Split fovea theory and the role of the two cerebral hemispheres in reading: a review of the evidence

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Abstract

Split fovea theory proposes that when the eyes are fixated within a written word, visual information about the letters falling to the left of fixation is projected initially to the right cerebral hemisphere while visual information about the letters falling to the right of fixation is projected to the left cerebral hemisphere. The two parts of the word must be re-united before the word can be recognised. Bilateral projection theory proposes instead that visual information is projected simultaneously to both hemispheres provided that it falls within the fovea (defined as the central 2 to 3 degrees). On this more traditional account, no interhemispheric transfer would be required in order to read a word presented within the fovea. We review the evidence in support of split fovea theory and consider some of the objections that have been raised. We argue that a split fovea affects the reading of words at fixation, something that must be recognised and accounted for by cognitive, computational and neural models of reading.

Key words: split fovea, hemispheres, macular sparing, reading, word recognition, visual field

1. Introduction

The essence of ‘split fovea theory’ (SFT) is that the fovea is anatomically and functionally divided down the middle, with all visual information that originates to the left of fixation projecting initially to the right cerebral hemisphere while all visual information that originates to the right of fixation projects first to the left cerebral hemisphere. In contrast, the longer-established bilateral projection theory (BPT) proposes that while information presented in the left and right visual fields outside the fovea projects to the right and left hemispheres respectively, foveal information (usually taken to be the central 2-3°) is projected simultaneously to both hemispheres. That would include all the letters in a centrally-fixated word that fall within the fovea.

When skilled readers are processing connected text, some words are skipped, but most are fixated. When a word is fixated, the fixation point typically falls about one-third of the way into the written word (O’Regan & Jacobs, 1992; Rayner, 1998). If the BPT is correct then, under normal reading conditions, the whole of a word that is contained within the fovea will be projected to visual areas in both hemispheres, including the language-dominant hemisphere from which word recognition can proceed. Word recognition will include access to the word’s meaning (semantics) and its spoken form (phonology). If, however, the SFT is correct, then those letters in a centrally-fixated word that fall to the right of fixation will be projected initially to visual areas in the left hemisphere while those letters that fall to the left of fixation will be projected first to visual areas in the right hemisphere. The two parts of the word will need to be brought together for identification, which would presumably involve the transfer of those letters projected to the non-dominant hemisphere across the corpus callosum to the language-dominant hemisphere. In readers with left hemisphere language dominance, which is the majority of readers, that would involve transfer of letters that fell to the left of fixation from the right hemisphere to the left hemisphere, where they could be reunited with the letters that fell to the right of the original fixation. If the SFT provides a better account of foveal processing of words and other visual stimuli, then researchers will need to explore the implications for cognitive, computational and brain-based models of reading, including how and where the left and right parts of a fixated word are re-united, and what problems might arise as a result of deficient callosal transfer (cf. Brysbaert, 1994, 2004; Ellis, 2004, 2009;

Henderson, Barca, & Ellis, 2007; Lavidor & Walsh, 2004; Monaghan & Shillcock, 2008; Shillcock, Ellison, & Monaghan, 2000; Whitney, 2001; Whitney & Cornelissen, 2008).

There are three main lines of evidence relevant to the issue of whether the human fovea is or is not split, and whether any putative split affects visual word recognition. The first line of evidence comes from research involving patients with loss of vision in one or other visual hemifield (hemianopia). SFT predicts that when vision is lost in one visual hemifield, that loss will extend right up to the midline, even within the fovea. In contrast, because the BPT proposes that the fovea projects to both hemispheres, the BPT predicts that the fovea should be spared in hemianopic patients in whom only one visual field is damaged. The second line of evidence relevant to whether the human fovea is split or not concerns so-called ‘split-brain’ patients whose cerebral hemispheres have been surgically disconnected, either wholly or partially. SFT predicts that the problems such patients experience in transferring visual information between hemispheres as a result of the severing of callosal fibres should mean that one hemisphere will be unable to access visual information falling in the opposite visual field, even when that input falls within the fovea. The BPT theory makes the opposing prediction that because the fovea projects in its entirety to both hemispheres, each hemisphere will retain full access to foveal information even when extra-foveal information can no longer be transmitted between hemispheres. The third and final line of evidence comes from studies of word recognition in normal, healthy readers which explore parallels between the processing of whole words in the left or right visual fields (beyond the fovea) with the processing of the left and right halves of centrally-fixated words. We will review each of these lines of evidence in turn, paying attention to the various points raised by Jordan and Paterson (2009) in their critical assessment of research in this area, an assessment which comes down in favour of BPT over SFT. Other reviews of the evidence, including more extensive coverage of older research, can be found in Brysbaert (1994, 2004), Ellis (2004), Leff (2004), and Lavidor and Walsh (2004). We should note that while our primary concern is with the implications of a split fovea for understanding reading processes, some of the crucial studies in the three different areas employed simple, nonverbal stimuli such as small dots or geometric figures. The importance of those studies for discriminating between BPT and SFT is such, however, that we will include them in this review.

2. Evidence from hemianopia

A basic source of evidence commonly cited in favour of BFT and against SFT was published by Huber (1962) who reasoned that by examining patients with hemianopia (i.e., loss of vision in one visual field as a consequence of unilateral ablation of primary visual cortex), he could determine the amount of central overlap (if any) between the left visual field (LVF) and the right visual field (RVF). Such overlap would be interpreted as indicating the region from which there is bilateral projection to both hemispheres. After presenting dots of light around the vertical meridian and asking patients if they could see them, Huber argued that there was an overlap of 0.5° to 1°, which widened to 1.5° on either side in foveal vision (i.e., to include the full fovea). Huber's conclusion seemed to receive strong support when Stone, Leicester, and Sherman (1973) cut the left or right optic tract in monkeys and observed the resulting retinal degeneration, reporting a strip of intermingling ganglion cells down the vertical meridian that extended 0.5° into each visual field. Because the fovea does not contain ganglion cells (they are displaced towards the parafovea to increase the density of the receptors) it appeared that the complete fovea was still functioning. The latter finding seemed to receive further corroboration when Bunt and colleagues (Bunt & Minckler, 1977; Bunt, Minckler, & Johanson, 1977) and Leventhal, Ault, and Vitek (1988) injected a retrograde labeler into the left or the right optic tract of monkeys and observed which ganglion cells in the retinas had been marked. Again, there was an intermingling of ganglion cells 0.5° into each hemiretina and a band of stained ganglion cells around the fovea, indirectly suggesting that the full fovea (3° in width) projected to the labelled optic tract, and therefore that the full fovea projected bilaterally to the primary visual cortices in both hemispheres.

Even though the above-mentioned studies did not present direct behavioural evidence showing hemifield overlap in foveal vision, they have been used repeatedly as the basis for proposing bilateral representation of foveal vision, both in ophthalmology and in psychology. In ophthalmology, the BPT seemed to present an explanation of *macular sparing* – the phenomenon whereby central vision is often preserved in patients with hemianopia. In psychology, BPT provided researchers with a reason not to incorporate split processing and interhemispheric communication into their models of foveal word recognition and a reason, more generally, to marginalize the literature on differences between the processing of words presented beyond the fovea in the LVF or RVF as relevant only to neuropsychology and the study of hemispheric differences. The picture has, however, changed considerably over the last 20 years or so, in terms of both anatomical understanding (Leff, 2004; Toottell, Mendola, Hadjikhani, Liu, & Dale, 1988)[1] and psychological theorizing (Brysbaert, 1994, 2004; Ellis, 2004; Shillcock et al., 2000; Whitney, 2001; Whitney & Cornelissen, 2008).

With respect to macular sparing in humans, the studies of Trauzettel-Klosinski and Reinhard (1998) and Reinhard and Trauzettel-Klosinski (2003) are of particular importance. Trauzettel-Klosinski and Reinhard (1998) examined the phenomenon of macular sparing under carefully controlled conditions. They used a scanning laser ophthalmoscope which allowed them to film the retina and to reveal the exact position of stimuli on the retina (Figure 1). In this way they were able to make sure that the data they obtained were not affected by inadequate fixation control. In addition, their stimuli (small black dots against a red background, presented for 120 ms) were specifically designed to ensure that the findings could not be explained in terms of light being scattered from one part of the retina to another. Scatter is a problem when bright stimuli are presented against a dark background: even though the source of the light cannot be perceived, light scattered from one part of the retina to another may disclose the fact that a stimulus has occurred out there in the visual world. Trauzettel-Klosinski and Reinhard (1998) took measurements for each eye separately and were able to distinguish three types of hemianopia: (1) hemianopia with large macular sparing (up to 5° in the affected hemiretina), (2) hemianopia with moderate macular sparing (up to 2-3° in the affected hemiretina), and (3) hemianopia with little or no macular sparing (no more than 0.5° in the affected hemiretina). Trauzettel-Klosinski and Reinhard presented evidence that the first two categories of macular sparing were due to spared functioning of parts of the affected visual cortex and were not due to bilateral representation of the central 4-10° of the visual field. A similar conclusion about the origins of macular sparing was reached by Miki, Nakajima, Fujita, Takagi, and Abe (1996) on the basis of brain imaging.

Figure 1 about here

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[1] At first sight, the title of the review by Tootell et al. (1998), “The representation of the ipsilateral visual field in human cerebral cortex”, seems to suggest that Tootell revised his earlier opinions. The Tootell et al. (1998) paper begins, however, by saying that, “in macaque monkeys, input to primary visual cortex (V1) appears completely crossed, with little or no measurable activation from the ipsilateral visual field.” (p. 818). The rest of Tootell et al.’s (1998) article deals with the functioning of ‘higher-tier cortical areas’, which have increasing input from the ipsilateral visual field and for which the authors hypothesize that, “Such electrophysiological variations in the ipsilateral activation may reflect corresponding variations in the density of *callosal input…* ” (p. 818, italics added). There is nothing in Tootell et al. (1998) that contradicts SFT. Another reference often cited in favor of BPT (Gazzaniga, 2000) concludes from an evaluation of research on macular sparing in split-brain patients that, “The callosotomy research thus supports other work showing that macular sparing cannot be explained by nasotemporal overlap.” (p. 1297).

Reinhard and Trauzettel-Klosinski (2003) continued their research by testing the subset of hemianopic patients who showed little or no macular sparing (i.e., the third type mentioned above). In particular, they asked whether these patients would show *foveal sparing*; that is, preservation of a smaller region of central vision in line with Huber's (1962) original claim. Reinhard and Trauzettel-Klosinski (2003) used the same methodology as in their previous study and were able to test a total of 34 eyes in 20 patients. In 12 eyes they found that the patients could see the dots presented 0.5° in the blind hemifield but not beyond. In 22 eyes the patients could see the dots at an eccentricity of 0.5° in parafoveal vision but *not* in foveal vision. In no eye did the authors observe the pattern of sparing in the foveal area proposed by Huber (see Figure 2). On the basis of these observations, Reinhard and Trauzettel-Klosinski (2003) concluded that Huber's (1962) findings must have been an artefact of inadequate eye fixation control and/or light scatter from the stimuli used. According to Reinhard and Trauzettel-Klosinski's data, the amount of foveal overlap is at most 0.5°, and could be 0° (given that the spatial accuracy of the measurements themselves was 0.5°).

Figure 2 about here

In sum, Trauzettel-Klosinski & Reinhard (1998) and Reinhard and Trauzettel-Klosinski (2003) showed in two careful studies that macular sparing is due to spared functioning of the affected cerebral hemisphere and that apparent foveal sparing can be explained as a result of either scattering of light across the retina to portions that lie across the vertical meridian and which project to intact visual cortex, or to preserved functioning of parts of the visual cortex in an otherwise damaged hemisphere. When these two possibilities were excluded, their estimate for the bilateral projection of foveal information varied across individuals from 0° to a maximum of 0.5° (about 1.5 letters under normal reading conditions). This evidence against significant bilateral foveal projection, coming from the best controlled studies of hemianopia in the literature, is the first finding on which the SFT is based.

3. Evidence from split-brain patients

This brings us to our second line of evidence for SFT which comes from the study of 'split-brain' patients. If the fovea is split, so that interhemispheric communication via the corpus callosum is required for foveal word recognition, a straightforward prediction is that central word recognition should no longer be possible in split-brain patients who have had their corpus callosum sectioned (provided that their eyes are not allowed to wander to one side of a word or the other, allowing whole words to be projected to a single hemisphere). According to SFT, the severing of callosal fibres in split-brain patients should mean that they are unable to recombine the portion of a briefly-fixated word that falls to the left of fixation, and is therefore projected to the right hemisphere, with the portion that falls to the right of fixation, and is therefore projected to the left hemisphere. The best that an isolated hemisphere could do would be to formulate a guess as to the possible identity of the word based on those letters that are projected directly to it. In contrast, BPT states that foveal words will project in their entirety to both hemispheres, so reading foveated words should not present a problem for split-brain patients.

Corballis and Trudel (1993) reported precisely the difficulties with central word recognition predicted by SFT in two split-brain patients, one of whom (LB) had undergone a complete sectioning of the corpus callosum for the treatment of intractable epilepsy while the other (DK) had undergone a posterior callosotomy, separating the visual areas at the back of the brain. Both patients were given a lexical decision task requiring the discrimination of 4-letter words from nonwords. The stimuli were displayed for 100 ms just to the left of fixation, just to the right of fixation, or across fixation (two letters to the left of the fixation point and two to the right). As one would expect, healthy controls with intact interhemispheric communication scored highly in all three conditions. The two patients were close to 100 per cent correct for words and nonwords displayed entirely to the right of fixation, and therefore projecting in full to their left hemispheres. On the basis of the results shown in Figure 5 of Corballis and Trudel (1993), Brysbaert (1994) estimated that DK scored at around 73 per cent on items displayed to the left of fixation, projecting to the right hemisphere, while LB scored around 82 per cent. These LVF performance levels indicate some capability for word recognition in the isolated right hemispheres of these patients (cf. Sidtis, Volpe, Wilson, Rayport, & Gazzaniga, 1981; Zaidel, 1998). Both DK and LB were, however, close to chance (around 57 per cent correct) for items presented across fixation, despite the fact that acuity is highest at this location. An inability to discriminate words from nonwords when those stimuli are presented at fixation is precisely what SFT would predict in split-brain patients, but is not predicted by BPT.

Corballis and Trudel (1993) also asked LB to read aloud briefly-presented words and nonwords (rather than simply indicate whether each item was a word or a nonword). LB performed well on RVF words and nonwords (10/10 on both). He managed to read 9/10 LVF words, suggesting once again a significant capability for reading familiar words presented in their entirety to the right hemisphere. His right hemisphere was much less adept, however, at reading LVF nonwords (2/10). He managed to read 5/10 centrally-presented words correctly but could read none of the 10 central nonwords. LB's responses to the 5 central words that he managed to read correctly were very slow and laboured. Corballis and Trudel (1993) suggested that LB may have succeeded in guessing some of the centrally-presented words on the basis of those letters that appeared in the RVF and were therefore projected directly to his left hemisphere. Guessing would not be an option for nonwords, which LB was completely unable to read when displayed across fixation. LB had previously been one of a set of patients studied by Sperry, Gazzaniga, and Bogen (1969). Those authors observed that "If a word like *catkin* [which is composed of two words, *cat* and *kin*] falls half in one field and half in the other, the two parts are perceived only as two separate words; the complete single word is never perceived as such unless the gaze is centred to the left or right of the whole word" (p. 277). This is exactly what SFT would predict.

Unfortunately, because the above research was not designed specifically to address the issue of SFT *vs* BPT, the stimuli used were not well controlled on their width. The words used by Corballis and Trudel (1993) extended 2° to either side of fixation. This leaves the possibility that the centrally fixated stimuli could not be recognized because the first letter fell outside the bilaterally projecting fovea. Sperry et al. (1969) did not provide information about the width of their stimuli, but given that the words were reasonably long, it is quite likely that their words also extended beyond foveal vision. The best controlled study with a split-brain patient that is relevant to SFT was published by Fendrich and Gazzaniga (1989), though theirs was not a study of word recognition. Fendrich and Gazzaniga asked a split-brain patient (VP) to compare target figures presented 1° or less from the retinal vertical midline with reference figures that were presented further from the midline in either the same or the opposite visual field. Target and reference stimuli consisted of four different geometric figures constructed from straight lines of equal length (a square, a bisected triangle, an asterisk, and an hourglass-like shape). On each trial, one of the figures served as the referent. It was presented for 1 sec. prior to the onset of the target, 2.5° to the left or right of the fixation point. The target figure was then presented for 200 ms with the referent remaining on the screen. The target was the same figure as the referent on half the trials and one of the three alternative figures on the remaining trials. The target was displayed in one of five positions – 15’ or 1° from the fixation point in the same visual field as the referent or 15’, 30’, or 1° from the fixation point in the opposite visual field. The patient’s task was to indicate whether target and referent were the same or different. Viewing was monocular (with the right eye) and eye fixations throughout a trial were tightly controlled with an eye-tracker and a gaze-contingent display technique (i.e., the stimuli were only visible when the participant was looking at the required fixation point). VP had few problems comparing geometric figures presented in the same visual field (90 per cent correct for targets presented at 15’ and 91 per cent for target presented at 1°). However, performance dropped dramatically when the figures appeared on opposite sides of fixation (to 60 per cent for targets presented 15’ in the opposite visual field, 57 per cent for targets at 30’, and 55 per cent for targets at 1°). On the basis of these findings, Fendrich & Gazzaniga (1989, pp. 277-278) concluded that “A change from near perfect accuracy to near chance accuracy was therefore produced by a one half degree shift in target position across the center of the subject’s fovea.” SFT predicts this pattern of results: BPT does not.

Fendrich, Wessinger, and Gazzaniga (1996) ran a similar study on another split-brain patient, JW. This time they were more interested in the temporal aspect rather than the spatial aspect. In particular, they compared performance for target durations of 200 ms (‘fast’) with target durations of 2 s (‘slow’). The stimuli in this study were sine wave gratings and the patient had to indicate whether the two gratings were both horizontal, both vertical, or one horizontal and one vertical. Eye movements were tracked to ensure that JW did not move his eyes during stimulus presentation. When the gratings were presented well away from fixation (2° to the left or right), JW was at or nearly at chance whether the presentation was fast or slow. When the gratings were close to fixation (1° to the left or the right), JW remained at chance with the fast presentations (49-56 per cent correct depending on the spatial frequencies of the gratings). Only with presentation time of 2 secs was JW able to get above chance to accuracy levels between 65 and 80 per cent (again depending on the spatial frequencies of the gratings). This suggests that some low-level information may be capable of being transferred from one hemisphere to the other in the absence of a corpus callosum, but that the quality of this information and the speed of transfer are too poor to be of use in normal reading (for a review of the type of visual information that can be transferred between the hemispheres in split-brain patients using non-callosal routes, see Corballis, 1995)[2]. JW was not able to match stimuli presented 1° to the left and right of fixation for 200 ms, something he should have been perfectly capable of doing if that region enjoys the bilateral projections to both cerebral hemispheres proposed by BPT.

The fact that split-brain patients cannot match briefly-presented stimuli displayed either side of fixation, even when the stimuli fall within the fovea, and have great difficulty reading words and nonwords presented at fixation despite being able to read items presented in the RVF (and sometimes in the LVF), forms the second line of evidence in support of SFT.

4. Evidence from normal readers

The evidence from hemianopia and split-brain patients strongly suggests the need for callosal transfer when processing foveal stimuli that cross the vertical meridian, including written words. The evidence is less than optimal, however, for drawing firm conclusions about the need for interhemispheric communication in normal word recognition. The hemianopia evidence is based on studies using simple, non-alphabetic stimuli, and only one of the split-brain studies used stimuli that were small enough to fit entirely within foveal vision. The studies reviewed in this section looked for evidence that a split fovea impacts on visual word recognition in healthy, skilled readers.

4.1. Optimal viewing positions for readers with left- and right-hemisphere language dominance.

Studies of the optimal viewing position for recognizing written words present the words briefly in such a way that across the trials of an experiment, fixation falls at different positions in the words (e.g., on each of the component letters of the word from first to last). Positioning of the words is randomized so that the participants have no way of knowing exactly where the word will appear on a given trial. Participants respond to each word as quickly as possible (e.g., by reading it aloud or making a lexical decision response). Fastest responses are typically observed

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[2] We note that a comparable phenomenon exists in hemianopia. When these patients are asked to guess where in the blind hemifield a stimulus has been presented, they are able to do so at an above chance level, a phenomenon called blindsight (e.g.,

when fixation occurs to the left of the centre of the word, while the slowest responses occur when fixation falls on the last letter (Brysbaert, 1994; O'Regan & Jacobs, 1992). Optimum viewing positions (OVPs) are probably determined by a range of factors including the distribution across words of information indicating the identity of the words (which tends to be skewed towards the initial letters which vary more across words than do final letters), the fact that visual acuity falls away with distance from fixation, and perceptual experience and learning derived from the fact that fixations in reading usually land in the first half of each word (Brysbaert & Nazir, 2005). But if SFT is correct, a fourth determinant of OVPs could be that when fixation falls in the first half of a word, the majority of the letters will be in the RVF, and will therefore project directly to the left hemisphere, which is the language-dominant hemisphere in most readers. Fixating to the left of centre will reduce the number of letters that fall to the left of fixation, and therefore project initially to the right hemisphere, requiring callosal transfer in order to be reunited with the other letters (Brysbaert, 1994; Brysbaert & Nazir, 2005). BPT, in contrast, maintains that the whole of the fovea projects to both hemispheres, so that provided words fall within the fovea, all the letters will project directly to the language-dominant hemisphere. BPT would then explain the OVP data in terms of some combination of information distribution, visual acuity and perceptual learning.

While most adults are left hemisphere dominant for language, a minority have right hemisphere language dominance (Knecht et al., 2000). According to BPT, language dominance should have no impact on OVPs, which are determined by factors other than hemispheric processing. SFT predicts, however, that OVPs should shift in right hemisphere dominant readers because for those individuals, interhemispheric transfer of letters from the nondominant to the dominant hemisphere will be least when fixation falls to the *right* of centre. SFT therefore predicts that OVPs will be different in left- and right-hemisphere dominant readers, while BPT has no reason to predict any such differences. Hunter, Brysbaert, and Knecht (2007) used two well-established techniques (fMRI and functional transcranial Doppler sonography) to distinguish two small groups of healthy, left-handed individuals – a group with left hemisphere speech dominance and a group with right hemisphere speech dominance. The discrimination was based on differences in levels of blood flow to Broca's area in the left hemisphere and its

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Cowey, 2004). However, there is no evidence that this residual capacity would be of any assistance in the identification of words presented at a normal reading speed.

homologue in the right hemisphere during a word production task. In their Experiment 2, Hunter et al. (2007) presented 4- and 7-letter words for 180 ms at different positions across fixation. The stimuli were short enough to fit within the fovea, even when seen from the first or the last letter, when the letters extended from 0.2° on one side of fixation to 1.7° on the other. A participant's task on each trial was simply to name the stimulus word as quickly as possible. We will focus on the results for 4-letter words which were presented in such a way that the first, second, third, or fourth letter fell at the point of fixation. Figure 3, which is based on Table 4 of Hunter et al. (2007), shows the results expressed as the mean RT for each group at each fixation position relative to the group average. Positive values mean that word naming RTs at that position were relatively slow for that participant group while negative values mean that RTs were relatively fast. The results are clearly different for left- and right-dominant participants. Whereas the left-dominant participants were 20 ms faster to name words fixated on the first letter than on the last letter, the right-dominant participants were 10 ms slower when fixating on the first letter than on the last. The differences in naming time between fixations on the first letter and the last letter perfectly predicted the speech dominance of the participants as assessed with fMRI (Hunter & Brysbaert, 2008-a) and were in full agreement with the VHF advantages shown by the same participants in a parafoveal word naming task (Hunter & Brysbaert, 2008-b). These results are as predicted by SFT and have no obvious explanation under the BPT.

Figure 3 about here

The study of Hunter et al. (2007) relied on instructions to participants to control fixation, combined with a proportion of trials in which digits presented very briefly at fixation that participants were required to identify (the idea being that those digits could only be identified if fixation was maintained accurately at the centre and did not stray to left or right). Jordan and Paterson (2009) have argued that such fixation control in insufficient, and that direct monitoring of eye movements is required. Van der Haegen, Drieghe, and Brysbaert (in press) ran a set of experiments to determine the extent to which more precise fixation control (and presentation to both eyes or just the dominant eye) might affect the shape of the OVP curve. Is it the case, for example, that the typical pattern of faster responses when fixation falls in the left half of a word reported in past experiments was due in some way to inadequate fixation control? In Experiment 1 of Van der Haegen et al. (in press) right-handed participants with right eye dominance were presented with 6-letter words that subtended 2.5^{o} of visual angle. The words were displayed for

150 ms at different positions across fixation. The task was to read each word aloud as quickly as possible. In addition to instructions emphasizing the importance of careful fixation, on 10 per cent of trials, single digits were presented at fixation for 80 ms, followed by an 80 ms mask (#). Participants were paid extra if they identified at least 80 per cent of the digits correctly. Naming responses showed the standard OVP curve, being fastest (500 ms) for fixation on the third letter (slightly to the left of centre) and slowest for fixation on the last letter (553 ms). Van der Haegen et al.'s Experiment 2 presented the same stimuli in such a way that letters never fell more than 1.5^o from fixation. Movements of the right eye were monitored directly. In the first part of the experiment, eye movements were simply monitored during stimulus presentation (the 'eye-monitoring condition'); in the second part of the experiment, conducted a week later, words were only presented when the eyes were fixating correctly (the 'eye position contingent condition'). There were no additional trials involving digits. Analysis of the eye fixation data showed that participants were fixated on the correct letter on 33.4% of trials in the eye-monitoring condition, and 71.9% of trials in the eye position contingent condition. Both conditions revealed a small tendency to fixate to the left rather than to the right of the designated fixation point, with an average leftward bias of 0.57 letter positions (0.16^o of visual angle) in the eye-monitoring condition, and 0.13 letters (0.04^o of visual angle) in the eye position contingent condition. Fixation fell within half a letter of the target location on 61.9% of trials in the eye-monitoring condition and 97.9% of trials in the eye position contingent condition. Overall naming latencies were longer (524 ms) in the eye position contingent condition than in the eye-monitoring condition (476 ms). Once again, naming was fastest for fixation on the third letter and slowest for fixation on the sixth letter. Importantly, there was no significant interaction between the type of eye movement monitoring and shape of the OVP curves, indicating that the nature of the OVP curve was similar in the eye-monitoring and eye position contingent conditions. A third experiment was the same as Experiment 2 except that only the dominant right eye was used (the left eye being covered with an eye patch). Error rates were higher and naming latencies longer than with the binocular presentation of Experiments 1 and 2, but the shape of the OVP curve was unchanged. In sum, the OVP data obtained by Van der Haegen et al. (in press) were essentially the same as those obtained by previous studies that used binocular presentation and 'traditional' methods of fixation control. The OVP curves were the same regardless of the form of eye movement control deployed, and regardless of whether presentation was binocular or monocular. These manipulations affected overall RTs and error

rates, but not the shape of the OVP curves. There is no reason to believe that the OVP results obtained by Brysbaert (1994) and Hunter et al. (2007), which lend support to the SFT, were in any way an artefact of inadequate fixation control.

4.2. EEG responses in Chinese readers.

Hsiao, Shillcock, and Lee (2007) presented right-handed Chinese participants with target words that were all composed of two characters. One of the characters comprising a word gave a clue as to the meaning of the word (the ‘semantic radical’) while the other gave a clue as to the pronunciation (the ‘phonetic radical’). Half of the words had the semantic radical on the left and the phonetic radical on the right (the most frequent pattern in Chinese). The other half of the words had the semantic component on the right and the phonetic component on the left (a less common arrangement). The words were presented centrally for 150 ms. The characters were all 0.6° x 0.6°, so fell well within foveal vision. Participants were required to hold a target word in memory for 1300 ms then compare it with a comparison word to decide whether the target and comparison words sounded the same. (Chinese contains many homophones that are written differently.) EEGs were recorded throughout. Hsiao et al. (2007) observed that for the words with the phonetic component to the right of fixation there was a stronger N170 (N1) effect in the left hemisphere than in the right hemisphere. The reverse was observed for words with the phonetic component to the left of fixation. If these two-character words presented entirely within the fovea were projected simultaneously to both hemispheres, as proposed by the BPT, then words with the phonetic component on the right or on the left should have been conveyed to both hemispheres simultaneously, in which case there is no reason why the strength of the N100 responses should depend on the location of the phonetic radical. SFT, in contrast, predicts that one character would be projected to one hemisphere and the other character to the other. Under such circumstances, lateralized EEG responses could depend on the relative positioning of the semantic and phonetic characters. In this case, the EEG response to the phonetic component of the word was stronger when that component fell to the right of fixation than to the left. According to SFT, a phonetic component presented to the right of fixation will project directly to the language-dominant left hemisphere where the phonological information it conveys will be extracted readily. A phonetic component presented to the left of fixation will be projected the non-dominant right hemisphere and will need to be transferred across the corpus callosum to the left hemisphere before its phonological content can be registered. The findings of Hsiao et al. (2007) are readily explained by SFT, and cannot be easily explained by the BPT.

4.3. Effects of the number of letters in a word that fall to the left or right of fixation.

A different approach to testing the predictions of SFT was taken by Lavidor, Ellis and colleagues (Ellis, Brooks, & Lavidor, 2005, Lavidor, Ellis, Shillcock, & Bland, 2001; Lavidor, Hayes, Shillcock, & Ellis, 2004). The starting point for those experiments was the observation that the magnitude of the RVF advantage for extrafoveal word recognition is not fixed, but varies with the characteristics of the words presented. The general form of the argument derived from SFT was to propose that if a factor has more of an effect on the recognition of words presented entirely in one visual field than the other (well away from the fovea), then the same factor may have differential effects on those portions of centrally-presented words that fall to one side or the other of the fixation point. For example, letter length affects recognition speed for familiar words in the LVF more than in the RVF (Ellis, 2004). Is it the case that recognition times for words presented centrally are more affected by the number of letters that fall to the left of the fixation point than by the number of letters that fall to the right? If they are, that would support SFT over BPT (which maintains that centrally-presented words are projected to both hemispheres and so will be processed by the language-dominant (usually left) hemisphere, with no need for callosal transfer)[3].

The first attempt to test this general line of reasoning was based upon the fact that if familiar words in normal formats (lower or upper case) are presented entirely in the LVF or the RVF, the magnitude of the RVF advantage varies with the number of letters in the stimulus words. Longer words generate larger RVF advantages because increasing letter length affects the speed and accuracy of processing LVF words more than RVF words (Bub & Lewine, 1988; Ellis, Young, & Anderson, 1988; Lindell, Nichols, & Castle, 2002; Young & Ellis, 1985). This holds

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[3] If BPT is correct, processing of central words should generally resemble processing of RVF more than LVF words (in people with left hemisphere language dominance).

true even when the spaces between letters in words are adjusted so that words containing different numbers of letters have the same physical length on the screen and on the retina, suggesting that the decline in performance with increased length in the LVF has to do with the numbers of letters in a word rather than any effects of acuity change that may result from longer words projecting further into the periphery (Bruyer & Janlin, 1989; Lavidor, Ellis, & Pansky, 2002).

Lavidor et al. (2001) tested the prediction derived from SFT that the speed of central word recognition should be more affected by the number of letters falling to the left of the fixation point than by the number of letters falling to the right. Five- and 8-letter words were presented to right-handed participants with the fixation point falling in one of two locations. The first location was between the second and third letters in words, which meant that the number of letters to the left of fixation in 5- and 8-letter words was constant at 2, while the number of letter falling to the right of fixation was either 3 (for 5-letter words) or 6 (for 8-letter words). The second fixation location was between the penultimate letter of a word and the letter preceding it. For 5-letter words that was between the 3rd and 4th letters, while for an 8-letter word it was between the 6th and 7th letters. For this location, the number of letters falling to the right of fixation was constant at 2 while the number of letters falling to the left of fixation was again either 3 or 6. The use of these two fixation positions made it possible to examine independently the influence of length variation to the left or right of fixation. None of the stimuli projected more than 0.8° from fixation, so all the stimulus words fell within the fovea. Lavidor et al. (2001) presented the words in a random order, interleaved with an equal number of 5- and 8-letter nonwords presented in the same way. The task was lexical decision: participants pressed one button as quickly as possible if the stimulus was a word and another if it was a nonword. The results showed that lexical decision speed was affected more strongly by variation in the number of letters falling to the left of fixation than by variation in the number of letters falling to the right. Figure 4A presents the results in such a way as to show the effect of variation in letter length on reaction times, measured as the percentage increase in RTs for longer compared with shorter words (i.e., the cost of increased letter length). The results for variation in the number of letters falling to the left of fixation (Central Lvar) or to the right of fixation (Central Rvar) in centrally-presented words come from Experiment 1 of Lavidor et al. (2001). The greater effect on lexical decision speed of left half variation in length than right half variation is apparent, and is mirrored in the results for words presented entirely in the LVF or RVF (data from the comparison of 4- versus 6-letter English words in Experiment 1 of Lavidor et al., 2002). SFT predicts that the number of letters falling to the left of fixation in foveated words will have more of an effect on word recognition than the number of letters falling to the right of fixation, which is what Figure 4A shows. BPT has no reason to predict that result.

Figure 4 about here

4.4. Effects of the number of orthographic neighbours aroused by that portion of a word that falls to the left or right of fixation.

The study by Lavidor et al. (2004) rested on a different set of findings; this time concerning the effect of 'orthographic distinctiveness' on the recognition of words presented in the LVF or RVF away from the fovea. One way of measuring the orthographic distinctiveness of a word is to count the number of other words that can be made by changing single letters. That number represents the number of close orthographic 'neighbours', and is known as the word's N count (Coltheart, Davelaar, Jonasson, & Besner, 1977). Lavidor and Ellis (2002-a,b) found that a word's N value (i.e., the size of its orthographic neighbourhood) had more of an effect on recognition speed in the LVF than in the RVF: lexical decision RTs were faster to high than to low N words in the LVF, while the effect of N in the RVF was not significant. In a study of lexical decision in Spanish, Perea, Acha and Fraga (2008) also found a facilitatory effect of N in the LVF, though in that study there was an inhibitory effect of N in the RVF (slower RTs to high N words than to low N words) rather than no effect.

Lavidor et al. (2004) extended the results of Lavidor and Ellis (2002-a,b) to the split fovea situation. If SFT is correct, word recognition speed may be more influenced by the number of orthographic neighbours aroused by that portion of a fixated word that falls to the left of fixation than by the number of neighbours aroused by the portion that falls to the right of fixation. Lavidor et al. (2004) selected 6-letter words which varied on the number of other 6-letter words that could be generated either by retaining the first three letters and changing the last three letters (referred to as 'lead neighbours'), or by retaining the last three letters while changing the first three (referred to as 'end neighbours'). For example, the lead neighbours of CASTLE, which share the first three letters, include CASHEW and CASINO, while the end neighbours, which share the last three letters, include BEETLE and SUBTLE. Words were chosen that had many or few lead neighbours, and many or few end neighbours. The four resulting word sets were matched on overall N. The words were presented in a lexical decision experiment with the fixation point falling in the middle of each word (or nonword), and with each stimulus subtending a visual angle of 1.1°. Figure 4B shows the results for centrally-fixated words which varied on the number of lead neighbours (Central Lvar) or the number of end neighbours (Central Rvar). For comparison, Figure 4B also the results for high and low N words presented entirely in the LVF or RVF (from Lavidor & Ellis, 2002-a). In each case, the effect of neighbourhood size is measured as the percentage increase in reaction times for words with few neighbours over words with many neighbours (i.e. the cost of having few neighbours). The greater effect of variation in the number of lead (left-half) neighbours than in the number of end (right-half) neighbours mirrors the greater effect of N for whole words presented in the LVF than in the RVF words (Lavidor & Ellis, 2002-a,b; Perea et al., 2008). That is as predicted by SFT. BPT has no reason to predict differential effects of the number of neighbours aroused by the letters that fall to the left or right of fixation.

4.5. Effects of case alternation applied to the portion of a word that falls to the left or right of fixation.

We noted above that word recognition in right-handed participants shows a substantial effect of length for words displayed entirely in the LVF but a much smaller (often non-significant) effect for words displayed entirely in the RVF. The implication is that the left hemisphere is better able than the right to process the component letters of words in parallel, reducing the differences in recognition speed between shorter and longer words (Ellis, 2004). That pattern only applies, however, to familiar words presented in a familiar format (i.e., normal, horizontal, lower or upper case presentation). If familiar words are presented in unfamiliar formats, such as vertically or in MiXeD cAsE, the pattern changes and comparable length effects are seen in both visual fields. That is because distorting the appearance of familiar words induces a sensitivity to word length in the RVF which is like that shown by words in the LVF under all presentation conditions (Fiset & Arguin, 1999; Lavidor & Ellis, 2001; Lavidor et al., 2002). The implication here is that parallel processing of the component letters of words by the left hemisphere depends on those words being presented in formats that the left hemisphere is skilled at dealing with. Presenting words to the left hemisphere in unusual formats causes the left hemisphere to process the component letters in a more serial fashion, which is how the right hemisphere processes all words, irrespective of format (Ellis, 2004).

SFT predicts that if the left hemisphere is more sensitive to format distortion than the right hemisphere, then distortion applied to those letters in a centrally-presented word that fall to the right of fixation should affect recognition speed more than distortion applied to those letters that fall to the left of fixation. Ellis et al. (2005) created 8-letter words in which case alternation was applied either to the first four letters (e.g., eXcHange) or the last four letters (e.g., infiNiTe). The words were presented centrally to right-handed participants in a standard lexical decision task with an equal number of similarly-manipulated nonwords. Presentation time was 150 ms and the fixation point fell in the middle of the word. The stimuli subtended an angle of 1.8°, so fell within the fovea. Figure 4C shows the impact of format distortion applied to those letters that fell to the left of fixation (Central Lvar) or to those letters that fell to the right of fixation (Central Rvar). For comparison, Figure 4C also shows the results for case alternation applied to whole words presented entirely in the LVF or RVF (6-letter words from Lavidor et al., 2002, Expt 1). Effects are again displayed as the percentage increase in reaction times for distorted over non-distorted words (i.e., the cost of case alternation). As with length and N variation, the effect of case alternation applied to the portion of a word that fell to the left or right of fixation mirrored the effects seen for words presented entirely in the LVF or RVF. This time, however, the effects were greater in the RVF and in the right halves of centrally-fixated words than in the LVF and the left halves. So, not all lateralized manipulations affecting recognition speed have stronger effects in the LVF where processing is generally slower. The results of Ellis et al. (2005) are as predicted by SFT and have no ready explanation under BPT.

The studies on neurologically-intact readers by Hunter et al. (2007) and Hsiao et al. (2007), combined with the results concerning the effects of length, N and case alternation in the left and right halves of words (Ellis et al., 2005; Lavidor et al., 2001, 2004), constitute the third line of evidence supporting our belief that SFT is worthy of serious consideration, and that a split fovea has consequences for normal reading.

5. Re-evaluating the criticisms directed against SFT

For a long time, SFT has been criticized only by reference to the empirical evidence provided by Huber (1962), Stone et al. (1973), Bunt and Minckler (1977), Bunt et al. (1977), and Leventhal et al. (1988). Although the critics usually include more recent articles (e.g., Gazzaniga, 2000; Lindell & Nicholls, 2003) to support their claims, these articles are simply reviews based on the older material. In section 2 (above) we gave our reasons for believing that such evidence is not incompatible with SFT, and that other, related evidence (Trauzettel-Klosinski & Reinhard, 1998; Reinhard & Trauzettel-Klosinski, 2003) positively supports SFT. In recent years, Jordan and colleagues have, however, reported new empirical evidence which in their view challenges the notion of a split fovea, particularly as applied to visual word recognition. In this section we will consider the extent to which those studies are genuinely problematic for SFT.

5.1. Failures to replicate the differential effects of the number of letters falling to the left or right of fixation in centrally-presented words.

Jordan, Paterson, and Stachurski (2009) and Jordan, Paterson, Kurtev, and Xu (in press) have presented a series of experiments which appear not to replicate the finding reported by Lavidor et al. (2001) that lexical decision performance is more affected by the number of letters falling to the left of fixation than by the number falling to the right. Jordan and colleagues claim that the differences in results between their studies and Lavidor et al. (2001) are due to the fact that their experiments controlled the gaze direction of participants more effectively than Lavidor et al. (2001) managed to do through simple instructions. At the same time, however, the experimental constraints imposed on the participants in the Jordan et al. studies meant that the accuracy of lexical decision responses was very low in some conditions (sometimes approaching chance) while reaction times were very long.

Jordan et al.'s (2009) Experiment 1 is presented as a direct replication of Lavidor et al. (2001), using the same materials and, as far as was possible, the same conditions of presentation. The results, however, were very different. Whereas Lavidor et al. (2001) found more of an effect of the number of letters falling to the left of fixation than to the right (see Figure 4A), Experiment 1 of Jordan et al. (2009) found no such differential effect. The only detectable effect in that experiment was a tendency for RTs to words to be faster when fixation fell towards the beginnings of the words than when it fell towards the ends (in line with the OVP effect shown in Figure 3; Hunter et al., 2007). The accuracy levels in that experiment were, however, much lower than in Lavidor et al. (2001), and the RTs were much longer. Thus, accuracy in Lavidor et al.'s experiment was 91% when fixation fell towards the beginnings of words and 86% when fixation fell towards the end. The corresponding accuracy levels in Jordan et al.'s (2009) Experiment 1 were 80% and 67%. These were lexical decision responses to stimuli that were half words and half nonwords, so chance was 50 per cent. The problem with low performance levels is that many of the 'correct' responses to words that enter into the analysis of reaction times will, in reality, be lucky guesses where the participant had little or no idea whether the stimulus was a word or not and just happened to press the right button. The inclusion of a significant proportion of 'lucky guesses' will add a great deal of noise to any analysis of RTs for supposedly 'correct' responses. Mean RTs for 'correct' responses to words fixated towards the beginning or the end in Experiment 1 of Jordan et al. (2009) were 769 ms and 815 ms respectively. In contrast, the corresponding RTs in Lavidor et al. (2001) were 428 ms and 449 ms, a full 350 ms or 80% faster than in Jordan et al. (2009).

Jordan et al.'s (2009) Experiment 2 was very similar to their Experiment 1 except that the position of eye fixations was monitored with an eye tracker. The pattern of results was similar to their Experiment 1, and therefore different from those of Lavidor et al. (2001). But accuracies were again substantially lower than in Lavidor et al., and RTs were again substantially slower (75% slower for fixations towards the beginnings of words and 94% slower for fixations towards the ends). Experiment 3 of Jordan et al. (2009) was like their first two experiments, except that this time the eye movement monitoring apparatus was used to ensure that stimuli were only presented when participants' right eyes were fixating at the desired location. Exposure durations were reduced to 50 ms from 150 ms (the exposure duration used by Lavidor et al., 2001, and Expts 1 and 2 of the same study). The resulting accuracy levels were 85% for words fixated towards the beginning and 77% for words fixated towards the end. The pattern of results was similar to that in Experiments 1 and 2 of the same study (i.e., different from Lavidor et al., 2001). Reaction times in this experiment were very slow indeed, being 89% slower than Lavidor et al. for words fixated towards the beginning and 98% slower (i.e., twice as long) for words fixated towards the end.

Jordan et al. (in press) report two more experiments using the Lavidor et al. (2001) stimuli and fixation positions. Presentation times were 50 ms (as in Jordan et al., 2009, Expt 3). Participants' non-dominant eyes were occluded using eye patches and stimuli were only presented when the dominant eyes were fixating correctly. Experiment 1 of this study used the same sized typeface as Jordan et al. (2009) while Experiment 2 used a larger typeface. Accuracy levels were somewhat better than in Jordan et al. (2009), though lexical decision accuracy for centrally-presented words fixated towards the ends was still only 69%. RTs were faster than in Jordan et al. (2009), but still more than 50% slower than in Lavidor et al. (2001). Curiously, there is clear evidence for a speed-accuracy trade-off between the two experiments in this study. The use of larger stimuli in Jordan et al.'s (in press) Experiment 2 increased the accuracy of responding to words but *slowed* RTs by 30-40 ms. Participants who were shown the larger stimuli seem to have taken the opportunity to respond more accurately than participants who saw the smaller stimuli, but they sacrificed speed in order to achieve those higher accuracy levels. In our experience, such speed-accuracy trade-offs are rare in studies of either central or lateralized word recognition. Importantly, the pattern of results in both of Jordan et al.'s (in press) experiments were the same as the pattern in the three experiments of Jordan et al. (2009), and therefore different from the pattern obtained by Lavidor et al. (2001).

5.2. Further replications of the differential effects of the number of letters falling to the left or right of fixation in centrally-presented words.

We are reassured in our belief that the results of Lavidor et al. (2001) are not entirely spurious because we know that similar patterns can be discerned in other studies (i.e., more of an impact on central word recognition of the number of letters falling to the left of fixation than the number of letters falling to the right). Ellis (2004) reanalysed data from Brysbaert (1994) who collected naming latencies from participants whose performance on three tests of lateralized perception indicated that they were left hemisphere dominant for language. The subset of naming RTs analysed by Ellis (2004) were for trials in which participants fixated on the first or last letters of Dutch words containing 3, 4, 5, 7 and 9 letters. When fixation was on the first letter, different numbers of letters fell in the RVF: when fixation was on the final letter, different numbers of letters fell in the LVF. Although the data in Brysbaert (1994) were not collected with such an analysis in mind, Ellis (2004) showed that naming speeds were more affected by the number of letters projecting to the left of fixation than by the number of letters projecting to the right, as reported by Lavidor et al. (2001).

Table 2 of Hunter et al. (2007) includes word naming RTs from German-speaking participants with left hemisphere language dominance (as determined by transcranial Doppler sonography). The naming RTs come from 3-, 5- and 7-letter words presented at different horizontal positions across fixation in a study that, like Brysbaert (1994), was concerned with optimal viewing positions for word recognition. Three-letter words fixated on the first letter have one letter at fixation and 2 letters extending into the RVF, while the same words fixated on the last letter have one letter at fixation and 2 letters extending into the LVF. Five-letter words fixated on the first or last letter have one letter at fixation and 4 letters extending into the RVF or the LVF, while 7-letter words fixated on the first or last letter have one letter at fixation and 6 letters extending into the RVF or LVF. By comparing mean RTs in those particular conditions we can see the effect of presenting words such that 2, 4 or 6 letters fall to the left or right of fixation, with a single letter at fixation and no letters in the opposite visual field. The results are displayed as the black bars in Figure 5 which shows that naming RTs were affected more by the number of letters extending into the LVF than by the number of letters extending into the RVF. That is the result of Lavidor et al. (2001) that was also detected by Ellis (2004) in the data of Brysbaert (1994).

Figure 5 about here

A similar analysis can be made by comparing RTs to 3-, 5- and 7-letter words fixated on either the second or the penultimate letter in the data of Hunter et al. (2007). The second and the penultimate letter are the same (middle) letter for 3-letter words, the second and fourth letters in 5-letter words, and the second and sixth letters in 7-letter words. In this comparison there is one letter at fixation, one letter to the left or right of fixation, and 1, 3 or 5 letters extending into the other visual field. The means are a completely different set from those employed in the previous analysis, yet the pattern is the same: naming RTs are affected more by the number of letters extending into the LVF than by the number of letters extending into the RVF (the white bars in Figure 5). The data in Figure 5 come from German not English or Dutch readers, and from naming rather than the lexical decision task used by Lavidor et al. (2001). Fixation was controlled by presenting digits which participants had to report very briefly (80 ms) at the fixation point once every 6 or 7 trials (on average). It is true that the longer words in both Brysbaert (1994) and

Hunter et al. (2007) projected beyond the fovea (to around 2.7° for the longest words in Brysbaert et al., 1995, and 3.5° for the longest words in Hunter et al., 2007), which makes them less than perfect for evaluating the SFT. We note, however, that SFT predicts continuity in the results obtained for foveal and parafoveal presentations (because *all* words and letters that fall to the left or right of fixation project only to the contralateral hemisphere, not just those stimuli that fall outside the fovea) where the BPT predicts discontinuity.

5.3. Why have different studies obtained different patterns of results?

Why then are the results of Jordan et al. (2009, in press) different from those of Lavidor et al. (2001), and different from the patterns discernible in the results of Brysbaert (1994) and Hunter et al. (2007)? Jordan and Paterson (2009) place the responsibility for the difference in findings firmly on the fact that the other studies failed to ensure accurate fixation with an eye tracker. However, Jordan and colleagues have never presented evidence indicating that monitoring fixation makes any difference to the pattern of results obtained in tasks where words are presented at fixation. On the contrary, when Van der Haegen et al. (in press) directly compared the OVP-curve under various conditions of fixation control, they failed to find any differences except for an overall increase in RT and error rate. Similarly, the attempted replications of Lavidor et al. (2001) by Jordan et al. (2009; in press) generated *exactly the same* pattern of results when fixation was unmonitored (as in Lavidor et al., 2001), when fixation was monitored with an eye tracker, when both eyes were open, when only the dominant eye was open, and when presentation was contingent on precise fixation. Monitoring fixation and using fixation-contingent presentation affected the overall speed and accuracy of responding in Jordan et al.'s studied, but did not change the pattern of results obtained. In addition, although Jordan et al. (2009) stressed the fact that in a simple monitoring condition fixation did not fall exactly on the fixation location on 42% of the trials, these deviations were rarely more than one letter position (i.e., less than 0.25°) to the left or to the right (cf. Van der Haegen et al., in press). Given their strong contention that precise fixation matters, it is a mystery to us why Jordan and colleagues have never reported analyses showing that errant fixations of up to one letter position drastically altered the pattern of results obtained, rather than just injecting a degree of noise into the data.

Our current best guess as to why the results Jordan et al. (2009; in press) differ from those of Lavidor et al. (2001), Brysbaert (1994), and Hunter et al. (2007) is that it has to do with overall performance levels (accuracy and RTs), not fixation monitoring. If we are to progress this debate, we first need to know that it makes a difference whether fixations are monitored precisely compared with alternative such as presenting occasional, small digits at fixation or simply impressing upon participants the importance of fixating carefully. If it can be shown that the results obtained with precise monitoring of fixation are different from those obtained using alternative methods (something which, we repeat, has yet to be demonstrated), then we need to know that results presented in support of SFT disappear when fixation is controlled *and* when performance levels are brought within the normal range for words presented at fixation, within the fovea.

Replication is vital in science. In other sciences, when a notable result is reported, other labs will attempt to replicate it as a matter of course. Psychology lacks a tradition of attempting to replicate important results, tending to rely too much on *p* values as indicators of reliability. Our concern is that Jordan and colleagues repeatedly adopt the tactic of pointing to a possible confound and using that as grounds to dismiss an empirical finding without ever explaining how the confound in question could bring about the disputed pattern of results (i.e., any results which support SFT). Exactly how could bias in eye movements induce a difference in OVP curves between left and right dominant participants (as in Figure 3)? What gaze bias would cause word recognition speed to be affected more by the number of letters to the left of fixation than by the number of letters to the right (Figure 4A)? What gaze bias would cause the number of ‘lead neighbours’ to affect recognition speed more than the number of ‘end neighbours’, or cause case mixing towards the ends of words to affect recognition more than case mixing towards the beginnings (Figs. 4B and 4C)? How would a gaze bias explain why Chinese words with the phonetic component to the right of fixation induce a stronger EEG response in the left hemisphere, whereas Chinese words with the phonetic component to the left of fixation induce a stronger ERP effect in the right hemisphere under conditions where the two forms of Chinese words were randomly intermixed (Hsiao et al., 2007)? These questions are never even posed by Jordan and colleagues, let alone answered. At the time of writing, Jordan and colleagues have failed to identify a single systematic bias in gaze direction that could explain any of the effects we have summarized above.

6. Re-considering the usefulness of the Reicher-Wheeler task in hemispheric and split fovea research

Many different tasks have been used to investigate central word recognition (Grigorenki & Naples, 2008; Lupker, 2008). Most of those tasks have then been borrowed by researchers interested in the word recognition capabilities of the two cerebral hemispheres (see Banich, 2004; Ellis, 2004). Jordan and colleagues have championed the use of the Reicher-Wheeler task in hemispheric research, including split-fovea research (e.g., Jordan, Patching, & Milner, 2000; Jordan, Patching, & Thomas, 2003; Jordan, Paterson, & Kurtev, 2009; Jordan, Paterson, & Stachurski, 2008). We believe, however, that the Reicher-Wheeler task has a number of shortcomings which limit its usefulness for addressing the questions of interest here.

The Reicher-Wheeler task is built around pairs of words that differ on a single letter (e.g., *beak, bean*). In a typical experimental trial, one of the two words is presented briefly to a participant. That single target word is followed by a pair of choice alternatives created by presenting the pair of letters which differentiate the two words, with the remaining letters replaced by dashes. For example, following the brief presentation of the target word *beak*, a participant would see three dashes then the letters *k* and *n* displayed one above the other. The participant's task is to choose which of the letters *k* or *n* occurred in that particular position in the target word. Presentation time of the targets is usually adjusted so that the overall performance level is around 66 per cent across all conditions. Reicher (1969), Wheeler (1970) and subsequent researchers showed that performance on the task is better if the stimuli are familiar words (e.g., *beak*, *bean*) than if they are letter strings which are unwordlike and hard to pronounce (e.g., *bqfk*, *bqfn*). This *word superiority effect* has been taken to imply the presence of top-down effects in which word-level representations influence the perception of the component letters of words. Explaining the presence of word superiority effects was considered an important requirement for the first generation of computational models of word recognition (e.g., McClelland & Rumelhart, 1981; Paap, Newsome, McDonald, & Schvaneveldt, 1982).

Jordan et al. (2008) questioned SFT on the basis of a study in which they presented four-letter words to the left or right of fixation, either in foveal vision (with their 'medial edge' at 0.15°, 0.25° or 0.35° from fixation) or in parafoveal vision (medial edge at 2.00°, 2.10°, or 2.20° from the fixation point). In an effort to equate foveal and extrafoveal performance levels, the words presented at the fovea were smaller (subtending a visual angle of 0.55°)

than the parafoveal words (subtending a visual angle of 1.10°). In a variant of the archetypal Reicher-Wheeler task, the briefly-presented target words were followed by a choice between two whole words presented centrally (not two letters accompanied by dashes as in the conventional form of the task). Jordan et al. (2008) found better performance on this task in the RVF than the LVF for parafoveal presentations but not foveal presentations. Performance within the fovea was symmetrical between presentations left and right of fixation. This, Jordan et al. (2008) argued, constituted evidence for a bilaterally projecting foveal region of at least 1-2°.

One major problem with the Reicher-Wheeler task is that it is performed off-line. Responses are not made to the target stimuli themselves in a way that would, for example, allow reaction times to be gathered that reflect processing as it happens (as in word naming or lexical decision). Instead, scores are based on the accuracy of choosing between two alternatives presented subsequent to the target. Typically, participants are under no time pressure to make their choice decisions: they can ponder as long as they like before deciding which of the two alternatives matches the briefly-presented target. The off-line, deliberative nature of responses in the Reicher-Wheeler task matters when it comes to interpreting the null findings of Jordan et al. (2008). SFT does not claim that interhemispheric transfer in healthy participants inevitably results in the incomplete or deficient transfer of information that could cause left foveal performance to be worse than right foveal performance. That should happen only in a participant with a split or badly-functioning corpus callosum. Figure 3 suggests that interhemispheric transfer in healthy participants introduces a time cost of only 20 ms. This is unlikely to be reflected in a decrement in performance accuracy in an off-line task such as the Reicher-Wheeler task. Hence, until the findings of Jordan et al. (2008) are repeated using on-line word processing tasks involving the measurement of reaction times to target stimuli, we do not regard them as compelling evidence against SFT.

There are other differences between performance on LVF and RVF words in the Reicher-Wheeler task compared with other, on-line processing tasks that may be important. For example, Jordan et al. (2000, Expt. 4) compared performance in the Reicher-Wheeler task for 4-letter words and unpronounceable nonwords (letter strings). The accuracy with which participants could indicate which of two letters had occurred in a specified position in the target stimulus was better for words than for letter strings when the target stimuli were presented in the RVF, but there was no significant difference between words and letter strings when they were presented as targets in the LVF. Jordan et al. (2000, p. 1204) concluded that, “The absence of even a slight word-nonword effect for LVF stimuli in our study suggests that words presented briefly to the right hemisphere were unable to make effective contact with any higher-order representations (i.e., for words or letter groups).” A similar insensitivity of the LVF to the normal superiority of words over unpronounceable nonwords can be discerned in the results of Jordan et al. (2003) and Jordan et al. (2008). In contrast to this evidence that LVF words may fail to engage lexical representations during the performance of the Reicher-Wheeler task, numerous studies involving naming or lexical decision have found lexical influences on the processing of LVF words. Thus, word frequency and imageability have been shown to affect the speed and accuracy of responses to LVF as well as to RVF words in naming and/or lexical decision (e.g., Boles, 1983; Chiarello, Liu, Quan, & Shears, 2000; Coney, 2005; Iacoboni & Zaidel, 1996; Scott & Hellige, 1998). This implies that the cognitive processes recruited in the performance of the Reicher-Wheeler task are not the same as those recruited in on-line word recognition tasks, particularly when words are presented in the left visual field beyond the fovea. These responses may be based on more low-level perceptual judgments which do not engage higher-level representations and which results in performance on familiar words that is indistinguishable from performance on unpronounceable letter strings[4].

In sum, the off-line nature of the Reicher-Wheeler task means that it is incapable of detecting effects that need to be measured in terms of costs to the speed of processing target stimuli. This, we suggest, may be why the study by Jordan et al. (2008) was insensitive to differences in responding to words that fell within the fovea but to the left or right of fixation. Brysbaert has argued in a number of papers that word naming is the simplest and most informative task for investigating issues of laterality and interhemispheric communication (e.g., Brysbaert, 1994; Brysbaert & Nazir, 2005; Hunter & Brysbaert, 2008-a,b; Hunter et al., 2007). Naming is on-line, is close to natural reading, and vocal responses can be timed with millisecond accuracy. Naming involves the mapping of orthography onto speech production processes which are clearly lateralized (Banich, 2004; Zaidel, 1998) and can be easily and reliably assessed with brain imaging (cf. Knecht et al., 2000).

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[4] Note that changing the case of letters between targets and probes does not prevent the use of low-level perceptual strategies in the Reicher-Wheeler task. Imagine, for example, that the target word was *beak* and that the participant was then offered the choice between ---K and ---N, or between BEAK and BEAN. In a situation where participants can take as long as they like to make a response, they only have to think whether or not the target word included an ascending letter (k) that projected above the rest of

7. Closing remarks

SFT is a relatively new arrival on the theoretical and empirical stage. There is much to be done before we will be in a position to know whether SFT, BPT or some third alternative provides the best explanation of the mapping between the retinae and the brain, and of the processing of stimuli that fall entirely or partially to the left or right of fixation. SFT has generated a range of novel and counterintuitive findings in relation to word recognition – observations that would not have been made without the prompting of the theory, but which now need to be accounted for by any satisfactory theory of visual word recognition. SFT has also stimulated significant theoretical developments; for example in the computational modelling work of Shillcock et al. (2000), Monaghan and Shillcock (2008) and Whitney (2000). We might take issue with aspects of those computational models, but that is not the point: the point is that they have inspired new thinking in an area of both theoretical and practical importance.

In contrast, nearly a decade of studies by Jordan and colleagues – from Jordan et al. (2000) to Jordan and Paterson (2009) – has focussed on questioning SFT data almost exclusively on the basis of inadequate fixation control. The resulting papers have been persistently negative in tone, content to point towards real or imaginary faults in other studies and to publish null results dressed up as failures to replicate effects under properly controlled conditions. Jordan and colleagues have never attempted to explain how the alleged faults of SFT experiments could generate the patterns of results upon which the claims of SFT are based, or how small biases in fixation location could generate those effects artefactually. Instead, they have been content to point out that the SFT is a minority position (as if that matters) and to imply that any apparent failure to replicate its predictions is enough to discredit the theory in its entirety.

SFT will not be the last word on the involvement of the hemispheres in perception and reading, but neither will BPT. The task right now is to decide which theory is leading us in the right direction. We thank Jordan and Paterson (2009) for stimulating us to conduct our own re-evaluation of the evidence for and against SFT. We look forward to

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the word. If it did, the answer is ---K / BEAK: if it did not, the answer is ---N / BEAN. The familiarity or otherwise of the word would not be expected to affect performance when such a perceptual strategy is employed.

the day when Jordan and colleagues employ BPT creatively to generate novel and original hypotheses which predict positive results (rather than null effects) that help discriminate BPT from SFT, and which the research community can sink its collective teeth into. In the meantime, we hope that readers of this article will be inspired to read the original articles reviewed by us and by Jordan and Paterson (2009), and to take their own unprejudiced, accurately-fixated look at whether the fovea is split and whether this has consequences for the way we recognise words in reading.

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Figure legends

Figure 1. Image from Trauzettel-Klosinski & Reinhard (1998) showing the retina of the participant, the fixation stimulus (the cross) and the stimulus presented (3 black dots against a red background presented for 120 ms; in the figure the dots are shown at an eccentricity of 4°). Participants had to indicate how many dots they saw on each trial (announced by an auditory signal). The inset (B) shows the criteria Trauzettel-Klosinski & Reinhard used. Scenarios (a) and (b) with far eccentricities were used to diagnose macular sparing or splitting. A person with macular splitting saw no dots (a), a person with splitting saw one dot. Scenarios (c) and (d) with close eccentricities were used to decide about a vertical strip of hemifield overlap: Without overlap, the persons sees no dots (c); with overlap the person sees all three dots (d). Source: Trauzettel-Klosinski & Reinhard (1998).

Figure 2. Amount of foveal sparing in hemianopia patients without macular sparing. This figure represents three possible scenarios of hemifield overlap. In the first scenario (A), there is a constant overlap of 0.5°. In the second scenario (B) there is a widening of the overlap in foveal vision, as claimed by Huber (1962). In the last scenario (C), there is an overlap of 0.5° in peripheral vision but not in central vision. Of the 34 eyes tested by Reinhard and Trauzettel-Klosinski (2003), 12 fell in scenario A and 22 in scenario C. No cases were observed of foveal sparing of the sort suggested by Huber (1962). Source: Figure 4 of Reinhard and Trauzettel-Klosinski (2003).

Figure 3. Word naming times relative to the group average for left dominant and right dominant participants as a function of the fixation position within the word. Participants with left speech dominance named foveally presented 4-letter words faster when they were presented in such a way that the participants were fixating on the first letter, whereas participants with right speech dominance had an advantage for words presented in such a way that participants were fixating on the last letter. Notice that the effect is a gradual one, not only present for fixations on the extreme letter positions but also for fixations on the second and the third letter. If the RTs are not corrected for the group averages, the curve of the rightdominant participants is higher than the curve of the leftdominant participants (see also Brysbaert, 1994). Because this between-group difference was far from significant due to the large variation within each group, it has not been retained in the figure, Source: Hunter et al. (2007).

Figure 4. Illustration of how the effects of letter length (4A), neighbourhood size (4B) and case alternation (4C) in those portions of fixated words that fall to the left or right of fixation mirror the effects seen for words presented entirely in the left or right visual field. LVF / RVF = words presented entirely in the left or right visual field, away from the fovea. Central Lvar / Central Rvar = central presentation with variation in length, neighbourhood size or

case alternation in that part of the stimulus word that falls to the left (Lvar) or right (Rvar) of fixation. **Fig. 1A**. Percent RT changes for LVF and RVF words is defined as (((LVF6 - LVF4)/LVF4) * 100) and (((RVF6 - RVF4)/RVF4) * 100) respectively, where LVF4, LVF6, RVF4 and RVF6 are the mean RTs for 4- and 6-letter lower case words presented in the LVF or RVF in Expt. 1 of Lavidor et al. (2002). Percent change as a function of length variation to the left or right of fixation in centrally-presented words is defined as (((Lvar8 - Lvar5)/Lvar5) * 100) and (((Rvar8 - Rvar5)/Rvar5) * 100) respectively, where Lvar5 and Lvar8 are the mean RTs for centrally-presented 5- and 8-letter words in Lavidor et al. (2001) when the words were positioned such that the variation in length occurred to the left of fixation, and Rvar5 and Rvar8 are the mean RTs for centrally-presented 5- and 8-letter words when the words were positioned such that the variation in length occurred to the right of fixation. **Fig. 1B**. Percent RT changes as a function of variation in number of orthographic neighbours (N). Mean RTs for whole words in LVF and RVF come from Expt. 1 of Lavidor and Ellis (2002-b) while mean RTs for variation in the number of neighbours for those letters that fall to the left or right of fixation in centrally-presented words come from Expt. 1 of Lavidor et al. (2004). **Fig. 1C**. Percent RT changes as a function of case alternation. Mean RTs for whole words in LVF and RVF come from Expt. 1 of Lavidor et al. (2002; 6-letter mixed and lower case) while mean RTs for variation in the number of neighbours for those letters that fall to the left or right of fixation in centrally-presented words come from Expt. 2 of Ellis et al. (2005; words left and right alternated *vs* lower case).

Figure 5. Word naming latencies for participants with left hemisphere language dominance, showing the effect for words presented at fixation of variation in the number of letters in one visual field when the number of letters in the opposite visual field is controlled (at 0 or 1). See text for details. Source: Hunter et al. (2007), Table 2.