for each participant in each stream, which provided the basis for calculating the dependent variable, *right deficit*, that we detail below.

Our primary (and preregistered) hypothesis was that the right deficit (left stream minus right stream) in accuracy would be same in the letters and the words condition. The data were analysed using the default Bayesian ANOVAs described by Rouder and colleagues (2012) and implemented in JASP (JASP Team, 2017).

To extract the effects of individual conditions, we compare models that contain a particular condition with models that are stripped of that condition. While our intention had been to use efficacy as our dependent variable and include stream as a factor in the model, we found that the number of factors in our original model increased the computational burden beyond practical limits. To reduce the ANOVA to a manageable size, instead of including stream (left versus right) in its design, we used the difference in efficacy for the left and right streams — which was in fact our main interest — as the dependent variable. In addition to the within-subjects condition factor (letters or words) which was the main manipulation, we also included as factors in the ANOVA whether targets were reported for the left or right stream first (within-subjects) and whether participants did the letters or words condition first (between-subjects). However, the Bayes factors indicated that models that contained these control variables were always less likely than models stripped of these control variables (first reported stream: $BF_{10} = 0.219$; first condition: $BF_{10} = 0.523$).

As detailed above, our primary analysis counts a response as correct when the participant reports a word that is identical to the target or a word that appeared temporally close to the target. By requiring that the participant report a correct word exactly, with no tolerance for differing letters, we ensured that our dependent variable measures accurate word recognition, as required for successful reading. As a secondary (and also preregistered) analysis, we investigated whether the pattern of spatial biases observed in our primary analysis would persist if we also counted responses that were orthographically similar to an item near the target as correct. Orthographically similar responses may indicate that a participant was able to extract a few letters from the stimulus, and then guessed a compatible word. Alternatively, other letters presented around the stimulus around the time of the target might have ‘intruded’ to create the perceived word, as with the letter migration phenomenon (Davis & Bowers, 2004).

To test that secondary hypothesis, we used Van Orden’s (1987) index to quantify the orthographic similarity between the participant’s response and a correct word on each trial. A complication was that a trial was counted as correct if participants reported an item that appeared temporally close to the target, and so it was first necessary to determine which item the participant’s response was based on. To do this, the participant’s response was compared to all other words in the stream, and it was then assumed that the participant’s response was based on whatever word in the sequence was most orthographically similar. We added the requirement that orthographically similarity estimate of this word must be beyond 0.7 in order to avoid capturing trials where participants missed the target and guessed a word that was not in the stream. All of the Bayesian analyses described above were repeated using this more lenient dependent variable in which the proportion of correct responses includes trials where the participant’s response was orthographically similar to the target.

Finally, we ran a further analysis to investigate whether the average letter position of errors was closer to the end of the word for responses in the right stream than the left stream. To do this, we calculated the letter position of errors for each trial (for example, trap rather than tram is a position 4 error) and averaged these for each participant. We did this only for those trials where participants had made responses that were orthographically similar to the target (as measured by a score on the van Orden (1987) orthographic similarity index of 0.7). We then used a one-tailed Bayesian t-test to test whether the average letter position of errors was higher for responses in the right stream than the left stream.

### 5.3.3 Results

#### *5.3.3.1 Target accuracy*

Our primary hypothesis was that the right-target deficit (left stream minus right stream accuracy) would be equivalent when the stimuli were words as when the stimuli were letters (ie we predicted support for the null hypothesis to be stronger than support for a hypothesis that the bias differed across conditions). However, as can be seen in figure 21, this was not the case. The obtained results are much more likely under the model of difference than the null model of no difference ($BF_{10}$ = 13.6 trillion).

Analysing the words and letters conditions separately, we found a trend for a right-side deficit in the letters condition, but only very weak evidence for it ($BF_{10} = 1.74$). In the words condition we instead found very strong evidence for a *left*-target deficit ($BF_{10} =$ 16,198).

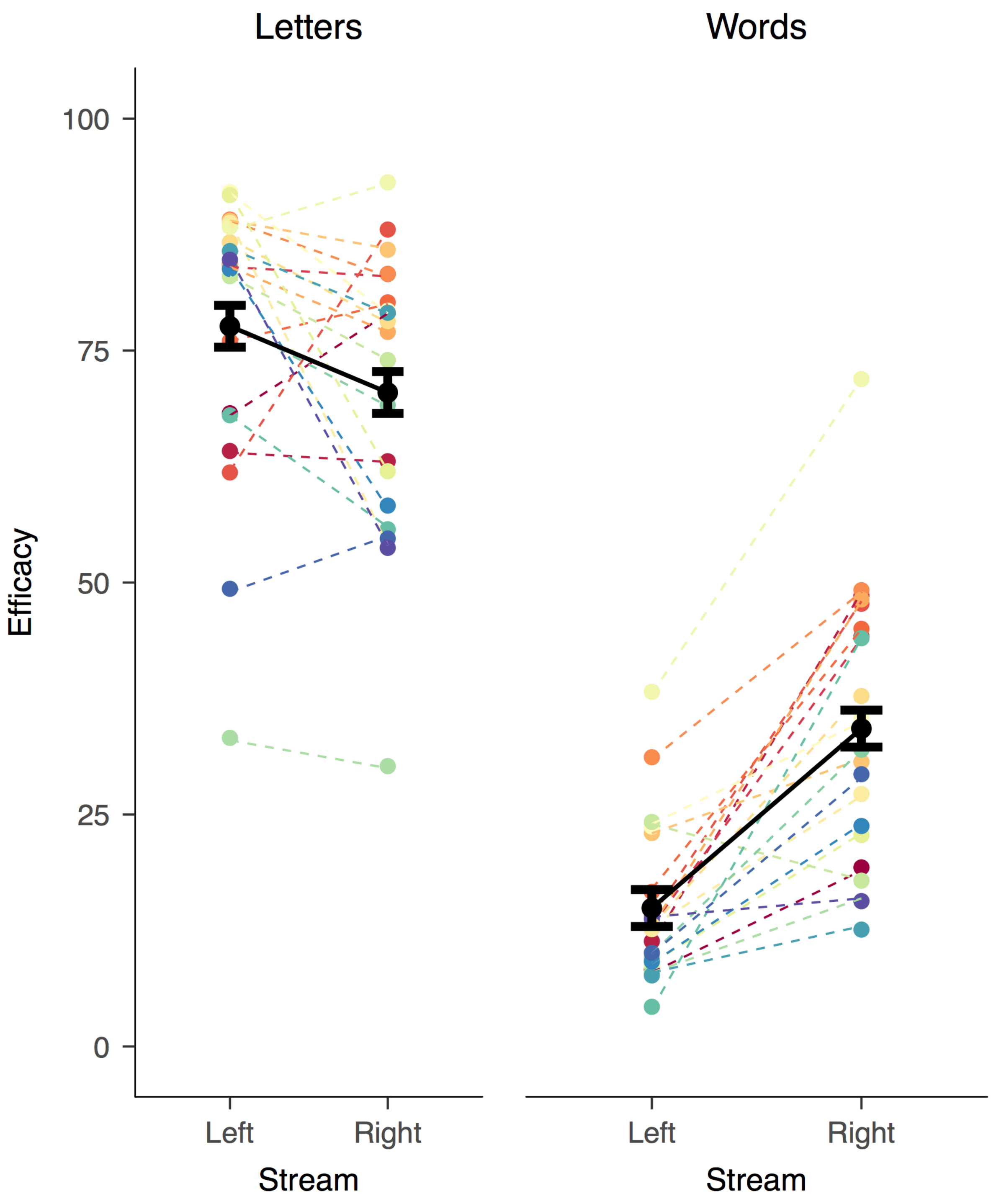

*Figure 21:* Efficacy by participant for letters and words conditions when response must be identical to target word to be counted as correct. Coloured dots are results for individual participants. Black dots (with error bars) are results averaged over participants.

#### 5.3.3.2 *Orthographic similarity*

When the proportion of correct responses includes trials where the participant's response was orthographically similar to the target (figure 22), as with the previous analysis, the measures of target accuracy for words and letters were found to be much more likely under the model of a difference between the conditions than the null model of no difference ($BF_{10}$ = 161.2 million).

When the words and letters conditions were analysed separately, we again found strong evidence for a right bias in the words condition ($BF_{10}$ = 32.76), but the data for the letters condition were only slightly more likely under a hypothesis of difference than under the null hypothesis ($BF_{10}$ = 1.744).

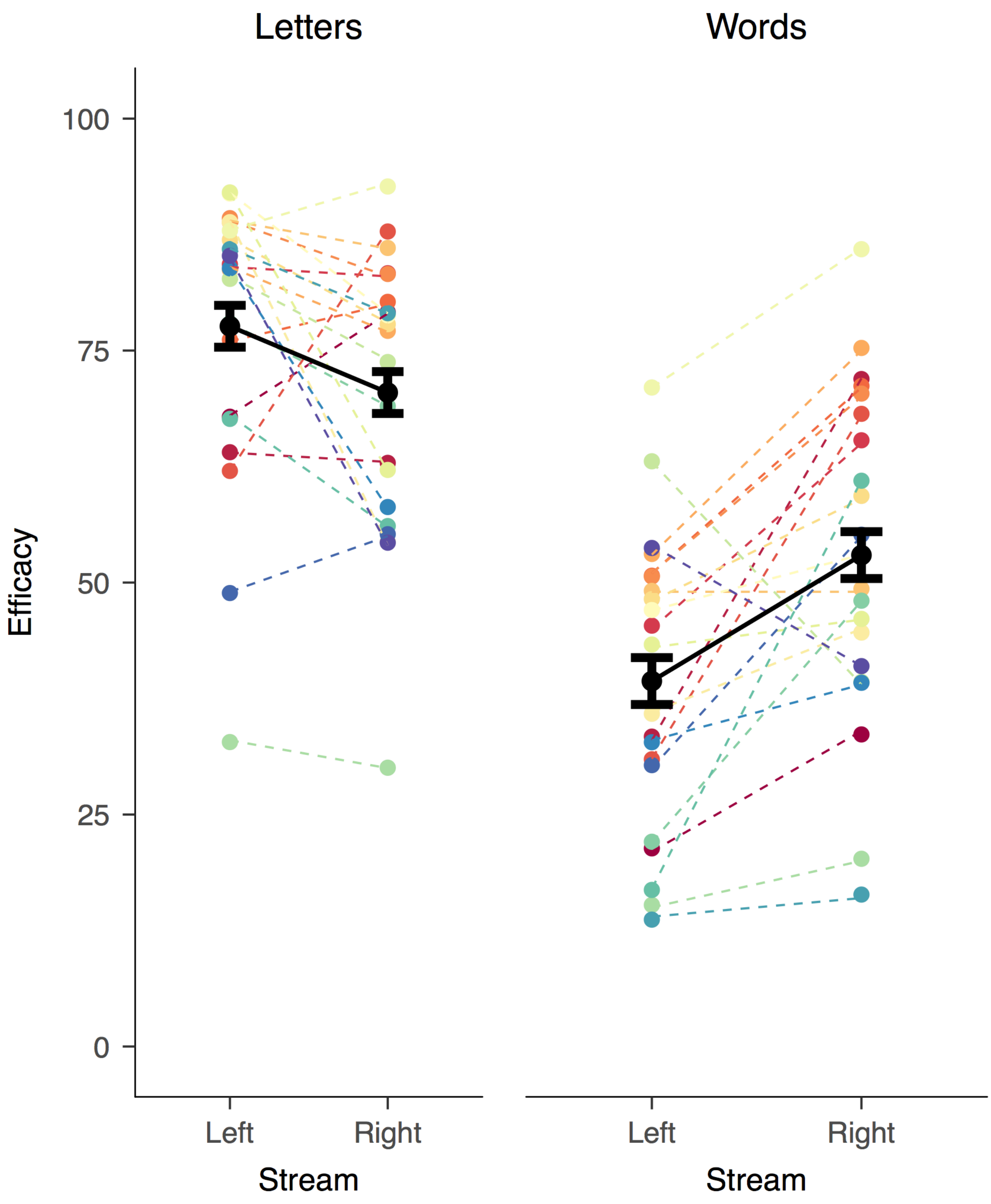

*Figure 22:* Efficacy by participant for letters and words conditions when orthographically similar responses are counted as correct. Coloured dots are results for individual participants. Black dots (with error bars) are results averaged over participants.

#### *5.3.3.3 Letter position of errors*

There was no evidence for a difference in the spatial position of errors within the words reported for the left and the right stream. A Bayesian t-test indicated that the small difference (left: M=2.50; right: M= 2.51, indicating slightly more errors towards the end of the word in the right stream) was almost twice as likely to be generated by chance than if there were an effect of the stream location ($BF_{01} = 1.84$).

### 5.3.4 Discussion

Previous experiments have documented a severe capacity limit that is exceeded when participants must report two letters at the same time. When these experiments used letters from a script that is typically read from left to right, participants tended to prioritise the left letter, leading to a deficit in reporting the letter on the right side. The present results showed an opposite deficit when the streams contained words rather than letters – participants were much better at reporting the words on the right than the words on the left. This is consistent with the right advantage for words that was found in the previous Chapter when two words were simultaneously presented, but not embedded in dual RSVP streams.

The letters condition showed a numerical right-side deficit, but analysis of this condition in isolation revealed that the Bayes factors were very close to one, indicating only very weak evidence of a right target deficit for letters. This contrasts with previous experiments using dual RSVP of letters, in which right target deficits have been consistently large (Goodbourn & Holcombe, 2015; Holcombe et al., 2017 and Chapter 3 of this thesis). It is possible that the experience of completing the words task, which elicits a strong left deficit, affected participants' biases in the letters condition block. However, if this were the case there should have been a difference between participants who did the words condition first and participants who did the letters condition first, which was not observed. One difference between the letters condition of this experiment and previous dual RSVP experiments with letters is that responses in this experiment were spoken, rather than selected from an array of possible options. It is possible that generating a spoken response increased activation of lateralised language processing areas in the brain, which may have provided an advantage for processing right visual field items that partly offset the effect of prioritisation in the direction of reading.

Successful reporting of words was 19 per cent higher for the right stream than for the left. The words on the right had their first letter closest to fixation, which makes it easier for participants to correctly guess these words, potentially contributing to the left deficit. However, additional analysis of the data suggests this had at most a small effect. The orthographic similarity measure that we used for the secondary analysis accepted most responses where participants misreported up to two of the four letters in the target word. Any effect due to differential guessing rates ought to have been smaller when this measure was the dependent variable. However, while this metric yielded a higher overall rate of correct responses for increased for both streams, it made very little difference to the magnitude of the deficit. Furthermore, analysis of the letter position of errors indicates that average position was nearly identical in the left and right streams. If participants were using the letters closest to fixation to inform guesses, we would have expected errors that relate to early letter positions to be relatively more likely for the stream on the left, which did not occur.

As discussed in Chapter 3, previous literature using dual RSVP stimuli consistently documented a right deficit for letters, and reported a variety of sources of evidence that the left prioritisation is a result of implied reading direction (Holcombe et al., 2017). But clearly another factor is involved, given the present evidence that words produce a large left deficit in the same dual RSVP paradigm. As discussed in the previous Chapter, it is fairly well documented that the left hemisphere is superior for word recognition (Cohen et al., 2000).

The pattern of results, then, may reflect a small reading-direction-related left bias that is counteracted by a large right-hemisphere advantage. Alternatively, the reading-direction bias may simply not be elicited by the words. Presenting the two stimuli in a vertical configuration should provide some insight into this possibility, as there should no longer be hemispheric influences, yet there may still be an effect of implied reading direction (with the top position favoured – see Goodbourn & Holcombe, 2015; Holcombe et al., 2017).

## 5.4 Experiment 2

### 5.4.1 Method

Only differences from Experiment 1 will be described.

#### *5.4.1.1 Participants*

35 participants (9 male, 26 female) completed Experiment 2. Data from one participant was omitted from the analysis because he indicated that he had misunderstood the instruction regarding report order.

#### *5.4.1.2 Stimuli and procedure*

On each trial, both streams were presented either 5.0° to the left of fixation, or 5.0° to the right of fixation. Which side was used on each trial was chosen randomly. One of the streams was always centred 5.0° above fixation and the other was centred 5.0° below fixation (see Figure 23).

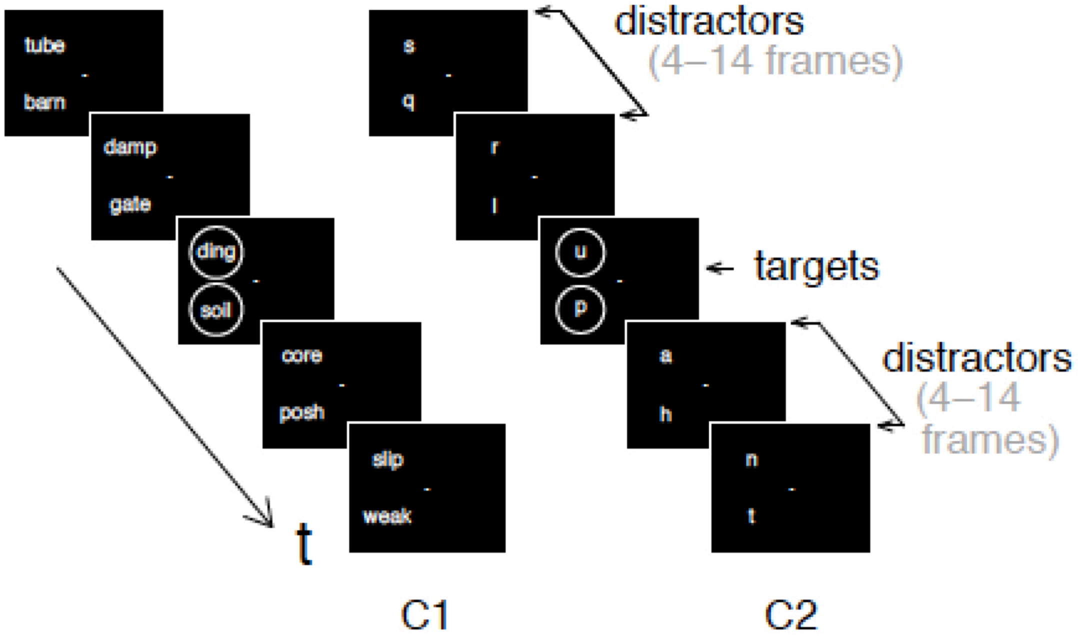

*Figure 23:* Stimulus used in Experiment 2. C1: words condition. C2: letters condition. The schematic shows streams presented to the left visual field. This occurred for half of the trials. For the other half, both streams were presented to the right visual field.

### 5.4.2 Analysis

Our primary (and preregistered) hypothesis was that the deficit (upper-stream minus lower-stream) in accuracy would be the same for the letters and the words condition. Support for this hypothesis would indicate that the differences observed in Experiment 1 were likely due to processing differences between the cerebral hemispheres.

We performed the same analyses as we did for Experiment 1, with the exception that a hemifield factor was introduced to test whether the effects were different when both streams were presented in the left visual field compared with when they were presented in the right visual field.

In addition to the primary analysis, which uses spatial bias as the dependent variable, we ran an additional analysis to investigate whether there was a general right side advantage for either words or letters. To do this, we used a Bayesian ANOVA to investigate whether the proportion correct was greater in the right hemifield than the left hemifield for both words and letters. Given the computational constraints on the number of factors in the model, we could not control for the order of conditions, or whether the top or bottom stream was reported first in this analysis. However, since these factors had only very small effects on the results of the previous experiment, it is unlikely that they would have a large effect on the current analysis.

### 5.4.3 Results

#### *5.4.3.1 Target accuracy*

Accuracy in the upper and lower streams for the words and letters condition is shown in Figures 24 and 25, which separately show trials in the left and right hemifields. In contrast to the findings from Experiment 1 (where the streams were concurrently presented to the left and right of fixation), the results support the hypothesis that the deficit (upper stream minus the lower stream) does not differ between the words and letters conditions ($BF_{01} = 5.15$).

The results were equivocal as to whether the deficit depended on whether the streams were presented in the left or right visual field. There was a small trend for the deficit to be larger in the left visual field when the stimuli were words (LVF: M = 25.92, SD = 18.32; RVF: M = 19.83, SD = 19.83), but not when the stimuli were letters (LVF: M = 31.93, SD = 15.04; RVF: M = 31.98, SD = 14.86). The Bayes factor only marginally favoured the null hypothesis that the deficit did not differ between hemifields ($BF_{01} = 1.41$), and was equivocal about whether there was an interaction between the hemifield and whether the stimuli were words or letters ($BF_{01} = 1.12$). While more evidence would be needed to completely rule out a difference, the posterior probability distributions on the effect sizes suggest that any difference between the hemifields is likely to be small.

When the words and letters conditions were analysed separately, we found strong evidence for a lower-stream deficit for both the letters condition ($BF_{10}$ > 1 trillion) and the words condition ($BF_{10}$ > 1 trillion).

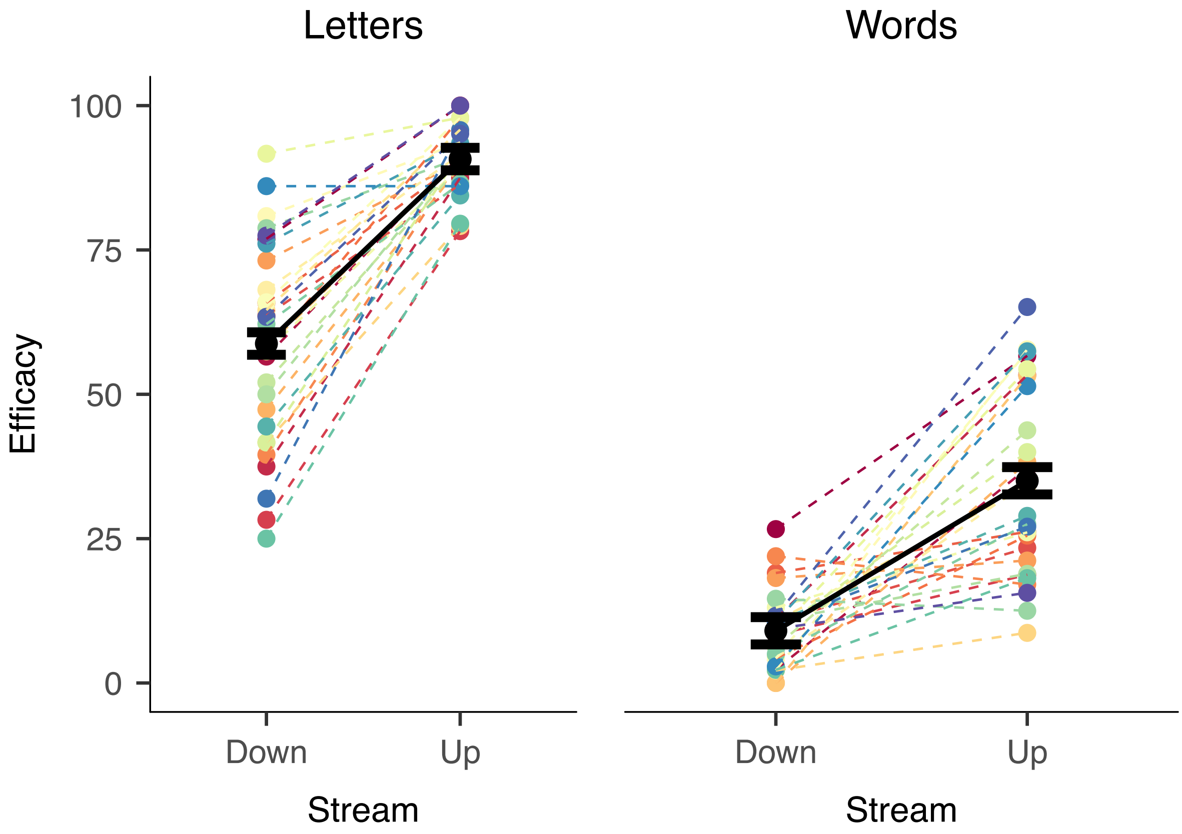

*Figure 24:* Efficacy for upper and lower streams when streams are presented to the left hemifield. Coloured dots are results for individual participants. Black dots (with error bars) are results averaged over participants.

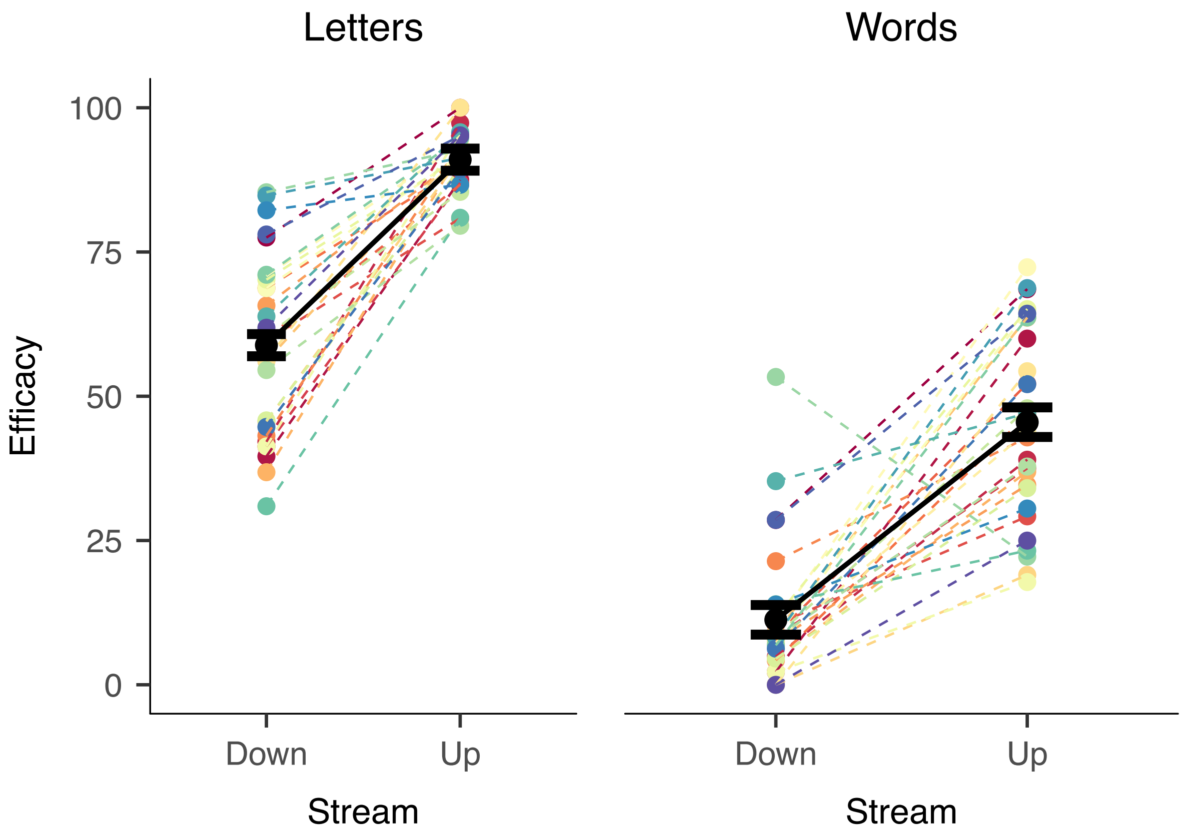

*Figure 25:* Efficacy for upper and lower streams when streams are presented to the right hemifield. Coloured dots are results for individual participants. Black dots (with error bars) are results averaged over participants.

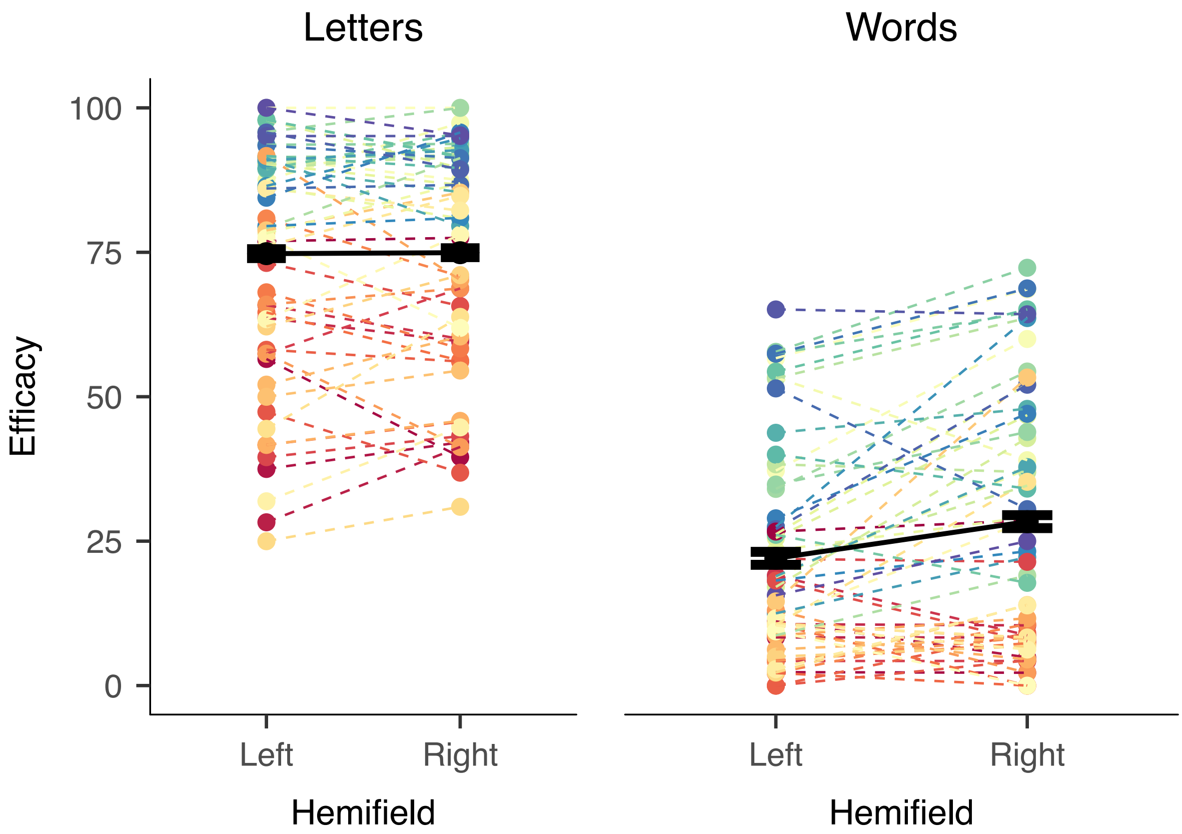

*Figure 26:* Efficacy for left and right hemifields when results for upper and lower streams are combined. Coloured dots are results for individual participants. Black dots (with error bars) are results averaged over participants.

#### 5.4.3.2 *Orthographically similar responses*

As in Experiment 1, we also analysed the data using a looser criterion for correctness, counting as correct all responses that were orthographically similar to a target (figures 26 and 27). As with the previous analysis, the obtained results favoured an interpretation that there is no difference between the deficit for letters and the deficit for words ($BF_{01} = 7.09$), and that the results do not differ depending on whether words are presented in the left visual field or the right visual field ($BF_{01} = 4.54$).

When the words and letters conditions were analysed separately, we again found strong evidence for a deficit in the lower stream in both the letters condition ($BF_{10} > 1$ trillion), and the words condition ($BF_{01} > 1$ trillion).

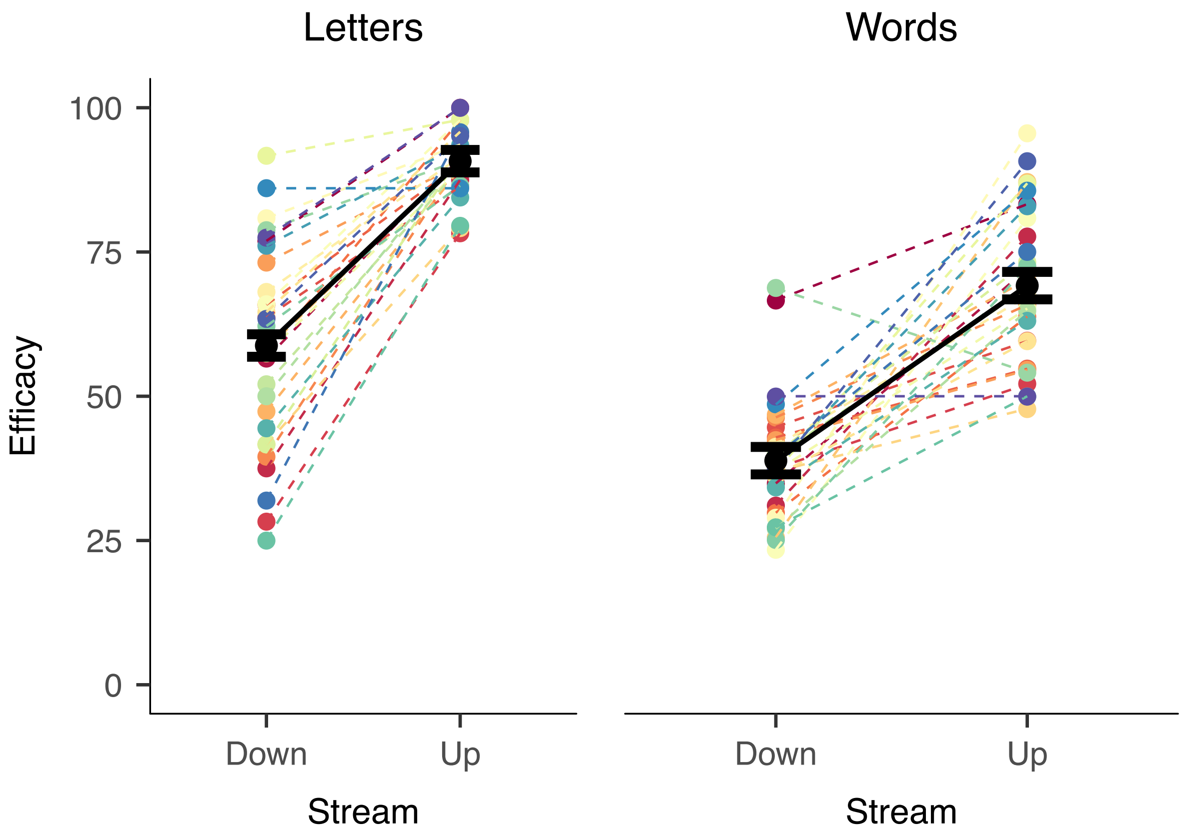

*Figure 27:* Efficacy by participant for letters and words conditions when orthographically similar responses are counted as correct and streams are presented in the left hemifield. Coloured dots are results for individual participants. Black dots (with error bars) are results averaged over participants.

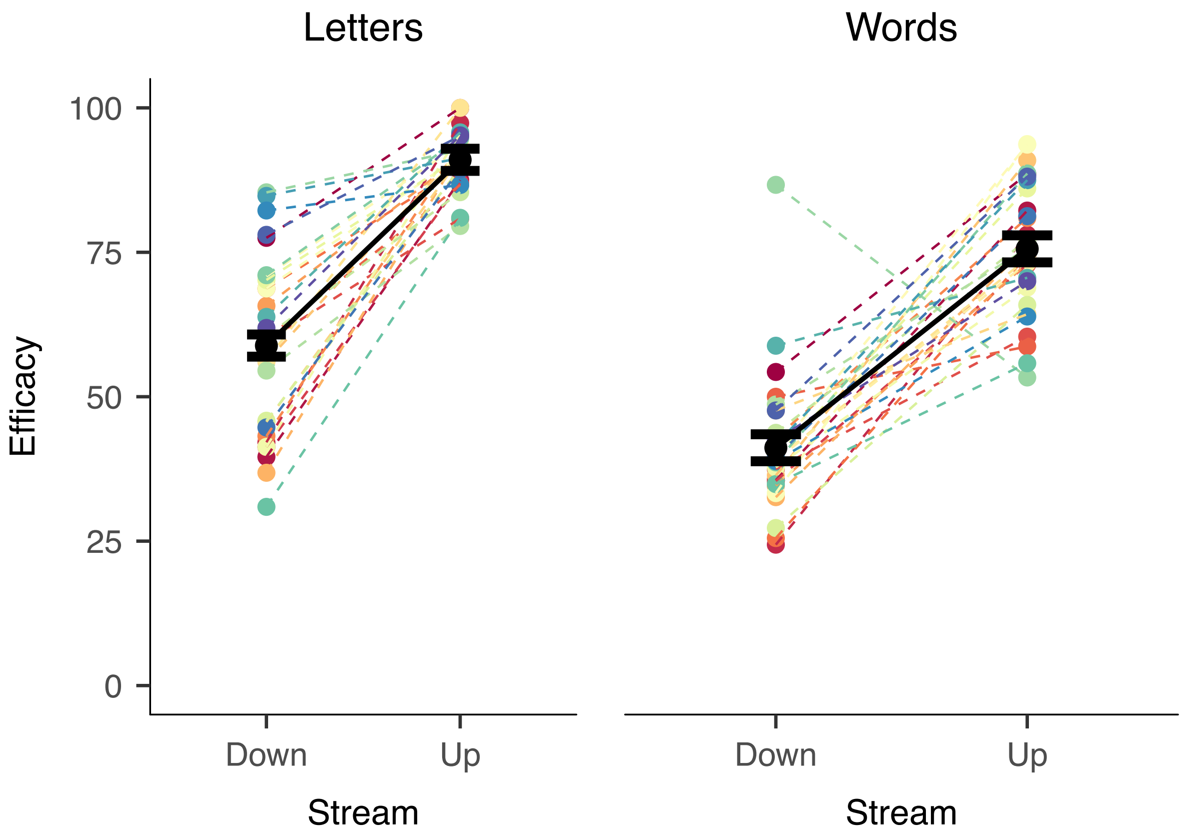

*Figure 28:* Efficacy by participant for letters and words conditions when orthographically similar responses are counted as correct and streams are presented in the right hemifield. Coloured dots are results for individual participants. Black dots (with error bars) are results averaged over participants.

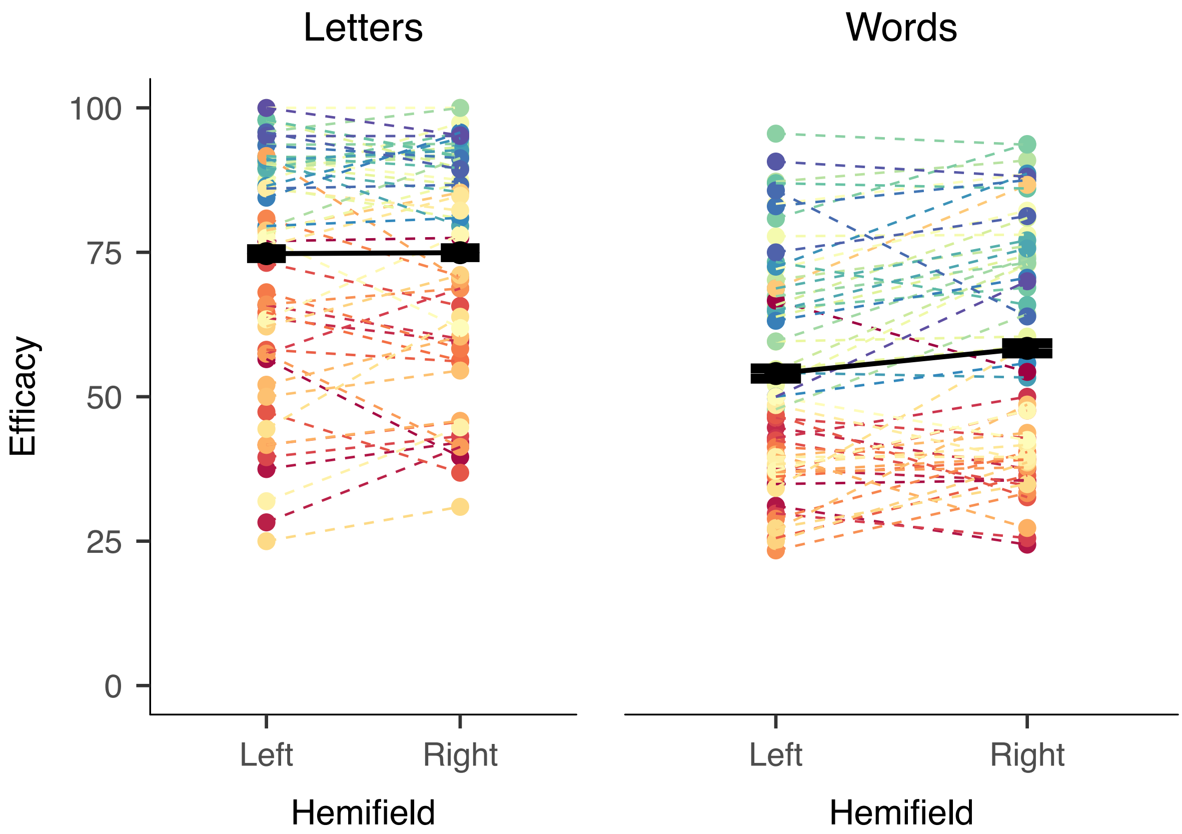

*Figure 29:* Efficacy for left and right hemifields when results for upper and lower streams are combined. Coloured dots are results for individual participants. Black dots (with error bars) are results averaged over participants.

#### 5.4.3.3 *Right visual field advantage for identifying words*

When correct responses (rather than bias) was the dependent variable, the Bayesian ANOVA revealed a likely interaction between condition and hemifield ($BF_{10} = 3.52$), reflecting a greater right side advantage for words (LVF: M = 21.59, SD = 8.42; RVF: M = 27.79, SD = 10.21) than for letters, where the numerical advantage was very small (LVF: M = 72.70, SD = 10.58; RVF: M = 74.67, SD = 10.22).

### 5.4.4 Discussion

Experiment 2 found a lower-field deficit that is similar for words and letters. The upper visual field advantage is consistent with that previously found in dual RSVP experiments using letters as stimuli (Goodbourn & Holcombe, 2015). The similarity of the bias in the letters and words conditions is in stark contrast to the results of Experiment 1, which elicited a deficit for words in the opposite direction to that found for letters. Using a more lenient criterion for correct responses (that treated responses as correct when they were orthographically similar to the target) had very little effect on the pattern of responses.

The results were equivocal regarding whether the deficit depends on whether the two streams were presented in the left or right visual field. A difference between the hemifields might have been expected if language processing was weighted towards serial mechanisms in the right hemisphere, and parallel mechanisms in the left hemisphere, as has been previously suggested (Ellis et al., 1988; Lindell & Nicholls, 2003; Whitney & Lavidor, 2004). While there was thus not strong evidence for a difference in the deficit between the two hemifields, a left-hemisphere advantage for linguistic processing may explain the right hemifield advantage for words, although the Bayes factor for that advantage was not large.

## 5.5 General Discussion

The second-target deficit found in dual RSVP experiments for a target letter in the right (for horizontal presentations) or lower (for vertical presentations) streams is thought to reflect a limitation at a late processing stage. This limitation may also be a factor in natural reading. If the capacity limit applies after letters have been combined to form representations of words, the deficit should be similar whether the stimulus is two widely-spaced letters or whether it is two widely-spaced words. The deficits for letters and words were, indeed, very similar when the two streams were vertically arrayed (Experiment 2), suggesting that the capacity limit likely occurs after representations of words have been established. When the streams were horizontally arrayed, however, words and letters yielded different patterns: words showed a left stream deficit while letters instead showed a trend for a right-side deficit. This is consistent with the right advantage found for words in experiments in the previous Chapter, where two words were presented simultaneously but not embedded in RSVP streams. It appears that something other than reading direction bias affects the pattern of performance when words are presented simultaneously in both the left and right hemifields.

The factor responsible for the left deficit for words in the horizontal condition is likely to be hemispheric specialisation. Neuroimaging studies have found that part of the left occipitotemporal cortex is selective for visually-presented words (Cohen et al., 2000; Vinckier et al., 2007) and is activated by words in both left and right visual fields (Jobard, Crivello, & Tzourio-Mazoyer, 2003). Even though this region has been shown to process items from both visual fields, it is known that stimuli in the right visual field are initially directed to the left hemisphere, and this has frequently been used to explain the right visual field superiority for a range of linguistic tasks (Davis & Bowers, 2004; Vaid, 1988; Willemin et al., 2016). Recent experiments have established that letter identification produces more even activation across the left and right hemispheres, leading to an account whereby letters identities can be processed in both hemispheres, but word identities require the left hemisphere (Vinckier et al., 2007). Thus, the left bias for letters occurs because identifying letters does not depend much on left hemisphere processing so prioritisation in the direction of reading prevails, yielding the left bias for the letters condition. In contrast, recognition of words depends critically on the left hemisphere, leading to the right bias observed in the words condition.

While the left hemisphere language advantage appears to dominate when the stimuli are words, and the left side reading-direction prioritisation appears to dominate when the stimuli are letters, it may be that both effects contribute to performance in all conditions. That is, like letters, words may be prioritised in the order of reading (from left to right in the present experiment), but this prioritisation is more than offset by a hemispheric advantage at a different processing stage. This could explain why the experiment in the previous Chapter found a slightly bigger right side advantage when only a single word was presented (and therefore there was not an effect of prioritisation), compared with when two words were presented — a finding that contrasts with previous studies comparing bilateral and unilateral displays which have found that spatial biases are generally larger and more likely to be significant in bilateral displays (Boles, 1990). Moreover, the situation where letters are formed into words and are horizontally arranged is likely to account for most of the experience that readers have with English text. As such, two horizontally presented words are more likely than other stimuli to incorporate reading direction effects.

Further insight into the role of prioritisation may be gleaned by its interplay with the hemispheric advantage. Neural models of the reading network suggest that the items in the left visual field (originally directed to the right hemisphere) are transferred to the left hemisphere for processing after units representing individual letters are activated, but well before an orthographic representation of the word is formed (Vinckier et al., 2007). Notwithstanding this early transfer, it appears that prioritisation in the direction of reading does not negate the hemispheric advantage of the word on the right — apparently the benefits of prioritisation do not include privileged access to left hemisphere lexical processing resources. This suggests that, at least in the context of the current task where participants must say the target letters and words, the left-side prioritisation occurs after lexical processing rather than before. It may be that prioritisation plays a role in ensuring that words are transferred to working memory in the correct order because of the importance of word order in constructing meaning, even if some earlier processing may be conducted for the words simultaneously. Further research investigating how lexical factors affect the reading direction bias would be useful in verifying this.

The process described above shares some features with the prominent E-Z Reader theory of reading, which also incorporates a left-to-right process that is thought to be important in achieving the correct word order ( Pollatsek et al., 2006; Reichle et al., 1998; Reichle et al., 2003). In particular, E-Z reader posits that lexical processing occurs for only one word at a time. First, the multiple words in a line of text are processed in parallel to extract low-level features and low spatial frequency information that are used to infer word length and determine the boundaries between words. On the basis of this preprocessing, one word is then attentionally selected for lexical processing. This attentional selection may be akin to the prioritisation we have observed here. However, the results of the present paradigm suggest a different processing sequence to that assumed by E-Z Reader. In particular, the prioritisation studied here does not seem to occur before lexical processing, for if it did, one would not expect the sizeable right visual field advantage that we observed; prior to lexical processing, some form of attentional selection of the two targets apparently occurs simultaneously. This is demonstrated by the fact that the stimulus most frequently reported from both streams are the target items designated by the cues, which are presented at the same time. In the present experiments using a 170 ms SOA, it was very rare for participants to mistakenly report an item just before or just after the ring, suggesting that selection occurred simultaneously in the two streams. In principle, selection might have occurred quickly, with a very rapid shift of attention between the two streams, but this possibility was largely excluded by Goodbourn and Holcombe’s (2015) earlier experiments using this paradigm. In their previous work, the streams were presented at faster rates, eliciting more frequent “temporal” errors in which participants frequently reported items that appeared before or after the cue. If selection occurred earlier for one of the items, this should be reflected in the relative timing of the temporal errors for the left and right streams. In fact, temporal errors were not significantly different in the two streams, suggesting that sampling occurred for the two streams in parallel.

The proposal that left to right prioritisation occurs at a relatively late stage of processing could contribute to our understanding of preview effects typically observed in eye-movement studies. Several studies using gaze contingent displays (see Schotter et al., 2012 for a full description) have shown that that having access to either the target word, or a related stimulus, in the parafovea prior to fixating the word reduces fixation duration when the eyes eventually land on that word. These 'preview' effects challenge the notion of strict, word-by-word, seriality in reading, though serial models such as E-Z-reader (Reichle et al., 2003) argue that these effects can be explained by the fact that serial attention sometimes moves to the next word in the sequence before an eye-movement is eventually made to that word. The finding that prioritisation in the direction of reading is likely to occur after lexical processing can alternatively explain preview effects by assuming that while consolidation into visual working memory may prioritise the left item, lexical processing itself favours items on the right. This means that, even though words on the right are consolidated later than words on the left, the privileges associated with left hemisphere processing at earlier processing stages facilitate this consolidation when it eventually happens. This account is consistent with evidence from Hohenstein, Laubrock & Kleigl (2010), who found that parafoveal preview benefits from semantic associates occur very early in processing of the fixated word.

The present experiment applied a paradigm that isolates a cognitive process that has been found to be sensitive to aspects of reading. This technique presents opportunities to enhance our understanding of the reading process by focussing on its component processes. The manipulation in the present experiment suggests that there may be a capacity limit that occurs as words are consolidated into short term memory, and elucidates the influence of hemispheric factors on spatial biases. Future experiments using manipulations of non-words, or different word lengths may be useful in further specifying the nature of the capacity limit.

# Chapter 6: Does the second-target deficit occur for successive targets

## 6.1 Chapter Synopsis

When a target appears in each of two streams of distractors, subjects display performance deficits for identifying one of the targets. This effect, termed the second-target deficit, occurs both when the targets are presented at the same time (simultaneous targets), and when the targets are separated by a short lag (successive targets). However, the deficits in these two variations of the task are typically explained by different processing limitations. This chapter investigates whether a single mechanism could explain the deficit in both simultaneous and successive target forms of the dual RSVP paradigm by comparing the deficits in two conditions — one with simultaneous targets and one with successive targets. The observed biases favour an interpretation of no difference between the simultaneous and successive target conditions, suggesting that these may indeed reflect the same neural mechanism. However, the deficits in both cases were different to those found in previous experiments, suggesting the mechanism responsible for the deficit may be sensitive to task demands. A theoretical framework that can accommodate these results is discussed, with reference to the recent RAGNAROC model of attention.

## 6.2 Introduction

This thesis has investigated a deficit in reporting the right-most of two targets that are presented at the same time. A right-side deficit has also been documented in a series of studies where targets are distributed over two streams but are always presented at different times (Asanowicz, Kruse, et al., 2017; Śmigasiewicz et al., 2010; Śmigasiewicz, Westphal, & Verleger, 2017; Verleger & Śmigasiewicz, 2015; Verleger, Śmigasiewicz, & Möller, 2011). In these studies, letter or digit items are presented in a dual RSVP paradigm similar to that used by Goodbourn and Holcombe (2015), except that the targets appear at different times in the streams. The two targets (T1 and T2) each appear on the left or right side with equal probability, meaning that on some trials the targets are presented in the same stream, and on other trials the targets appear in different streams. While T1 is reported equally well on the left and right sides, T2 is much better reported on the left side, regardless of whether T1 was presented in the same stream, or in a different stream. This Chapter describes the stimuli used and spatial deficits reported in simultaneous and successive forms of the dual RSVP paradigm. It then investigates whether the right stream deficits in the two different forms of the dual RSVP paradigm are likely to reflect the same neural mechanism, or alternatively, stem from different processing limitations.

### 6.2.1 The right-target deficit in successive and simultaneous target experiments

While experiments using both simultaneous and successive forms of the dual RSVP paradigm have often included manipulations of the stimulus to test relevant hypotheses, it is usual for these experiments to present a standard version of the task as a control condition.

Many aspects of these standard tasks are common to the simultaneous and successive dual RSVP paradigms. For example, both paradigms involve presentation of two targets embedded in dynamic streams of letters that are located to the left and right of a central fixation points. Participants are asked to report both targets, though these may be reported by either saying the response, typing it on a keyboard, or selecting the item from an array of letters depending on the experiment. The main difference between the two experiments relates to the composition of the targets. In particular, successive target experiments tend to follow the practice established in attentional blink experiments of separating targets by variable lags between T1 and T2 (typically with three different lag conditions ranging from lag 1 to lag 5), and measuring the spatial bias at each lag. These studies typically define T1 by colour (it is typically red) and T2 by category (it is typically a digit amongst letters). In contrast, simultaneous target experiments always present both targets at the same time, and typically define targets by presenting circles around them (as is done in Chapters 3 and 5 of this thesis). Given there is no temporal separation between the targets, simultaneous targets can be thought of as lag 0. Figure 28 provides an indication of the size and direction of the spatial bias in both simultaneous and successive versions of the dual RSVP paradigm. The data have been extracted from 12 studies that have reported results for a ‘standard’ condition in which targets are presented in different streams, that are horizontally arranged and contain English letters. As is apparent from figure 28, the right target deficit for lag 0 trials reported in simultaneous target experiments is remarkably similar to lag 1 trials reported in successive target experiments. While it is possible that the apparent association between these right target deficits is spurious, the similarity in the biases may alternatively indicate that the same mechanism is responsible for the biases in both cases.

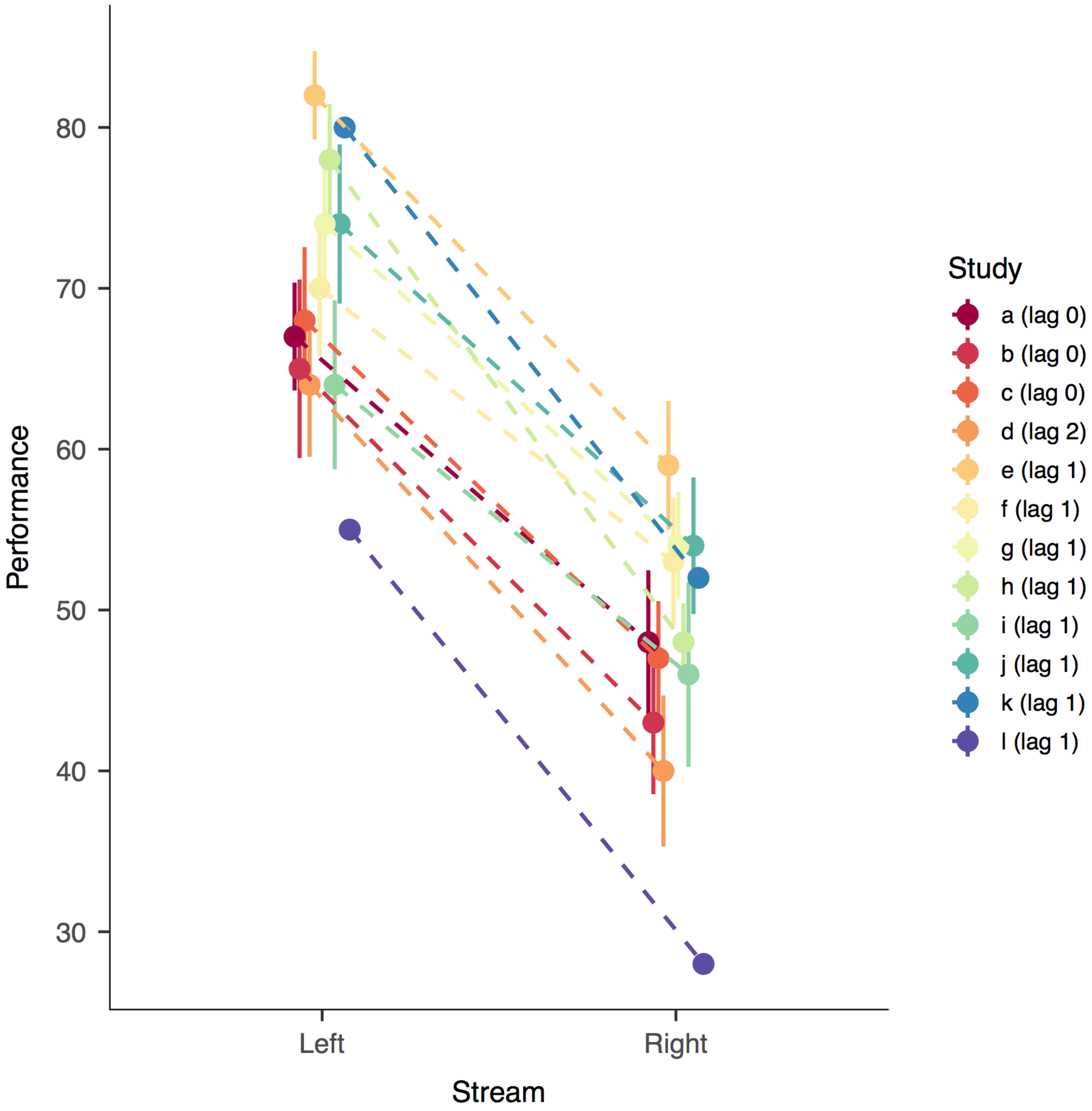

*Figure 30.* Success in reporting left and right stream targets from bilateral presentation conditions in previous studies. The studies are: a. Goodbourn and Holcombe (2015), Experiment 1 - dual target condition; b. Chapter 3 of the present thesis - English condition, c. Holcombe and colleagues (2017), Experiment 1, Canonical condition; d. Asanovics and colleagues (2017), Experiment 1 - bilateral task. e. Verleger, Smigasiewicz and Moller (2011), Different target condition; f. Asanowicz, Smigasiewicz and Verleger (2013), Experiment 1 - standard task, dual target condition; g. Smigasiewicz and colleagues (2010), Experiment 1 - different target side condition; h. Verleger and colleagues ( 2008), Experiment 1 - different target side; i. Verleger and colleagues ( 2008), Experiment 3 -

different target side condition; j. Asanovics and colleagues (2017), Experiment 1 - latin letters condition - different targets side; k. Hollander, Corballis and Hamm (2005), control condition; l. Scalf and colleagues ( 2007), different target sides condition. Circles indicate mean performance across participants. Error bars reflect standard errors (error bars are not included for studies k and l, which did not provide a measure of variance that would allow standard error to be calculated). Performance refers to efficacy in studies a, b and c, and T2 given T1 for the remainder of studies.

### 6.2.2 Accounts of the right target deficit

Despite the empirical similarity in spatial biases produced by dual RSVP experiments with simultaneous and successive targets, the right target deficits observed across the two paradigms have been attributed to different causes. Specifically, experiments with simultaneous targets have argued that the bias occurs as a result of prioritisation at serial bottleneck, and experiments with successive targets have argued that the bias occurs as a result of a right hemisphere advantage in spatial orienting. These accounts are described below, along with a recent model that provides an account of reflexive orienting and also incorporate parallel processing of simultaneous targets.

### 6.2.3 Prioritisation of the left item at a post-sampling bottleneck

As discussed extensively in previous Chapters of this thesis, Goodbourn and Holcombe suggested that the second-target deficit in their dual RSVP experiments with simultaneous targets was likely to be the result of a serial bottleneck at post sampling stage of processing. The experiment in Chapter 3 corroborated the claim that the deficit occurs at a post-sampling stage of processing, with evidence that the temporal errors that participants made (that is, instances where participants report an incorrect item that was within a few serial positions of the target) were not not significantly different between the left and right streams, which would have been likely if participants were sampling from the left stream first and then the right stream. However, the partial-report experiment in Chapter 4 did not corroborate the claim that the deficit reflected a serial bottleneck, leaving open the possibility that the right deficit observed in experiments with simultaneous targets reflects a different (possibly parallel) mechanism. A serial bottleneck account also cannot explain biases in experiments with successive targets. This is because serial bottleneck theories attribute the spatial bias to the fact that the prioritised target (for stimuli in English, the left target) is the first to be processed and so representation of the non-prioritised target has more chance of decaying before it can be converted to a more stable memory form. When targets are successive, T1 appears before T2 and so it is likely to be processed first, regardless of its spatial position. While it is conceivable that reading direction prioritisation (or some other spatially relevant factor) may cause T2 to be prioritised ahead of T1 when the lag is small (say, lag 1), it is unlikely that this would extend to later lags (say, lag 5) where there would be several hundred milliseconds between T1 and T2.

### 6.2.4 Right hemisphere advantage in spatial orienting

Dual RSVP experiment with successive targets have predominantly attributed spatial biases to a right hemisphere advantage in orienting attention to the location of the target (Śmigasiewicz et al., 2010; Śmigasiewicz et al., 2017). Orienting to a target requires participants to shift attention from its present location to another location in the visual field in order to attend to new information (Posner, 1980). The key difference between orienting and prioritisation relates to the stage of processing at which it occurs. Theories of orienting often don't specify, but typically seem to assume that, a location is selected for the deployment of attention before basic type information about the target is extracted. In contrast, theories of prioritisation discussed previously in this thesis (such as serial bottleneck theories), that assume that prioritisation occurs after the intitial extraction of type information but before later processing stages such as tokenisation or consolidation into working memory. Evidence for a role of orienting in the right deficit comes from a recent study that has found that the usual right deficit in reporting the second of two targets presented in the same stream is eliminated when left stream and right stream trials are presented in separate blocks such that participants can predict the location of the targets (Asanowicz, Kruse, et al., 2017). Being able to predict the location of the target means that participants can fix their attention on this location for the entirety of the trial, and thus avoid the need reorient attention when the target is presented. Further evidence linking the bias to spatial orienting comes from experiments in which valid, invalid and neutral cues precede the target by 50 ms (Śmigasiewicz et al., 2017). An invalid cue in the left visual field had a more detrimental effect on the ability to report a T2 presented at the midline than an invalid cue in the right visual field suggesting that participants may have had trouble disengaging from the left target. In addition, an invalid cue at midline had a more detrimental effect on the ability to report T2 in the right visual field than in the left, suggesting an advantage for orienting to the left. When the cue was valid, participants performed equally well on the left and right sides, suggesting that the bias is not explained by a general advantage in attending to the left cue. While the spatial orienting account is consistent with the spatial biases reported in experiments with successive targets, it cannot account for spatial biases in experiments with simultaneous targets, which are likely to be sampled at the same time.

### 6.2.5 The RAGNAROC model

While not focussed on spatial biases, the recent RAGNAROC model (Wyble et al., 2018) provides a single framework that can explain why attention appears to shift between targets when they are successive, yet appears to be deployed in parallel when targets are simultaneous. RAGNAROC builds on the episodic account of attention provided in previous literature (Swan & Wyble, 2014; Tan & Wyble, 2015), which considers that the role of attention is to primarily to divide visual information into chunks of temporally similar items that are suitable for later stage processing. According to the model (which is described in figure 29), presentation of a stimulus at a particular location (for example, T1 in a dual RSVP experiment) activates topographically organised representations in early visual processing stages. These representations project to later visual processing areas, at which stage activity is weighted according to both the salience and task relevance of the items. The weighted representations (which still reflect topography, though with less precision due to the larger receptive fields in later processing regions) then project to corresponding locations of an attention map, which incorporates a series of inhibitory connections to neighbouring nodes on the attention map that cause activity to convergence on the location of the target. When the neural activity in the attention map reaches a critical threshold, this triggers a deployment of attention that enhances early visual processing in corresponding locations, that feeds-forward through the stages again, eventually creating a 'lock-on' state that triggers encoding of items to visual short term memory. If a second item (for example, T2 in a dual RSVP experiment) is presented at a different time than the first and while a lock-on state is occurring for the first item, early and late stage representations for this item will project to an area of the attention map which has been inhibited, and so will be unlikely to reach the critical threshold necessary to generate its own lock-on state. As such, this second item may not generate the activation necessary to trigger encoding into working memory. The exception to this is when two items are presented at the same time (and are of equal salience and goal relevance), which would cause activity to converge at two different locations in the attention map, which each trigger the deployment of attention, thus allowing two targets to be reported as long as they are similar in timing, salience and goal relevance.

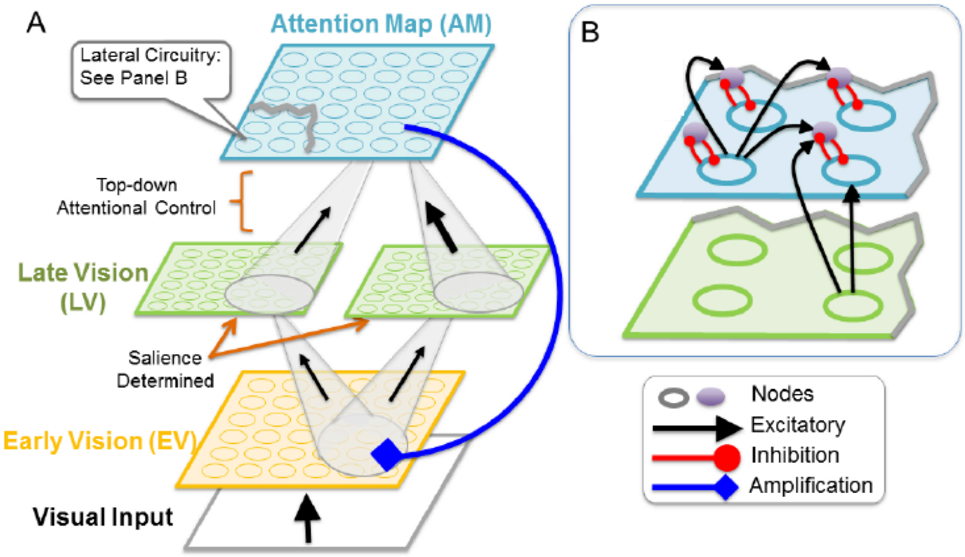

*Figure 31:* Schematic of the RAGNAROC model (Wyble et al., 2018). Visual input is extracted at early visual stages and projects through late visual stages to an attention map. The attention map contains inhibitory links that cause attention to converge on the location of the target. When a region of the attention map reaches a critical threshold, this triggers a deployment of attention to the corresponding area of early visual processing, which feeds through early and late visual stages again, thus further enhancing processing at that location. Adapted from “Understanding visual attention with RAGNAROC: A Reflexive Attention Gradient through Neural AttRactOr Competition” by Wyble, B., Callahan-Flintoft, C., Chen, H., Marinov, T., Sarkar, A., Bowman, H. (2018), bioRxiv doi: 10.1101/123456.

Spatial biases could be incorporated into the RAGNAROC model by adjusting the inhibitory connections that suppress activity at non-target locations on the attention map to provide stronger inhibition in one direction than in another. (For example, connections to the right may cause stronger inhibition than connections to the left.) This would mean that targets in a prioritised location would be more likely to reach the levels of activation necessary to trigger a lock-on state (which facilitates encoding) than targets in the non-prioritised location. Note that, while such a weighting can explain the right deficits when targets are presented in different streams, this does not explain why several studies with targets at different times have also found right deficits for reporting T2 when targets are presented in the same stream. Other factors, such as hemispheric differences, would be required to explain this.

### 6.2.6 The present experiment

The present experiment investigates whether the deficits observed in previous studies with simultaneous and successive targets are likely to stem from a common mechanism. It does this by comparing spatial biases at four different lag points. Three of these (lags 1, 3 and 5) are typical of the lags used in successive target experiments, while one (lag 0) is equivalent to a simultaneous target condition. While previous experiments have compared simultaneous and successive target trials in the same experiment (Bay & Wyble, 2014), these have unfortunately not reported any spatial biases that might be present in the data. To provide a direct comparison across the different lags, spatial biases will be measured as the difference in T2|T1 (accuracy at reporting T2 given T1 was successfully reported — see introduction for a full description) when T2 is in the left stream and when T2 is in the right stream. When targets are simultaneous (lag 0), one of the streams will be randomly designated as T1 for data analysis purposes.

Two confirmatory hypotheses were preregistered (https://osf.io/wqmtv/). The first is that a right deficit will occur at all lag levels. Right deficits have been reported separately for both simultaneous and successive target experiments. Support for this hypothesis would confirm that this result also persists when simultaneous and successive target conditions are combined in the same experiment. The second hypothesis is that the spatial bias at lag 0 is similar to that at lag 1. Support for this hypothesis would indicate that the spatial bias in simultaneous and successive targets experiments are likely to derive from the same mechanism. If the spatial biases in simultaneous and successive experiments instead derived from different mechanisms, it is predicted that the spatial biases at lag 0 and lag 1 would still favour the left side, though there is no reason to predict that the effect size would be the same for both conditions.

The analysis will investigate one further hypothesis that was not preregistered. This is that the average T2|T1 over left and right streams (not converted to spatial bias) will be greater for lag 0 than lag 1. Such a result would be consistent with Bay and Wyble's (Bay & Wyble, 2014) account of lag zero sparing, which they claim reflects an ability to attend to two items in parallel when they are presented at the same time.

## 6.3 Method

### 6.3.1 Participants

Participants were recruited from the first-year subject pool at the University of Sydney and received course credit for participating. Thirty five participants (17 male, 18 female) completed the experiment.

According to the Revised Edinburgh Handedness Inventory (Williams, 2010), all participants were right-handed. Participants were required to be native readers of English. Several indicated that they also had experience reading other scripts, but none had experience reading languages that were read from right to left.

### 6.3.2 Apparatus

Stimuli were generated using Psychopy (Peirce et al., 2011; Peirce, 2009) on a MacBook Pro, and displayed on a Diamond Pro 2070 SB CRT monitor. The monitor had a resolution of 1600 × 900 pixels and a refresh rate of 85 Hz. Participants were seated in a dark room with their head supported on a chin-rest 57 cm from the monitor. Participants commenced each trial by pressing a key on a standard keyboard.

Eye movements were monitored using an Eyelink 1000 eyetracker.

### 6.3.3 Stimuli

The two RSVP streams presented on every trial consisted of lower-case letters. The letters or words were drawn with Arial font, in white against a black background. A white fixation circle of 0.25° diameter was located at the centre of the screen. One letter stream was positioned so that the centre of the word was 6.0° directly to the left of fixation, and the other was positioned so that the centre of the word was 6.0° directly to the right of fixation. The height of the tallest letter was 2.1° (measured using letter *j*) and the width of the widest was 1.6° (measured using letter *m*). On each trial, for each of the two streams, all letters of the alphabet were presented.

### 6.3.4 Procedure

Participants completed 192 trials in total (48 for each lag condition). Before beginning the procedure, participants were allowed to undertake practice trials until they were confident they understood the task. This usually took around eight trials. The whole procedure (including calibration of the eyetracker) took approximately two hours, and participants were required to take three breaks within this period.

Participants were instructed to fixate on the central white dot for the duration of each trial. An auditory tone and two white rings at the locations of the streams (both of 250 ms duration) indicated that a trial was about to commence. The first item appeared 1 s later. Each letter in a stream was presented for 80 ms followed by a 20 ms blank interval. The lag and T1 stream was randomly selected (without replacement) on each trial. The serial position of the first target item was between the 9th and 15th inclusive and was randomly chosen on each trial. Each target item was cued by a ring that enclosed it. The rings were white, of 0.1° thickness, subtended 5°, and were presented for the same duration as the letter (80 ms). Targets were separated by four different lags. These were 0, 1, 3, and 5 (Figure 30 shows lag 0 and lag 1 conditions). In each lag condition, T1 was on the left for half the trials and on the right for the other half of the trials.

A response screen appeared immediately after offset of the final items. This comprised 26-letter vertical arrays on the left and right side of the screen, presented in alphabetical order from top to bottom. One array was active at a time, with the inactive array rendered in grey. The array that was the first to become active was chosen randomly on each trial. Participants used the mouse to select the target letter from the active array, at which point the selected letter appeared at the corresponding stream location. Participants were free to reselect until they confirmed their answer (with an additional mouse click), after which the second array became active.

This experiment was approved by the University of Sydney Human Research Ethics Committee.

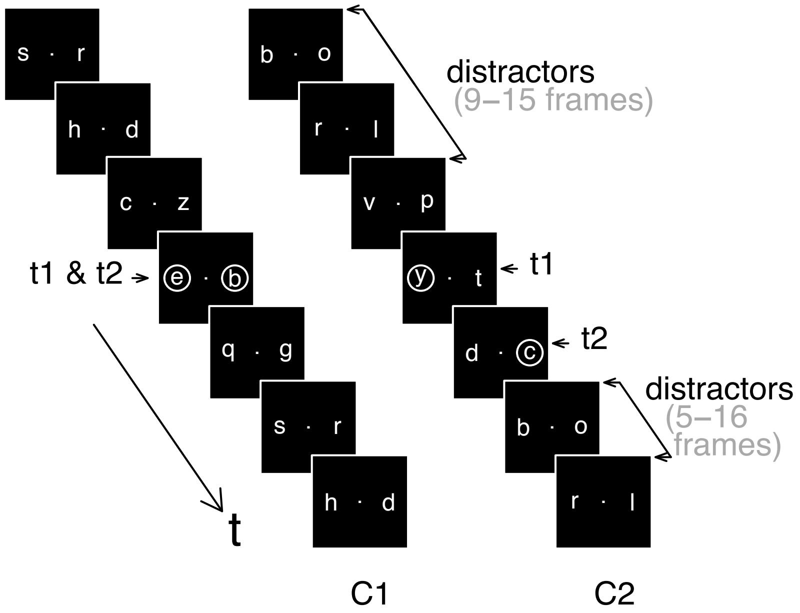

*Figure 32:* Stimulus used in experiment. C1: lag 0 (simultaneous targets) condition. C2: lag 1 (successive targets) condition. Targets could also be presented at lag 3 and lag 5 (not shown here.)

## 6.4 Analysis

As prescribed in our preregistered data analysis plan (https://osf.io/wqmtv/), participants were considered to have made an eye movement if their eyes moved more than one degree from the fixation point while the RSVP was in progress. A participant would be omitted if he/she made eye movements on more than 35 per cent of trials. 9 participants met this criterion. The remaining 26 participants made eye movements in an average of 8 per cent of total trials each. These trials removed from the analysis.

Consistent with the preregistration, this study applies the same rule of thumb as the dual RSVP experiment with letters and words presented in Chapter 5 to determine whether a target was correctly reported. This rule of thumb (discussed in more detail in Chapter 5) is that responses will be counted as correct if the serial position error (that is, the difference between the position in the stream of the target and the position in the stream of the participant’s response) is between +2 and -2 (inclusive).

The main analysis will compare the proportion of trials in which T2 was correctly reported given accurate report of T1 (T2|T1) for trials where T2 is on the left with that where T2 is on the right for each of the lag conditions. The left-advantage is calculated as T2|T1 on the left minus T2|T1 on the right.

The first hypothesis was that T2|T1 would be greatest when T2 is in the right stream for all lag conditions. The data were analysed using default one-tailed Bayesian one-sample t-tests described by Rouder and colleagues (2009) and implemented in JASP (JASP Team, 2017).

The second hypothesis was that the spatial bias in T2|T1 would be similar in magnitude for lag 0 trials and lag 1 trials. The Bayesian methods used throughout this these are well suited to testing hypotheses of equality. Two tailed Bayesian repeated measures t-tests were used to evaluate this hypothesis.

## 6.5 Results

### 6.5.1 Right target deficits for each lag

The first hypothesis was that there would be a right-target deficit in T2|T1 for each of the lag conditions. When results were averaged across participants, there was a very slight right bias at all lag levels (see figure 31). However, this was a much smaller effect than is typically observed in either the successive or simultaneous paradigms, where deficits of 20 percentage points are often observed. One-tailed Bayesian t-tests indicate that the data are slightly more plausible under the null hypothesis than under a hypothesis of a left advantage for lags 0 ($BF_{01}$ = 3.687), 1 ($BF_{01}$ = 1.022), and 5 ($BF_{01}$ =3.909), while the analysis at lag 3 slightly favours the alternative hypothesis that the left advantage is greater than zero ($BF_{01} = 0.449$). However, the Bayes Factors at all lags are less that the 5:1 threshold that we suggested was necessary to support one hypothesis over another.

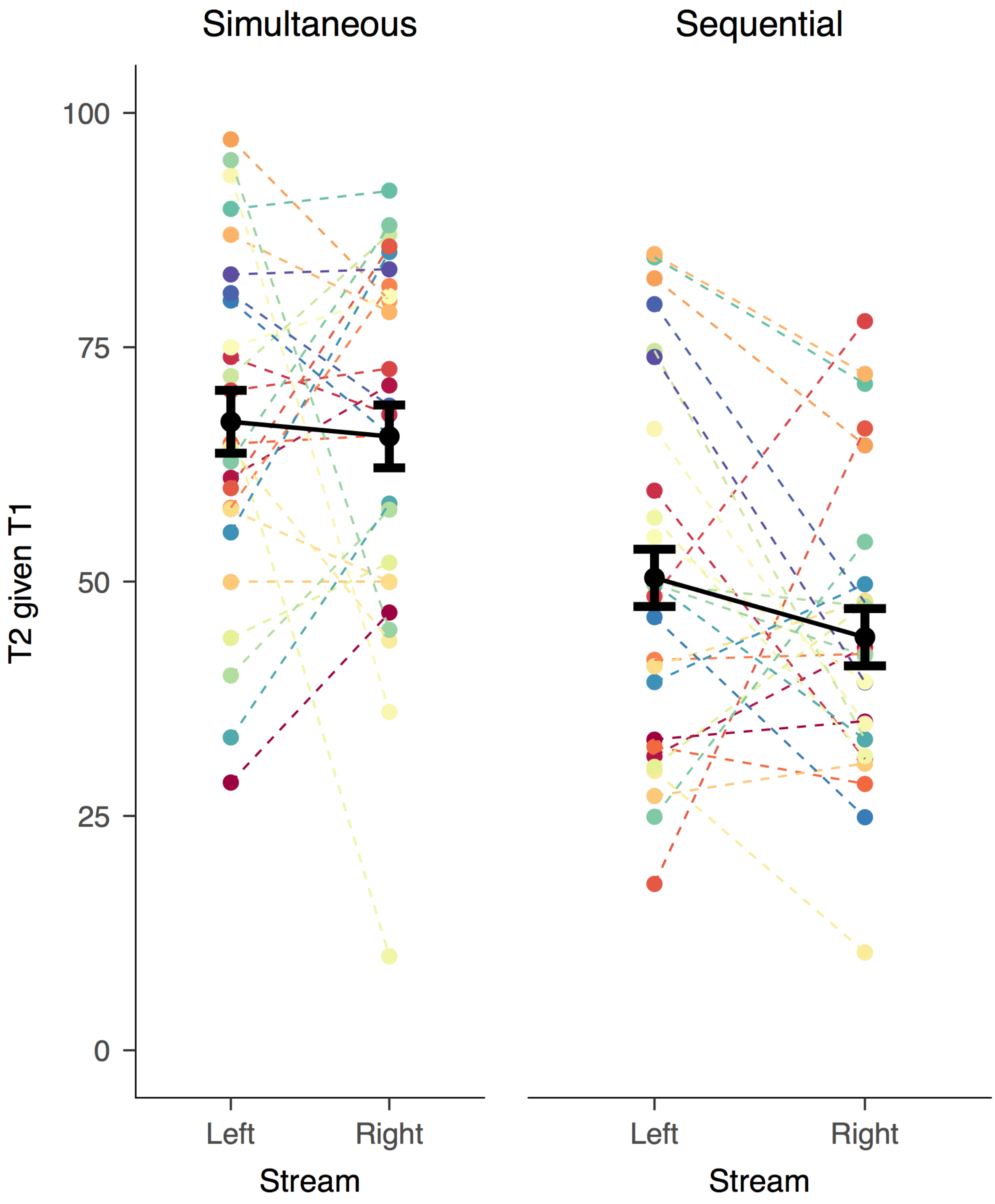

*Figure 33:* T2 given T1 for trials when two targets are presented at the same time (lag 0) and when two targets are presented at different times (lag 1). Coloured dots are results for

individual participants. Black dots (with error bars) are results averaged over participants.

### 6.5.3 Right target deficits for lag 0 and lag 1

The second hypothesis was that the right deficit at lag 0 would be similar to that at lag 1. A two tailed bayesian paired samples t-test indicates that the data are just under three times more likely to be explained by a model that the right target deficit is the same at the lag 0 and lag 1 than by a model that the right target deficit is different at the two lags ($BF_{01}$ = 2.970). Again, however, the Bayes factor is small.

### 6.5.4 Average performance at lags 0 and 1

When performance across left and right streams is averaged (and not converted to a measure of bias), two-tailed bayesian paired samples t-tests show that performance at lag 0 is much better than lag 1 ($BF_{10}$ = 327,244). This is consistent with previous studies that have compared lag 0 and lag 1 results within the same experiment (for example Bay & Wyble, 2014).

## 6.6 Additional analyses: Comparison with other experiments

The fact that the simultaneous condition of the present experiment did not yield a convincing right deficit was surprising given the large effect found in previous experiments using a nearly identical stimulus (at least for that condition). While not part of our preregistration, two additional analyses are presented here with the intention to provide further insight into this unexpected result.

### 6.6.1 Comparison of effect size with previous studies

Figure 32 shows the posterior distribution of effect sizes (which indicates the probability of the effect size after results are taken into account) in Goodbourn and Holcombe (2015) (panel a) and the present experiment (panel b). While there is some overlap between the two distributions, the bulk of the distribution for the Goodbourn and Holcombe experiment is to the right of the distribution for the current experiment, suggesting that the true spatial bias is likely to be larger for their experiment than for the present experiment. Note that the true distributions may actually be narrower than indicated here, due to the fact that the analyses are achieved using the default priors in JASP which are likely to be conservative relative to an informed prior that takes into account that the effect documented in Goodbourn & Holcombe was similarly as large in other dual RSVP experiments with simultaneous targets only. As such, it is very probable that the true effect sizes differ across the two experiments.

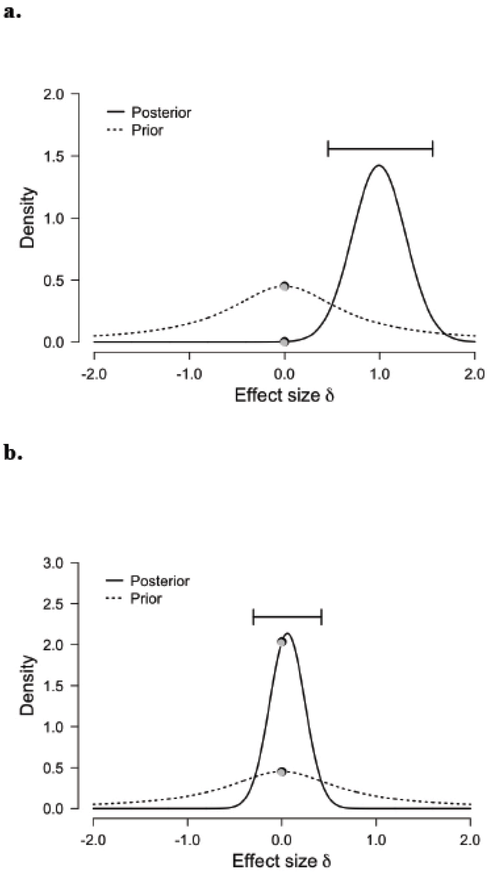

*Figure 34.* Prior and posterior distributions for effect sizes in a. Goodbourn and Holcombe; and b. the current experiment. While there is some overlap in the posterior distributions across the two experiments, the bulk of the distribution from the Goodbourn and

Holcombe experiment is to the right of the distribution from the current distribution.

### 6.6.2 Between-subject variation

In addition, the amount of between-subject variation in the data is much greater than in previous studies. While the mean result was for a right side deficit, a large percentage of participants showed deficits in the opposite direction in all lag conditions (lag 0: 58%; lag 1: 38%; lag 3: 35%; lag 5: 50%). For comparison, deficits that deviated from the usual direction were observed in around 25% of participants for experiments presented earlier in this thesis that used an English letters condition in a horizontal configuration (25% of participants in the English condition in the Arabic readers study presented in Chapter 3; and 23% of participants in the letters condition of the letters vs words experiment presented in of the Chapter 5). This may indicate that participants in the present experiment used a greater variety of strategies to perform the task than did participants in previous experiments.

## 6.7 Discussion

Right-side deficits in reporting simultaneous and successive targets from RSVP experiments with one target in each hemifield have been explained by different mechanisms, despite being empirically similar across experiments. The present study compared the deficits in an experiment that interleaved trials with simultaneous targets (lag 0) and successive targets at three different lags (1,3 and 5), and again found evidence for a similar pattern of spatial biases between simultaneous and successive paradigms (though the Bayes factors were small). However, neither condition produced the usual right deficit; the observed pattern of results were more likely under a no-bias model than under a right deficit model for all but the lag 3 conditions. While the similar results across simultaneous and successive target conditions suggests a common mechanism may determine spatial biases for both conditions in the present experiment, this is unlikely to be the same mechanism responsible for the deficits found in previous experiments.

Why is the usual right deficit for simultaneous target paradigms diminished when simultaneous target trials are intermixed with successive target trials? It is possible that this occurs because participants adopt different cognitive strategies in the two types of experiments. When all trials have the same target form (either all simultaneous or all successive) participants will adopt the associated strategy, which will affect their ability to identify the target in a consistent way. However, when participants do not know whether targets will be presented simultaneously or successively, there will be some trials where participants apply a strategy that will not normally be associated with that form of target. Applying a different strategy may affect a participant's ability to report the target and so generate a different pattern of results to that seen when a condition is applied in isolation. The present experiment did not directly investigate the types of cognitive strategies that participants were using to report the targets. However, one strategy that participants may have used is to adjust the focus of their covert attention prior to the presentation of targets. For example, participants could make an adjustment towards their favoured side to reduce the chance that they would miss both targets, or alternatively, an adjustment towards their less favoured side to increase their chance of reporting both. Electrophysiological studies, or studies that use single target trials to probe the locus of attention (as was done in Chapter 3) may be useful in providing further insight into the strategy that participants use.

Due to the fact that successive targets were presented in three lag conditions (lags 1, 3 and 5), and simultaneous targets were only presented in one (lag 0), it might be predicted that strategies associated with successive targets would dominate and so be used on both successive and simultaneous target trials. While this explains the large difference in the spatial biases between the simultaneous condition in this study compared to previous studies, it does not explain why the pattern of results in the successive condition would also deviate from that reported in previous experiments. It is possible that this reflects differences between the present stimulus and previous experiments. In particular, in the present experiment, both targets were indicated by circles while in previous experiments, T1 was indicated by a feature (it was red) and T2 was defined by a category (it was a digit). Thus, in previous experiments a switch between feature and category was involved, whereas in the present experiment, T1 and T2 were both defined by a feature. The relationship between tasks in which targets 'switch' between features and categories and tasks that do not require a switch has been the subject of some controversy in the attentional blink literature (see Gillian Dale & Arnell, 2013; Kelly & Dux, 2011), though a recent study by Dale, Dux and Arnell (2013) aimed at resolving this conflict has found that individual differences in performance are correlated across switch and non-switch tasks, suggesting that these reflect the same underlying mechanism. While this study did not specifically investigate the effect of targets being enclosed within circles, it is likely that these would be similar to other targets defined by features (such as colour targets). Another difference was that the present experiment considered items to be correct when they were within two serial positions of the target. Previous experiments with successive targets have only considered exact target reports to be correct.

An alternative (and preferred) explanation for why the bias in successive target trials appeared to deviate from that found in previous experiments is that previous RSVP experiments with successive targets that have presented trials with one target in each hemifield have typically interleaved these with trials in which both targets are presented in the same hemifield. It is possible that the right side deficit in those experiments reflects a strategy that is principally directed at the same-hemifield trials, but has an incidental effect on different stream trials. The RAGNAROC model suggests a further link between the spatial biases found in same-hemifield trials in successive target experiments, and those found in experiments with simultaneous targets. According to this model (and its predecessors, such the episodic simultaneous type/serial token (eSTST) model by Wyble et al., 2009), a key feature of the attentional system is to divide visual information into episodic chunks to ensure that temporally similar items are grouped together, and temporally disparate items are kept separate. RSVP experiments contain two main situations in which different items can be processed in the same episode. The first is when two targets are presented in the same location in either consecutive serial positions (lag 1 sparing) or in an uninterrupted sequence (no distractors) of targets (spreading of sparing). The second is when targets are simultaneous, as in the dual RSVP experiments presented in previous Chapters of this thesis. Importantly, trials with successive targets presented in different hemifields do not show lag 1 sparing. In this case, it is only possible to process both targets as separate attentional episodes. Thus, a speculative interpretation of the right deficit across previous experiments with simultaneous and successive targets is that it reflects a cognitive strategy that relates to prioritising items processed in the same attentional episode. It is possible that participants in the present experiment were more likely to adopt strategies aimed at improving performance on trials with targets at different times, which are never processed in the same attentional episode. As such, their results did not show effects of prioritisation to the same extent.

If the failure to find the usual right deficit is a result of strategies as posited here, this suggests that the spatial biases in dual RSVP experiments are likely to be more sensitive to task demands than previously contemplated. This is consistent with the related finding from recent studies that reading direction biases in dual RSVP experiments can be manipulated by presenting the text in unfamiliar orientations such as mirror-reversed on marquee (Holcombe et al., 2017). The fact that a relatively subtle change in the timing of the targets on some trials can cause the spatial biases to disappear suggests that it cannot simply be derived from a difference in processing ability between the cerebral hemispheres. Nor can it reflect a bias solely in hardwired connections that has developed through consistently reading in the same direction. Rather, the results are consistent with a spatial weighting mechanism that can be configured quickly to match the likely demands of the task.

Such a mechanism could be accommodated within the RAGNAROC framework. RAGNAROC incorporates a channel through which (unspecified) task demands can influence the deployment of attention to a particular location in the visual field. The cognitive strategies implicated in the explanation of the present results are conceptually similar to task demands in that they represent some form of participant control on the priority given to certain aspects of the visual scene, and so may influence attention through the same channel. Importantly, under RAGNAROC, the effect of different task demands or strategies may be amplified by an attention map (see figure 29), which facilitates convergence of activity at the location of the target. Thus, when two items are presented at the same time, differences in task demands may affect whether activity converges to one or two locations on the attentional map, and so affect whether one or both items are attended. This could explain why participants in experiments with simultaneous targets can sometimes report both targets and other times will report only one.

The present study highlights the empirical similarity between the spatial biases documented in experiments with simultaneous targets presented in previous Chapters of this thesis and those documented in a series of studies that have used stimuli with targets presented at different times. This similarity suggests the spatial biases in the two different forms of experiment may have a common underlying cause. In contrast to the previous accounts based on attentional shifts (for successive target studies) and serial bottlenecks (for simultaneous target studies), explanations that allow attention to be deployed to two items at once have the greatest potential to provide a unified explanation for deficits across the two experiments. The recent RAGNAROC model may be a good starting point for building such an explanation.

# Chapter 7: Conclusions

Recent experiments using dual RSVP streams of English letters have documented a right deficit in reporting simultaneously presented targets that is thought to indicate a capacity limit in visual processing. The experiments in this thesis suggest that this bias reflects a flexible mechanism that contributes to visual processing by prioritising items at a capacity limited stage according to task demands. Contrary to previous conceptions of spatial biases, this particular mechanism appears not to be hard-wired, but rather, to be remarkably sensitive to aspects of the task. Such a responsive mechanism may provide a functional advantage in adapting visual processing across varying environments.

These findings contribute to the three primary goals of this thesis. These were: (1) to understand the processes that determine which item is prioritised at the capacity limit; (2) to investigate the nature of the processing responsible for the capacity limit; and (3) to investigate the links between these phenomena and the normal reading process. Specific insights as they relate to these goals are discussed below. This is followed by a discussion of the potential applications of these findings, and limitations and next steps.

## 7.1 Goal 1: To understand processes that determine which item is prioritised at the capacity limit

A key contention in Goodbourn and Holcombe's explanation of their dual RSVP results is that spatial biases reflect prioritisation in the direction of reading at a capacity limited stage of processing. This explanation was favoured over the traditional account of spatial biases as a reflection of processing differences between the cerebral hemisphere because it can explain the spatial biases between vertically configured RSVP streams (which should not be affected by differences in the hemispheres) as well as those between horizontally configured RSVP streams (Goodbourn & Holcombe, 2015). Chapter 3 presents an experiment that corroborates Goodbourn and Holcombe's reading direction explanation by finding that the right deficit is eliminated when presented in text read from right to left. Participants with experience reading in English and Arabic script showed a left bias when the stimulus was presented in English text. The bias was similar in size to the left bias that Goodbourn and Holcombe had documented in their study that had used participants drawn from a predominantly English reading population. However, when the stimulus was presented in Arabic, participants showed a numerical advantage for reporting the letter on the right side. Recent studies have found that modulating reading direction by presenting the stimulus in mirror reversed script produces a similar pattern of results (Holcombe et al., 2017).

The effect of reading direction prioritisation shows remarkable responsiveness to specific aspects of the task. The experiment in Chapter 3 showed that participants who could read English and Arabic show left deficits when presented with one script and right deficits when presented with the other, even though there was only limited exposure to each script before each block (participants read instructions and completed a short reading speed test in the script that would be used for the subsequent block). This suggests that the prioritisation mechanism that gives rise to the second-target deficit can be reconfigured when exposed to a text with a different implied reading direction. This finding is supported by other studies using the dual RSVP paradigm that have found the second-target deficit varies within participants depending on whether the streams contain English letters in their canonical form, or the same letters mirror-reversed. Indeed, an unpublished experiment conducted by Holcombe has found that second-target deficit shows an effect of reading direction even when trials with letters in their mirror-reversed form are randomly interleaved between trials with letters in their canonical form. The first indication that participants have of whether letters will be canonical or mirror reversed is when the first item in the stream is presented. It appears that the few hundred milliseconds between the first item and the target is sufficient to engage prioritisation in the direction of reading.

While prioritisation may occur without extensive priming, it is unlikely that it is immediately engaged on presentation of a relevant stimulus. Evidence for this comes from the experiment in Chapter 6, which found that the usual right deficit for reporting simultaneous targets in RSVP streams of English letters was eliminated when these trials were interleaved with trials in which targets were separated by a lag. While the method of interleaving trials from one condition with trials from another appears superficially similar to that applied in the unpublished study mentioned in the previous paragraph, the contrasting pattern of results may reflect the fact that the manipulation only concerned the targets (and not items in the stream), which meant that participants could not predict whether the trial was simultaneous or successive in advance of the point at which the first target was presented. It is possible that advance knowledge of the condition is necessary for participants to engage the usual pattern of prioritisation, and so cause spatial biases to deviate from the usual pattern of right deficits. Note that, the fact that the deficit only occurs with advance knowledge of the task settings does not imply that the prioritisation is a deliberate strategy on the part of the participant. In all RSVP experiments, participants were instructed to try to report both targets on all trials. Thus there was no perceivable advantage from reporting items in a particular spatial location. An experiment that manipulated the direction of the text without a participant's explicit knowledge would be useful in providing a more definitive evidence that the bias was not under the volitional control of participants.

An interesting aspect of the results from the Arabic study is that while presenting the stimulus in a script read from right to left caused the right deficit to diminish relative to when the stimulus was presented in a script read from left to right, it did not reverse to produce a corresponding deficit in the opposite direction as would have been predicted if the prioritisation mechanism was solely determined by reading direction. This may indicate that the observed spatial bias incorporates an effect of cerebral lateralisation that facilitates reporting of the left target and impairs reporting of the right target in both English and Arabic condition, though it is also possible that factors specific to the experiment caused the reading direction prioritisation to be weaker in the right to left reading condition. An effect of hemispheric differences (this time favouring processing in the right visual field) is also apparent in Chapter 5, which finds that words (thought to be predominantly processed in the left hemisphere) generate a left deficit, while letters (which are thought to be processed in both hemispheres) generate a right deficit. Differences between letters and words were eliminated when the two streams were presented in the same hemifield, thus supporting the interpretation of the difference of results in the horizontal configuration as an effect of cerebral lateralisation.

## 7.2 Goal 2: To investigate the nature of processing responsible for the capacity limit

Capacity limits can arise from a range of different serial and parallel processing mechanisms and at various stages of processing. The traditional spotlight account of visual attention assumed that attention was limited to one item at a time, and multiple items in a visual scene could only be attended by shifting attention from one item to another. There is now a growing body of literature (including this thesis), demonstrating that in certain circumstances, multiple spatially separated items can be attended at a time. Many such models now distinguish between attentional sampling (that is, the initial selection of items for further processing), which is posited to allow multiple items to be processed at a time and later stages of processing such as working memory consolidation, which may be limited to processing a single item at a time.

The dual RSVP paradigm used by Goodbourn and Holcombe (2015), and adapted in experiments presented in this thesis, produces information about temporal aspects of processing that provide insight into different capacity limits that occur at sampling and later stages of processing. In particular, both Goodbourn and Holcombe and the Arabic readers study in Chapter 3 have measured the time at which the reported items appeared relative to the target letter (referred to as latency in mixture modelling jargon) and found that on average participants reported items that appeared in the left and right streams at roughly the same time. This suggests that initial representation of the items were likely to be sampled at the same time — if participants had sampled from the prioritised stream first, they would have been expected to report items that occurred earlier in the left stream than in the right stream — and so the spatial biases in responding are unlikely to reflect a shift in attention from one item to another. The spatial biases observed across the experiments throughout this thesis are therefore likely to occur at a later stage of processing. Previous research suggests that stages involved in consolidating visual memory may have limited capacity and is therefore a good candidate for the limited stage in the dual RSVP experiments.

In addition to their claim that the deficit occurred at a late stage of processing, Goodbourn and Holcombe speculated that the spatial bias occurs as a result of a serial bottleneck which allows only one item to be processed at a time. According to their explanation, the prioritised item is processed first and so has a good chance of being reported by the participant. Processing of the non-prioritised item is delayed, but can be sustained for a short time in a buffer. If the delay in processing exceeds a critical threshold, the representation of the item will decay and so participants will not be able to report the item. Chapter 4 investigated this claim by presenting two words in a static display and manipulating whether participants were told which item to report immediately (which may allow participants to reprioritise attention to the target item) or after a delay (which would be likely to be too late for there to be a benefit of reprioritisation). If the spatial bias was the result of delayed consolidation, it would be expected to reduce when participants were given early information about the which item to report. In fact, the study found that providing participants with early advice did not affect spatial biases in responding. This may suggest that the spatial bias is not the result of delayed consolidation as Goodbourn and Holcombe claim but instead reflects a different neural mechanism which may involve parallel consolidation of items.

Parallel models are becoming increasing popular in attentional blink research following evidence from previous studies that the usual limitation in reporting a second target is eliminated if the two targets are presented in immediate succession (Potter et al., 1998; T. A. W. Visser, Zuvic, Bischof, & Di Lollo, 1999), which appears to contravene the assumption of serial bottleneck models that only one item can be processed at a time (for example, Chun & Potter, 1995)). They explain spatial biases not as an effect of the order in which the two targets are processed, but rather, as a bias in how much information is extracted from each of the two simultaneously processed items. Thus, a right deficit in a parallel model reflects a process in which left and right targets were sampled simultaneously, but more information was extracted at the location of left target. Wyble and colleagues' RAGNAROC model (discussed extensively in Chapter 6), assumes that there is competition between items at different spatial locations at an superordinate 'attentional-map' layer of processing, which could ultimately cause attention to converge to the location of one of the targets but not the other. This may explain why Goodbourn and Holcombe found the size of the bias to be similarly large regardless of whether the streams were configured on a vertical, horizontal, diagonal or anti-diagonal plane -- it would require a remarkable coincidence for the strength of the advantage between left and right stimuli to be so similar to that between upper and lower stimuli, and those between diagonally arranged stimuli if different factors are responsible in each case.

Crucially, participants are sometimes able to report simultaneous targets from dual RSVP streams (and indeed are better at this than when the items are successive but temporally close), which suggests that attention does not always converge to a single location. Presumably, the degree of prioritisation attached to one of the items must reach a critical threshold in order to trigger convergence. As discussed in Chapter 6, the direction of prioritisation afforded to a particular stream appears to vary with aspects of the stimulus and task demands. It may be that these same factors affect whether attention converges on one of the targets or two.

## 7.3 Goal 3: To investigate the links between these phenomena and the normal reading process

A key finding of this thesis is that the deficit is sensitive to the direction in which a script is typically read. This suggests that the prioritisation mechanism that causes the deficit may play a role in natural reading. Many current models of reading incorporate some form of prioritisation that is influenced by the direction of the script (in particular, see E-Z reader:

Reichle et al., 2003). However, there is disagreement in the literature about the nature of prioritisation (in particular, whether more than one word can be processed at a time), and the role that it plays in reading. By providing a detailed account of the nature of processing that is likely to cause the second-target deficit in dual RSVP experiments, the experiments in this thesis also provide insight into the components of reading that may be relevant to this ongoing debate.

The dual RSVP experiments in Chapters 5 and 6 suggest that the prioritisation is likely to occur at a later stage of processing than is usually contemplated in models of reading. In particular, the spatial biases in experiments in Chapter 5 are consistent with a view that lexical processing can occur for multiple words in parallel, with prioritisation occurring at a post lexical stage of processing. Such a late-stage prioritisation mechanism may play a role in ensuring that representations of items are transferred to memory in the correct order. This account is extended in Chapter 6, which suggests that this prioritisation is achieved by boosting activity corresponding to one location on a late-stage attention map and suppressing activity corresponding of other locations on the attention map. The resulting imbalance in activity to the two items may trigger a deployment of attention that boosts processing of cells corresponding to the location of the item in early stages, which feeds through the system, increasing the likelihood that the prioritised item will be transferred into working memory, and decreases the likelihood that the non-prioritised item will be transferred. However, as suppression is not encountered until an initial representation reaches the attention map, non-prioritised items may still be partly processed, which may explain the preview effects that have been well documented in eye-movement studies. This is because the activation of a non-prioritised item — even if not converted to memory — may still facilitate processing at a later fixation.

Experiment 2 in Chapter 5 provided evidence that the spatial bias is not affected by whether the streams contain letters or words when they are vertically configured. This suggests that prioritisation occurs at a stage of processing after letters have been grouped together to form words (prioritisation found in experiments that have used letters in the streams presumably do so because the letters are treated as short words, perhaps by virtue of the large spatial separation between them). In light of this, it was surprising that when words were configured horizontally (both in the partial report paradigm used in Chapter 4 and the dual RSVP paradigm used in Experiment 1 of Chapter 5), the right stream was better reported. This right advantage is likely to reflect an effect of hemispheric differences that occurs at an earlier processing stage than the reading direction prioritisation. In a dynamic reading situation (at least for scripts read from left-to-right), this may mean that lexical processing occurs for the word to the right of the fixation point at the same time as it occurs for the fixated word.

Another intriguing question relates to the developmental profile of reading direction prioritisation. Reading is a learnt skill, and so the mechanisms responsible for prioritisation in the direction of reading must develop as a result of either knowledge of or experience with the conventions associated with a particular text. None of the experiments presented here have specifically aimed to address the developmental profile of the capacity limit. Nonetheless, some aspects of the results presented here may be relevant for future studies. Specifically, two studies included in this thesis included measures of participants' experience reading in a particular direction. These were the Arabic language study in Chapter 3, which reported participants' reading speeds in Arabic and English; and the partial-report study in Chapter 4, which measured reading experience using the Author Recognition Test. In both cases, the Bayes factors marginally favoured there being no effect of experience reading in a particular direction, suggesting that participants already had sufficient experience reading in a particular direction to engage the prioritisation fully. However, in light of the low Bayes factors recorded in these analyses, more evidence would be needed to make firm conclusions about this.

## 7.4 Potential applications of this research

A key feature of the prioritisation mechanism investigated in this thesis is its sensitivity to specific aspects of the task. Across a number of experiments, spatial biases were shown to be sensitive to differences in the items of the streams, and the timing targets, suggesting that the mechanism is not determined by hard-wired neural circuitry, but rather, by a flexible mechanism that can be adapted to provide a functional advantage in a range of different situations where multiple items are encountered at the same time.

While the advantages of such a prioritisation mechanism are likely to extend to a range of different tasks, this thesis has focussed on implications for reading. In this context, prioritisation may play a role in ensuring that words are transferred to memory in the correct order. A number of studies have linked the reading difficulties experienced in dyslexia to disorders in spatial attention. For example, Francesschini and colleagues (2013) have demonstrated that dyslexia is improved by playing action video games, which are thought to exercise spatial attention systems. Another model put forward by Vidyasagar and Pammer (2009) posits that some forms of dyslexia may reflect a failure of readers to process the text in the correct order (left to right for English). While they suggest that this may reflect difficulty shifting attention in the right direction, the same disordered processing could occur if there was a deficit in prioritising items at a late stage of processing. Investigating the patterns of spatial biases on dyslexic readers, or early readers may help to establish whether the prioritisation mechanism here is responsible for reading difficulties in these conditions.

## 7.5 Limitations and Directions for further work

While this thesis has suggested a number of implications for our understanding of reading, an important caveat is that the experiments have always used stimuli with items appearing either side of a fixation point, and with targets identified by a salient cue. In natural reading, targets to be identified are simply the next item in the sequence of text. In addition, fixating in-between two words is unusual — normally fixations are very close to the centre of a word (G. Underwood, 2009). As such, it is unclear whether two items can be sampled at once in the natural circumstance. However, it seems likely that it does, on the basis that the second-target deficit is likely to have developed through situations in which multiple items are processed at one time. Further research looking at spatial biases when a word is presented at fixation would provide more confidence about these findings.

The experiments in this thesis demonstrate that spatial biases can provide useful information about capacity limits in vision. As such, the techniques used here may be a useful alternative to traditional methods for studying this paradigm. The dual RSVP methodology used in experiments presented in Chapters 3, 5 and 6 has specific utility in distinguishing shifts in visual attention (indicated by sampling earlier items from one stream than the other) from relative prioritisation of target items (indicated by a greater likelihood of reporting items from one stream rather than another). From this method, the thesis has been able to ascertain that the spatial bias was not the result of shifting attention from one item to another, but rather, reflects prioritisation of one of the items that may occur at a later stage in processing. Presumably this method can be used with other stimuli to differentiate between attention shifts and differences in prioritisation. In particular, Bay and Wyble (2014) have suggested that attending to two items at once is only possible in response to a salient cue at the location of the target. Investigating other cues may be important in understanding the situations in which prioritisation occurs between multiple targets.

The experiments in Chapter 5 of this thesis provide some evidence that the capacity limit occurs after letters have been grouped to form words. However, it may be possible to develop a more fine-grained understanding of the stage in the reading process at which the capacity limit occurs by manipulating aspects of the words presented such as word frequency, or investigating whether the spatial bias also occurs for non-words or letter strings. These manipulations may be allow comparisons to be made of the bias between words (which typically elicit a strong left hemisphere advantage) and letter strings (which typically elicit a much weaker left hemisphere advantage), which may provide insight into how reading direction prioritisation interacts with the left hemisphere advantage for processing words.

Further work may usefully focus on mapping the developmental profile of the reading direction prioritisation. This may involve testing children at various stages of learning to read. There may also be opportunities to test adults as they learn to read in a different direction, by using second language learners of scripts read in opposite directions, or participants that are trained to process an experimental text in a particular direction.

A limitation of the dual RSVP method is that each trial requires a large number of stimuli that can be processed quickly. This was pushed to the limit in the experiment in Chapter 5, which the two streams were configured of four letter words. In that experiment, the presentation speed was reduced to 6 items per second, and participants still only reported the target word for the right stream (or a word presented within two serial positions of the target) on 34 per cent of trials and the target word for the left stream (or a word presented within two serial positions of the target) on less than 15 per cent of trials. Applying this technique to stimuli that take longer to process than words (for example, non-words, and letter strings) is unlikely to be feasible. For the same reason, it may not be possible to gain meaningful results from early or impaired readers using dual RSVP experiments.

The partial report paradigm used in Chapter 4 may provide an opportunity to measure spatial biases over a much greater range of stimuli. Trials can also be completed much more quickly, which may be important if running experiments with early readers. This paradigm does not provide any evidence of the relative time at which the streams are sampled, and so cannot be used to determine whether two streams are sampled at the same time. However, it can provide an indication of relative prioritisation between the two streams, which is most relevant to understanding the capacity limited stage.

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