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Reviews and perspectives

Re-evaluating split-fovea processing in word recognition: A critical assessment of recent research

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ABSTRACT

In recent years, some researchers have proposed that a fundamental component of the word recognition process is that each fovea is divided precisely at its vertical midline and that information either side of this midline projects to different, contralateral hemispheres. Thus, when a word is fixated, all letters to the left of the point of fixation project only to the right hemisphere whereas all letters to the right of the point of fixation project only to the left hemisphere. An informed assessment of research in this area requires an accurate understanding of the nature of the evidence and arguments that have been used to develop this "split-fovea theory" of word recognition (SFT). The purpose of this article is to facilitate this understanding by assessing recent published support for SFT. In particular, we assess (i) the precision with which experiments have been conducted, (ii) the assumptions made about human visual ability, and (iii) the accuracy with which earlier research has been reported. The assessment reveals shortcomings and errors that are likely to impact on an accurate understanding of research in this area and, therefore, on an accurate understanding of SFT.

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A major challenge for visual word recognition research is to delineate the hemispheric processing responsible for recognizing a word from its retinal image. It has been known for many years that a fundamental determinant of this processing is the anatomical arrangement of the human visual system which causes information in each visual hemifield to project to the contralateral hemisphere. Thus, when fixating the centre of the visual field, information in the left hemifield projects to the right hemisphere (RH) and information in the right hemifield projects to the left hemisphere (LH).

* Corresponding author. E-mail address: Prof.TimJordan@le.ac.uk (T.R. Jordan). The functional relevance of these contralateral projections for word recognition remains to be fully determined. However, numerous studies suggest that the two hemispheres process words in different ways (see Lindell, 2006, for a recent review) and these findings have inspired considerable debate about the hemispheric processing involved in word recognition when words are encountered at different locations in the visual field.

While it is well established that information presented to the left and right sides of each retina outside the fovea projects to each contralateral hemisphere (for reviews, see Gazzaniga, 2000; Jordan, Patching, & Milner, 1998; Jordan, Patching, & Milner, 2000), the projection of information in foveal vision (i.e., around the point of fixation) has recently become a matter of debate in word recognition research. At the origin of this debate is the long-accepted

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view that a sizeable area of overlap (typically, 1–3 degrees wide) exists at the centre of foveal vision such that information around the point of fixation projects (bilaterally) to both the LH and the RH (for relevant reviews, findings, and opinions, see e.g., Brandt, Stephan, Bense, Yousry, & Dieterich, 2000; Bunt & Minckler, 1977; Fendrich, Wessinger, & Gazzaniga, 1996; Gazzaniga, 2000; Leventhal, Ault, & Vitek, 1988; Lindell & Nicholls, 2003; Reinhard & Trauzettel-Klosinski, 2003; Stone, 1966; Stone, Leicester, & Sherman, 1973; Tootell, Mendola, Hadjikhani, Liu, & Dale, 1998; Tootell, Switkes, Silverman, & Hamilton, 1988; Trauzettel-Klosinski & Reinhard, 1998). In recent years, however, some researchers have promoted the contrasting view that a fundamental component of the word recognition process is that each fovea is divided precisely at its vertical midline and all information encountered right up to this midline projects (unilaterally) to the contralateral hemisphere (for reviews, see Lavidor & Walsh, 2004a: Lindell & Nicholls, 2003). According to this view, when a string of letters is fixated so that its retinal image straddles the vertical midline of each fovea, all letters to the left of the point of fixation project to the RH whereas all letters to the right of the point of fixation project to the LH (e.g., Shillcock, Ellison, & Monaghan, 2000; Shillcock & McDonald, 2005). Thus, if the stimulus "word" were fixated at the inter-letter space between "o" and "r", "wo" would project only to the RH and "rd" would project only to the LH. If this "split-fovea theory" of word recognition (hereafter SFT) is correct, different parts of fixated words would be processed (at least initially) by different hemispheres and this would represent a major contribution to our understanding of the processes responsible for word recognition.¹

The contribution of SFT to our understanding of word recognition will no doubt be revealed fully in due course. In the meantime, an accurate assessment of SFT requires an accurate understanding of the nature of the evidence and arguments that have been used to develop the theory. The purpose of this article is to facilitate this understanding by critically assessing the support for SFT that has been published in the literature in recent years. In particular, we assess (i) the precision with which experiments have been conducted in SFT research, (ii) the assumptions made about human visual ability by proponents of SFT, and (iii) the accuracy with which earlier research has been reported in the SFT literature. Thus, the aim of this article is to clarify the state of the science and to reveal some of the issues that should not be overlooked when determining the viability of SFT.

1. The precision of conducting SFT research

A major objective of research aimed at investigating split-fovea processing in word recognition is to establish precise relationships between retinal location and hemispheric processing. In particular, because a key aspect of SFT is the notion that different parts of a fixated word project to different hemispheres, the location of participants' fixations when a word is presented in an experiment is of paramount importance for research in this area. Indeed, so critical is the role of fixation location in SFT that, according to the theory, even small shifts in fixation from one inter-letter space to the next can alter dramatically the hemispheric processing available for a fixated word (e.g., Shillcock et al., 2000; Shillcock & McDonald, 2005). As an example of the importance attached by SFT to fixation location, a much-cited study by Lavidor, Ellis, Shillcock, & Bland (2001; see also Skarratt & Lavidor, 2006) draws on the notion that increasing the number of letters that project to each hemisphere affects RH processing but not LH processing (e.g., Ellis, Young, & Anderson, 1988; Young & Ellis, 1985). Accordingly, Lavidor et al. presented words so that the majority of letters were projected to either the left (yea|rn, lovelo|rn) or right (ex|cel, ex|orcise) of a central fixation point (designated here by |). In this way, word displays were designed to project variable numbers of letters (3 or 6) to either the left or right of fixation and, if SFT is correct, variable numbers of letters to the RH and LH, respectively. Lavidor et al. report that increasing the number of letters impaired performance only when this increase occurred to the left of fixation (i.e., yea|rn, lovelo|rn). Thus, according to the logic of this study, this finding indicates that letters to the left of fixation projected to the RH (because the number of letters affected performance) and letters to the right of fixation projected to the LH (because the number of letters did not affect performance) and so provides evidence of split-foveal processing of fixated words.

The requirement that participants fixate the designated location within each word (determined by a fixation point presented on the screen) is clearly critical for the logic of this research. However, Lavidor et al. (2001; see also a similar study by Skarratt & Lavidor, 2006) did not objectively monitor or control the location of participants' fixations and opted only to instruct participants to fixate the required fixation location. Unfortunately, it has been known for several decades that participants often have great difficulty monitoring and controlling their own eye movements when attempting to fixate a specified location and instructions alone do not ensure precise fixation in studies of word recognition (for reviews, see Gazzaniga, 2000; Jordan et al., 1998; Jordan et al., 2000; see also Anliker, 1977; Batt, Underwood, & Bryden, 1995; Findlay & Kapoula, 1992; Jones & Santi, 1978; Jordan & Patching, 2006; Jordan, Patching, & Thomas, 2003a; Jordan, Patching, & Thomas, 2003b; Patching & Jordan, 1998; Sugishita, Hamilton, Sakuma, & Hemmi, 1994; Terrace, 1959). Indeed, as an indication of the problem this presents for split-fovea research, a recent study (Jordan, Paterson, & Stachurski, 2009) used the same stimuli, displays and procedures as Lavidor et al. (2001) but also an eye-tracker to reveal the actual locations of fixations made by participants who, following the original study, were only instructed (but instructed emphatically) where to fixate. The findings revealed that participants failed to fixate the designated inter-letter space on approximately 50% of trials, and inaccurate fixations fell at least 0.25 degrees (over 2 letters) and up to 1 degree (more than the width of a complete word) away. The frequency and extent of these inaccurate fixations indicate that the intended (and critical) projection of letters to the left and right of fixation was severely compromised and cast considerable doubt on the notion that the findings of Lavidor et al. provide support for SFT. Indeed, over the three experiments conducted in their study, including an experiment where fixations were controlled using an eye-tracking device, Jordan et al. found no evidence to support the findings of Lavidor et al., even when accurate fixations were ensured and even when different stimulus exposure durations (50 and 150 ms) were used. Instead, each experiment showed that word recognition was simply better when fixations were made near the beginning of words rather than the end, and so replicated the well-established "optimal viewing position" effect previously reported in the literature (e.g., O'Regan, 1981; O'Regan & Levy-Schoen, 1987; O'Regan, Lévy-Schoen, Pynte, & Brugaillère, 1984; Stevens & Grainger, 2003). As Jordan et al. concluded, not only were Lavidor et al.'s findings not replicated but also the findings that were obtained are readily explained by established effects of fixation location on word recognition without the need to involve putative influences of split-foveal processing.

Jordan, Paterson, and Stachurski's (2009) re-evaluation of Lavidor et al.'s (2001) findings used the procedure of presenting stimuli binocularly (i.e., as in normal viewing) because this is the procedure that Lavidor et al. adopted (see also Skarratt & Lavidor,

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¹ It should be pointed out that the notion of split-fovea processing in word recognition is not new. For example, it was considered, investigated, and rejected many years ago by Mishkin and Forgays (1952).

2006). As we describe in more detail later in this article, this procedure has its own complications for SFT (and for assessments of the viability of the theory) because disparities often occur between the locations fixated by each eye during binocular viewing (for a review, see Kirkby, Webster, Blythe, & Liversedge, 2008). Accordingly, further research was conducted using fixation-controlled monocular presentations (Jordan, Paterson, Kurtev, & Xu, in press-a) and this replicated the findings of Jordan, Paterson, and Stachurski (2009), indicating further that the findings of Lavidor et al. are not reliable. Moreover, over both of these studies, Jordan and colleagues found that despite conducting a total of five experiments using numerous participants, each screened for normal reading and normal acuity (this was especially necessary because the stimuli used by Lavidor et al. were physically very small), the overall levels of reaction times and error rates reported by Lavidor et al. could also not be replicated, despite often employing stimuli physically larger than those used by Lavidor et al. (including stimuli subtending visual angles that approximated those encountered in normal reading). In particular, although Lavidor et al. report reaction times averaging about 440 ms and error rates averaging about 10%, our experiments using the same very low frequency 5- and 8-letter words (mean occurrence 4.7 per million) revealed reaction times averaging no lower than 670 ms and error rates averaging no lower than 16%. These differences do not appear to be due to stimulus exposure duration because Jordan, Paterson, and Stachurski (2009) obtained similar levels of reaction times and error rates when stimuli were presented for 50 and 150 ms (as in Lavidor et al.'s study). It is also unlikely that they reflect the use of eye-tracking control because Jordan, Paterson, and Stachurski (2009) obtained similar levels of reaction times and error rates with and without eye-tracking control. Indeed, the values for reaction times and errors rates Jordan and colleagues obtained in their studies resonate with the findings of other studies in the literature using very low frequency words (e.g., Allen, Smith, Lien, Grabbe, & Murphy, 2005; Allen, Smith, Lien, Weber, & Madden, 1997; O'Regan & Jacobs, 1992; Perea & Pollatsek, 1998; Sears, Campbell, & Lupker, 2006) and, indeed, resemble the findings of the similar study by Skarratt and Lavidor (2006) who also used very low frequency 5- and 8-letter words (mean occurrence 4.4 per million) and who also found much longer reaction times (mean 660 ms) and error rates (mean 18%) than those reported by Lavidor et al. Thus, although the findings obtained by Jordan and colleagues have consistently shown no support for the proposals of either Lavidor et al. or Skarratt and Lavidor, it is unlikely that these findings were due to abnormalities in performance.²

The fixation errors observed by Jordan, Paterson, and Stachurski (2009) occurred more or less equally to the left and right of the required fixation location. Thus, it may be tempting for some researchers to argue that such fixation inaccuracy provides only "noise" in an experiment (although defining approximately 50% of trials as noise would clearly present further problems of interpretation). Unfortunately, inaccurate fixations are often *not* distributed

equally to each side of the central fixation point but, instead, show systematic biases to the left or right (e.g., Batt et al., 1995; Findlay & Kapoula, 1992; Jones & Santi, 1978; Jordan et al., 1998; Jordan & Patching, 2006; Jordan et al., 2003a; Jordan et al., 2003b; Terrace, 1959). Indeed, following publication, further analyses of the data of Jordan, Paterson, and Stachurski revealed some support for the pattern of effects reported by Lavidor et al. (2001) only when inaccurate fixations occurred to the right of the required fixation location, suggesting that the findings reported by Lavidor et al. were contaminated substantially by a rightward fixational bias. (We are currently investigating the effects of fixational biases further). Consequently, although it may be tempting to think that inaccurate fixations can be safely ignored in experiments designed to investigate SFT, the reality is that not knowing where participants are fixating on each trial makes the link between word recognition performance and hemispheric asymmetries unacceptably weak. Whereas SFT research would be much easier to conduct if participants produced accurate fixations "on request," the clear indication is that investigating hemispheric asymmetries using stimuli presented either side of a designated fixation location without using an eye-tracker to monitor and control fixation location is likely to produce substantial amounts of misleading data.

Eye-trackers are used widely in many areas of word recognition and laterality research to monitor and control fixation location (e.g., Findlay & Kapoula, 1992; Gazzaniga, 2000; Jordan et al., 1998; Jordan et al., 2000; Jordan & Thomas, 2007; Liversedge & Findlay, 2000; Rayner, 1998) and offer an excellent means of monitoring and controlling fixation location in SFT research. In particular, a fundamental assumption of SFT is that consistent, precise fixation of a specified location within a word is a normal determinant of word recognition that defines the contributions of LH and RH processing. Consequently, it should be obvious that using an appropriate eye-tracking system to assess the consistency and precision with which a designated location is fixated in an experimental display can provide considerable insight into the validity of SFT. Moreover, by using an eye-tracker linked to a fixation-contingent display (for details of this procedure, see e.g., Gazzaniga, 2000; Jordan & Patching, 2006), stimuli can be presented only when accurate fixation is taking place, which then ensures that stimuli are presented in the appropriate retinal location and, in particular, that appropriate stimulus information is presented to the left and right of fixation.

Unfortunately, the critical importance of ensuring fixation precision is overlooked in the majority of articles promoting SFT, both empirical and review (e.g., Brysbaert, 1994, 2004; Brysbaert, Vitu, & Schroyens, 1996; Ellis, 2004; Hsiao & Shillcock, 2005; Hsiao, Shillcock, & Lavidor, 2006; Hsiao, Shillcock, & Lee, 2007; Hunter, Brysbaert, & Knecht, 2007; Lavidor, 2003; Lavidor et al., 2001; Lavidor, Hayes, Shillcock, & Ellis, 2004; Lavidor & Walsh, 2003; Lavidor & Walsh, 2004a; Lavidor & Walsh, 2004b; Lavidor & Whitney, 2005; Martin, Thierry, Démonet, Roberts, & Nazir, 2007; Shillcock et al., 2000; Shillcock & McDonald, 2005; Skarratt & Lavidor, 2006; Van der Haegen, Brysbaert, & Davis, 2009; Whitney, 2004; Whitney & Lavidor, 2004; Whitney & Lavidor, 2005; see also Lavidor & Bailey, 2005). Indeed, although proponents of SFT rightly place considerable emphasis on the importance of fixation location in experiments where a word is presented close to or straddling a designated fixation location, the experiments conducted in the empirical articles listed above (and thereafter cited in reviews) relied heavily on only instructions where to fixate and did not monitor the fixations that were actually made by participants or ensure that the required fixations actually occurred (i.e., by using an eye-tracking device). Thus, although the clear objective (and claim) of each of the experiments was to project specific information to a particular hemisphere by ensuring that participants were precisely fixating the required location when each stimulus

² Another interesting discrepancy between the findings of Jordan and colleagues and the findings of Lavidor et al. (2001) and Skarratt and Lavidor (2006) is that Jordan and colleagues found evidence for the optimal viewing position with all word stimuli whereas Lavidor et al. and Skarratt and Lavidor found that performance for 5-letter words remained the same irrespective of whether the designated fixation location was at the beginning or end of these stimuli. This finding is largely ignored by Lavidor et al. and by Skarratt and Lavidor but indicates that the well-established effect of optimal viewing position (which, in contrast to the specific fixation requirements of SFT, requires only that fixation occurs in a broad area between the beginning and the centre of words) was compromised and, therefore, that normal processes of word recognition may not have been established in either of these studies. Thus, the findings of Lavidor et al. (and Skarratt and Lavidor) may have been impossible to replicate because both studies produced fundamentally abnormal patterns of word recognition performance.

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was presented, considerable empirical evidence indicates that, in the absence of appropriate technological control, fixation of these locations is unlikely to have occurred on even the majority of trials.³

The problems produced for the study of SFT by lack of fixation precision are not restricted to ensuring the accurate projection of information to a specific hemisphere. In particular, inaccurate fixations in SFT research may induce processing differences between information presented to either side of a designated fixation point because of imbalances in the basic visual processing of this information (we touched on this problem earlier in our re-evaluation of the findings of Lavidor et al., 2001 by further analyses of the data of Jordan, Paterson, & Stachurski, 2009). Of particular concern is that assessments of the physiology of the human visual system (e.g., Green, 1970; Hilz & Cavonius, 1974; Jones & Higgins, 1947; Østerberg, 1935; Polyak, 1941; Riggs, 1965; Weymouth, Hines, Acres, Raaf, & Wheeler, 1928) indicate that cone receptor density changes rapidly over the central 2 degrees, falling approximately fivefold, with inevitable consequences for visual processing. Consequently, if fixations in studies of SFT land to one side of a designated fixation point, by even a few minutes of arc, information to the left and right of this point may exert different effects on word recognition performance because of differences in the visibility of this information rather than asymmetries in hemispheric processing (for further discussions, see e.g., Jordan et al., 1998, 2000, 2003a,b; Jordan & Patching, 2006; Patching & Jordan, 1998). In this way, information in a stimulus that is simply more visible to participants may be processed more readily, and this may lead to the spurious interpretation that participants' performance reflects spatially divided access to hemispheric processes and, as a consequence, support for SFT. Indeed, following the findings of Jordan, Paterson, and Stachurski (2009), an imbalance of this type produced by a rightward fixational bias may have contributed to the finding of Lavidor et al. (2001) that varying the number of letters to the right of fixation did not affect performance and may explain why this pattern of effects disappeared when accurate fixation occurred.

A small number of studies promoting SFT do report using an eyetracker to assess and control fixation location (at the time of writing, we can find four in the literature: Ellis. Brooks. & Lavidor. 2005: Lavidor & Ellis, 2003; Lavidor, Ellison, & Walsh, 2003; Whitney & Lavidor, 2004). However, in view of the critical role assigned to fixation location by SFT, these studies fall considerably short of providing the methodological exactitude required for this area of research. Ellis et al. (2005) report the following: "Participants' eye movements were monitored by an infra-red eye-tracker (Toolbox by Cambridge Research Ltd.) with a sampling rate of 1000 Hz and spatial resolution of 15 min of arc. The eye-tracker was interfaced with a Pentium computer which collected the eye position data. Eye movements were recorded from the onset of the 500 ms fixation cross through the 150 ms target presentation, and for an additional 150 ms so that a total of 800 ms in each trial were recorded (each trial lasted 500+150+150ms). Trials were eliminated if fixation was not stable throughout the 800 ms recording period." (p. 1131).

A likely interpretation of this report by a reader is that central fixation was ensured on the vast majority of trials. However, it is far from clear that this actually happened in the experiment. The eye-tracking system used to ensure central fixation in this study does not function as the authors report (Cambridge Research Systems, personal communication). In particular, the system has a sampling rate of just 50 Hz (not the 1000 Hz stated) and a theoretical spatial resolution of between 15 min and 30 min, although the real resolution is likely to be much lower in an experiment (i.e., when tracking the actual eye movements made by participants; Cambridge Research Systems, personal communication). Without accurate information about the spatial resolution of the device actually in use, supported by information about the procedure used to obtain this resolution, the information provided in this article actually provides no indication that the eye-tracker was ensuring fixation of the required location. Indeed, in view of the imperfect fixation abilities of human observers we have already described, it is unlikely that fixation would have remained stable throughout the 800 ms period on any trial, suggesting that the fixation accuracy implied in this article reflects a spatial resolution that was sufficiently "slack" to provide an impression of stability (see Jordan & Patching, 2006). In addition, the study provides no indication that fixations actually occurred at the required location on each trial, only that fixations were "stable". Using an eye-tracker to ensure that fixations were stable but not necessarily in the correct location would be of little value for research where fixation location is so critical, but no indication of where participants were actually fixating on each trial is provided by the authors.

Lavidor and Ellis (2003) report using an eye-tracker made by the technical unit of the psychology department where the research was conducted. A great deal of information is provided about the hardware characteristics of the eye-tracker but information about its spatial and temporal resolution (either theoretical or in operation) and the accuracy of participants' fixations is absent. Eye-trackers vary considerably in their spatial and temporal abilities and require careful and accurate setting up and calibration if they are to operate optimally (or even adequately). Thus, as in the study by Ellis et al. (2005), without accurate information about the spatial and temporal resolution of the device in use, including information about the procedure used to obtain this precision, it is impossible for readers to determine that the eye-tracker was ensuring fixation of a particular location, despite the critical role assigned to fixation location in SFT research.

In a similar vein, Lavidor et al. (2003) report using a Skalar IRIS eye-tracker with a spatial resolution of 2 min of arc. However, this figure is only the manufacturer's statement of the theoretically optimal abilities of the hardware characteristics of the tracker which indicates the noise generated by the system and does not refer to the actual (lower) resolution of the equipment in use (i.e., when actually tracking the eyes of participants in an experiment; Skalar, personal communication; Cambridge Research Systems, personal communication). As a consequence, the real operational accuracy of the eye-tracker is not reported. This problem is compounded by Lavidor et al.'s claim that when participants were instructed to fixate a central fixation point, fixations outside the reported 2 min window occurred on only 0.09% of all trials. In view of the well-established limitations of human fixation ability that we have already described (see also the next section) and the inappropriate presumption of a 2 min spatial resolution for the eye-tracker, Lavidor et al.'s claim of near-perfect fixation accuracy provides an implausible indication of the actual fixation accuracy of participants in this study. Similar problems exist in the study by Whitney and Lavidor (2004) in which the only relevant information provided is that "Participants' eye movements were monitored by an infra-red eye-tracker, and were recorded for the first 700 ms of each

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³ In an attempt to overcome effects of fixation error, some studies (e.g., Brysbaert, 1994; Hsiao & Shillcock, 2005; Hsiao et al., 2006; Hsiao et al., 2007; Hunter et al., 2007) have used a secondary fixation task requiring identification of a stimulus (e.g., a digit) presented at the required fixation location. However, accurate performance on a secondary fixation task does not require accurate fixation, does not ensure fixation accuracy, and may contaminate performance on the primary task (i.e., word recognition; see e.g., Jordan et al., 1998, for review and discussion). In fact, recent empirical evidence reveals that when a secondary fixation task is used to control fixation accuracy in a classic SFT paradigm, accurate fixation occurs on only 25% of trials and this level of accuracy is no better than when no secondary task is used (Jordan, Paterson, Stachurski, Kurtev, & Xu, 2007; Jordan, Paterson, Kurtev, & Xu, in press-b).

trial" (p. 1685). Thus, the accuracy with which fixation location was actually measured is again not reported, and yet the authors claim that fixation remained stable on the fixation cross throughout the first 700 ms of each trial for all but 3% of word displays and 5.1% of nonword displays. However, resonant with the problems associated with the claims of Ellis et al. (2005) described earlier, the imperfect fixation abilities of human observers make it unlikely that fixations would have remained stable throughout 700 ms on any trial, suggesting that the fixation accuracy implied in this article reflects the use of a spatial resolution for eye-tracking that was sufficiently generous to provide an impression of fixation constancy. In sum, because of the critical role assigned to fixation location by SFT, the absence of accurate, appropriate information about the temporal and spatial resolution of the eye-tracking system in operation or the procedures used to ensure fixation accuracy make the implied indications of fixation precision in each of these four studies meaningless and misleading to readers, and raise concerns over the technical precision with which the experiments reported were actually conducted.

Unfortunately, the critical emphasis that SFT places on the role of fixation location when accounting for hemispheric processing in word recognition means that accurate fixation of a designated location is no less crucial when other techniques are included to assess hemispheric involvement. For example, notwithstanding the substantial problems of ensuring fixation accuracy already described, some studies supporting SFT have also included transcranial magnetic stimulation (e.g., Hsiao et al., 2006; Lavidor & Walsh, 2003; Lavidor & Walsh, 2004b; Lavidor et al., 2003; Skarratt & Lavidor, 2006), electroencephalography (e.g., Hsiao et al., 2007; Martin et al., 2007) and functional transcranial Doppler sonography (e.g., Hunter et al., 2007) in attempts to provide evidence of the precise division in LH and RH processing proposed by SFT. However, because divided hemispheric processing at the point of fixation is so fundamental to the SFT account, these technologies can provide support for SFT only if fixation location is known because only then can accurate inferences be drawn between the presentation of information either side of this location and its effect on LH and RH activity. Unfortunately, and as we have already described, the procedures and methodology actually used indicate that it is unlikely that any of these studies actually ensured accurate fixation.

The problem of accurately determining effects of fixation location in SFT research is often complicated further by the use of stimuli that exceed the area of foveal vision. In particular, since the notion that unilateral contralateral projections exist outside foveal vision is well-established and not contentious (for a review, see Gazzaniga, 2000), support for the view that unilateral contralateral projections affect word recognition right up to the point of fixation (i.e., as SFT proposes) would be more credible if evidence for this division was obtained using stimuli that did not extend from fixation into extrafoveal locations (e.g., beyond a maximum of 1.5 degrees each side of fixation). Lavidor et al. (2001) report using stimuli that could fit entirely within foveal vision. However, in addition to the problems of ensuring fixation accuracy already described, several studies reporting empirical support for SFT have used stimuli that exceeded the physical dimensions of each fovea, making it impossible to determine whether the effects observed when stimuli were presented either side of a fixation point were due to influences of unilateral projections in foveal vision rather than unilateral projections in extrafoveal locations (e.g., Brysbaert, 1994; Brysbaert et al., 1996; Hunter et al., 2007; Martin et al., 2007; see also Brysbaert, 2004; Ellis, 2004). For example, Brysbaert et al. (1996) investigated recognition of words presented at different eccentricities around a central fixation point. Across the experiment, words were offset to the left or right of the fixation point so that they either straddled the point at various locations or were

shown entirely to the left or right of the fixation point in nearby locations. The findings showed a word recognition advantage when most of the letters in a word, or words in their entirety, were shown to the right of the fixation point, and these effects were interpreted as evidence for unilateral projections to LH and RH processes on either side of fixation due to split-fovea processing. Using a similar technique, Brysbaert (1994) and Hunter et al. (2007) investigated word recognition in participants who were either LH or RH dominant for language processing. The findings from these studies showed a processing advantage when most or all of the letters in a word were shown to the right of the fixation point but only for participants with typical (i.e., LH dominant) hemispheric lateralisation. Consequently, according to Brysbaert (1994) and Hunter et al. (2007), word recognition in these studies was determined by the dominance of the hemisphere to which letters to the left and right of fixation were projected and this was consistent with split-fovea processing.

However, Brysbaert (1994) presented stimuli of 3, 4, 5, 7, and 9 letters in length and only stimuli of 3 and 4 letters were sufficiently physically small to always be shown entirely within foveal vision. For all other lengths, stimuli frequently exceeded the area of foveal vision (extending up to 3 degrees from the designated fixation point), making it unclear how effects of presenting stimuli to the left and right of the designated fixation point reflected the influence of unilateral projections in foveal, rather than extrafoveal, locations. Similarly, Brysbaert et al. (1996) used stimuli of 3, 5, and 7 letters but, in line with the study by Brysbaert (1994), only 3-letter stimuli were sufficiently physically small to always be shown entirely within foveal vision and all other stimuli frequently exceeded this area. Hunter et al. (2007) do not report the physical size of the stimuli used in their study and so provide no indication of the extent to which stimuli were presented in foveal and extrafoveal locations. But since this study is reported as a replication of Brysbaert's (1994) study using only different methods of determining hemispheric asymmetry, the indication is that similar problems of disentangling effects of foveal and extrafoveal projections still existed.

Most recently, Martin et al. (2007: see also Martin, Nazir, Thierry, Paulignan, & Demonet, 2006) examined electroencephalographic activity of participants who were presented with 5-letter words that straddled a central fixation point at various locations. Martin et al. found that when either the first or last letter coincided with the fixation point so that stimuli were presented almost entirely to either the right or left of the fixation point, the P1 component of the event related potential record peaked over the contralateral hemisphere before the ipsilateral hemisphere, indicating unilateral contralateral projections. When any other letters coincided with the fixation point, and so stimuli extended to both sides of the required fixation location, the P1 peaked at about the same latency over both hemispheres, indicating simultaneous projections to both hemispheres. According to the interpretation presented in this study, this pattern of effects indicated a division in hemispheric processing at the point of fixation, and so provides support for SFT. However, the stimuli used in this experiment subtended 6.65 degrees (5-letter words would subtend about 1.25 degrees in normal reading; e.g., Rayner & Pollatsek, 1989), and so more than 75% of each stimulus could have been presented in extrafoveal locations when either the first or last letter coincided with the fixation point. Moreover, such was the considerable physical size of the stimuli used that when any other letter position (2-4) coincided with the fixation point, stimulus information could have been presented simultaneously in extrafoveal locations on both sides of the fixation point. Consequently, although evidence of unilateral activation was observed only when stimuli were presented almost entirely to either the right or left of the fixation point, it is far from clear that this pattern of effects was due to a split in foveal processing and not

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to the inadvertent presentation of stimuli in extrafoveal locations. Consequently, the use of over-sized stimuli makes it impossible to determine whether the effects observed were due to the influence of unilateral contralateral projections in foveal vision (as SFT proposes) rather than well-established unilateral contralateral projections in extrafoveal locations. Indeed, in a recent study (Jordan, Paterson, & Stachurski, 2008; see also Jordan, Paterson, & Kurtev, 2009), words were presented to the left or right of fixation either entirely in extrafoveal locations or entirely within foveal vision, and fixation accuracy was controlled using an eye-tracker linked to a fixation-contingent display. A LH advantage was observed for words presented in extrafoveal locations (the "classic" LH advantage) but no hemisphere advantage (left or right) was observed for words presented within the fovea. Thus, when the problem of straying into extrafoveal locations was avoided for foveal displays, no evidence of a role for split-foveal processing in word recognition was obtained.

Stimuli that fit entirely within the fovea clearly offer an important way of determining the validity of SFT, and researchers can make good use of the fact that visibility in the visual field is not determined by absolute size but by scaling (i.e., size and retinal location). Thus, overall word visibility can be held constant across different retinal eccentricities by appropriate changes in font size, and this draws on standard, well-established psychophysical findings and practice (e.g., Drasdo, 1977). However, this approach should not be confused with studies of hemispheric asymmetry which investigate the effects of changing stimulus visibility by presenting different font sizes in constant hemifield locations (e.g., Pring, 1981). As the studies by Jordan et al. (2008) and Jordan, Paterson, and Kurtev (2009) demonstrate, when levels of stimulus visibility are matched across foveal and extrafoveal locations, important differences in the involvement of hemispheric asymmetries can be revealed.

The problems associated with the use of over-sized stimuli to investigate hemispheric asymmetries in foveal word processing are exacerbated in some studies (e.g., Brysbaert, 1994; Hunter et al., 2007) by the use of naming as a measure of word recognition performance. In particular, because speech production in the vast majority of individuals is lateralised to the LH, naming can produce a spurious advantage for information projected to the LH in experiments merely because this information is projected to the hemisphere responsible for producing a response rather than because this hemisphere is superior for recognizing that information. A confound of this kind may have contributed to the apparent right hemifield advantage observed for the LH dominant individuals investigated by Brysbaert (1994) and Hunter et al. (2007) and, indeed, may have contributed to the different effects produced by individuals showing LH and RH dominance in those studies. Recall that Brysbaert (1994) and Hunter et al. (2007) investigated word recognition in participants who were either LH or RH dominant for language processing and found a performance advantage when most or all of the letters in a word were shown to the right of the fixation point rather than the left, but only for participants with typical (LH dominant) hemispheric lateralisation. According to the logic of Brysbaert (1994) and Hunter et al. (2007), performance was determined by the word recognition dominance of the hemisphere to which letters to the left and right of fixation were projected. However, since both studies used naming, a major component of this hemispheric dominance may actually have been response production rather than word recognition. Thus, when participants were (atypical) RH dominant for language, the dominance of information to the right of fixation observed with typical LH dominant participants may have disappeared because this information was no longer projected to the hemisphere responsible for producing a response.

This problem of interpretation is clearly relevant when stimuli extend outside the fovea but could also occur for stimuli presented within foveal vision if an anatomical split in foveal processing actually exists along the lines proposed by advocates of SFT but which is not functional for word recognition. For example, even if human foveae are split anatomically, the transmission of information between the two hemispheres may be sufficiently rapid to obviate a functional role for this anatomical divide (e.g., Dehaene, Cohen, Sigman, & Vinckier, 2005). However, if naming is used to assess the existence of a functional split, a finding of dominance for foveal information presented to one side of fixation (typically, to the right) may imply a functional split in hemispheric word recognition but may actually reflect a functional split in hemispheric naming ability. Indeed, naming may be a confound generally in SFT research (e.g., Hsiao & Shillcock, 2005) because individuals taking part in these studies are usually selected to be LH dominant and appear to produce various advantages for information presented to the right of fixation and yet no account is taken of the systematic imbalance in hemispheric processing and overt performance that naming may produce in such experiments.

2. The assumptions made about human visual ability

So, despite the critical role assigned to fixation location by SFT, the use of appropriate eye-tracking procedures to determine the locations actually fixated is rare in studies reporting evidence supporting SFT and, when eye-tracking has occurred in these studies, its actual contribution to fixation accuracy is far from convincing. Moreover, many studies have compounded this problem by using stimuli that extended into extrafoveal locations, often substantially. However, the absence of adequate fixation control in SFT research belies a critical assumption made by proponents of SFT about the role of human visual ability in processing words. Specifically, according to SFT (e.g., Shillcock et al., 2000; Shillcock & McDonald, 2005), consistent, precise fixation of specific locations (typically, inter-letter spaces) is a normal determinant of word recognition and occurs even when a word is normally encountered (i.e., without the help of a fixation point to pre-cue the required fixation location). However, the substantial difficulties and variations in fixation location normally experienced by human observers and revealed in many studies over several decades (see the previous section) indicate that words cannot be fixated consistently at precisely defined locations without considerable experimental control. As a consequence, even if the anatomical existence of split foveae were assumed, the parts of words that fall on different sides of fixation in a word in natural reading situations would not normally project consistently to different hemispheres, and so would not normally form consistent codes for word recognition (cf. e.g., Shillcock et al., 2000; Shillcock & McDonald, 2005). Thus, if SFT is to be viable, this substantial variation in the divided projection of words between the two hemispheres must be accommodated.

While we have already highlighted the problems associated with using stimuli that extend beyond foveal vision, the problem of ensuring consistent, precise fixations is also exacerbated in SFT research by the use of letter strings that are unusually small. For example, from the information provided in the study by Skarratt and Lavidor (2006; see also Lavidor & Whitney, 2005; Lavidor et al., 2001), each letter in a string in these studies subtended a visual angle of approximately 0.08 degrees and each inter-letter space (the location where participants were required to fixate) subtended a visual angle of approximately 0.02 degrees, or 1/50th of a degree. Thus, participants in these experiments were being instructed to fixate repeatedly and without fail an inter-letter space that approached the spatial limits of normal human visual acuity (e.g., Olzak & Thomas, 1986). Indeed, when Jordan, Paterson, and

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Stachurski (2009; see also Jordan et al., in press-a) reassessed the study of Lavidor et al. (2001) and monitored the actual locations of the fixations made by participants (recall that Lavidor et al. did not monitor or ensure fixation location), it was apparent that, although our participants had been screened for normal acuity and were given ample time to fixate the designated location on each trial, consistent fixation of the designated location was visually impossible when using stimuli of the same-size as those used by Lavidor et al.

In sum, a major problem for SFT is that the theory itself and the experiments conducted in its support make proposals about human word recognition that are based on unrealistic assumptions about human visual ability. But other problems concerning human visual ability present concerns for the critical role assigned to fixation location by SFT. According to SFT, when a string of letters is fixated so that its retinal image straddles the vertical midline of each fovea. all letters to the left of fixation project to the RH whereas all letters to the right project to the LH. However, an additional, implicit yet fundamental assumption of SFT is that the points of fixation for the left and right eyes coincide precisely during reading. In particular, the theory assumes that visual information from the left and right hemifield of one eye will match the visual information from the left and right hemifield of the other eye. However, imperfections and asymmetries between the two eyes occur naturally (e.g., Fioravanti, Inchingolo, Pensiero, & Spanios, 1995) and produce frequent disparities between the fixation locations of each eye in a word when reading (e.g., Blythe et al., 2006; Juhasz, Liversedge, White, & Rayner, 2006; Kirkby et al., 2008; Liversedge, White, & Rayner, 2006; Liversedge, Rayner, White, Findlay, & McSorley, 2006). Indeed, as these studies reveal, fixation disparities of more than one letter in width occur on almost 50% of fixations. Consequently, when fixating a word during normal (binocular) reading, two fixation locations will often occur, one for each eye, and so information on either side of the foveal midline will often differ between the two eyes. More recently, Paterson, Jordan, and Kurtev (in press) have shown that the same types of disparities occur with single word presentations (the type used typically in SFT research), although these disparities did not seem to affect word recognition performance.

So far, SFT has not accommodated disparities in binocular vision and has overlooked the influence of these disparities in experiments reported in support of split-foveal processing. Of additional concern is that both the nature and the magnitude of fixation disparity are likely to vary from fixation to fixation, thus changing both the form and the amount of overlap in information projected to each hemisphere from fixation to fixation in word recognition, and from trial to trial in an experiment. Given these problems, it seems that the fixation requirements of experiments designed to provide support for SFT and the account of word recognition provided by the theory itself, may present, at best, an oversimplified view of the role of visual ability in word recognition, and possibly one that is simply implausible. Indeed, from the findings of Paterson et al., the variable and inconsistent projection of information to each fovea has little effect on word recognition performance, indicating again that actual word recognition proceeds without the fundamental requirements of fixation coordination, location, and precision that lie at the heart of SFT.

3. The accuracy of reporting earlier research

Human fixation ability clearly presents problems for the experiments and arguments used to support SFT but these problems are generally not apparent when previous research concerning fixation ability is reported in studies promoting SFT. For example, in support of their claim that participants in their experiment consistently maintained fixation to within 2 min of arc, Lavidor et al. (2003, see previous section) argue that similar levels of fixation accuracy have been reported in other experiments by citing two previously published studies (Batt et al., 1995; Evans, Shedden, Hevenor, & Hahn, 2000) and an unpublished study (Nazir, Deutsch, & Frost, 2002; subsequently published as Nazir, Ben-Boutayab, Decoppet, Deutsch, & Frost, 2004). However, on closer inspection, none of these studies actually provide the support for fixation precision implied by their inclusion in Lavidor et al.'s paper. In the study by Batt et al. (1995), fixation was deemed to be accurate if it occurred within 1 degree either side of the required fixation location. Consequently, Batt et al.'s finding that 86% of fixations fell within this 2 degree range clearly does not indicate high levels of fixation precision in their experiment. In a similar vein, Evans et al. (2000) placed great emphasis on instructions to participants to fixate accurately in their study but also used electro-oculogram (EOG) electrodes to detect eve movements. However, fixation accuracy of the order critical for the study of SFT was not the focus of Evans et al.'s experiment and no further details of how eye movements were recorded (including details about fixation accuracy and the temporal and spatial precision of their EOG monitoring) are included in their study. Thus, as in the study by Batt et al. (1995), Evans et al.'s finding that 90% of trials did not contain artefacts of eye or muscle movement provides no indication that high levels of fixation precision were actually occurring. Finally, in the study by Nazir et al. (2004), fixation was deemed to be accurate if it occurred within 0.6 degrees either side of the required fixation location. Consequently, the finding that 92% of fixations fell within this 1.2 degree range clearly also does not indicate that participants in this study produced the high levels of fixation precision claimed by Lavidor at al. and required for an accurate assessment of SFT.

Similar problems exist in Whitney and Lavidor's (2005) report of a study by Estes, Allmeyer, and Reder (1976). Whitney and Lavidor's view on hemispheric asymmetries in word recognition incorporates split-fovea processing and is challenged by the evidence that fixation errors occur in lateralised displays (see previous sections) and, in particular, that fixation errors produce different patterns of serial position performance in each visual hemifield (e.g., Jordan et al., 2003a,b). Accordingly, the authors cite a much earlier study by Estes et al. in which similar patterns of serial position performance had been reported in each visual hemifield when, according to Whitney and Lavidor, participants were "trained to maintain central fixation" (p. 192). In reality, Estes et al. make no mention of training participants to fixate centrally. Instead, what Whitney and Lavidor mistakenly refer to as training was simply a procedure used by Estes et al. at the start of the experiment to calibrate the tolerance of an early example of an eye-tracker. In fact, Estes et al. report experiencing considerable problems with eye-tracking accuracy during the experiment. Thus, although Whitney and Lavidor cite the Estes et al. study as evidence of the true nature of hemispheric processing when central fixation is ensured, closer inspection reveals that this study is particularly unsuited to this purpose.

Whitney and Lavidor (2005) also question the role of fixation precision in word recognition research by suggesting that, when precise fixation has been ensured in experiments by using an eye-tracking device, "it is likely that the stringent demands of the fixation task itself altered attentional and perceptibility patterns" (p. 192). According to this suggestion, when participants are instructed to fixate a fixation point in an experiment, instructions alone are acceptable but ensuring that what is instructed actually takes place somehow impairs the research. Whitney and Lavidor offer no empirical evidence to support their suggestion but empirical evidence does exist to indicate that the suggestion is unsound (Jordan & Patching, 2006; see also Jordan et al., 2003b). In fact, Whitney and Lavidor's suggestion actually raises problems for SFT

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research rather than removes them. First, it is clear from the literature that proponents of SFT try to ensure precise fixation in their experiments; why else would these researchers take the trouble to emphatically instruct their participants to fixate a fixation point on each trial? Consequently, if ensuring precise fixation by using an eye-tracking device creates problems for word recognition, these problems impact on the actual paradigm of requiring precise fixation in SFT research rather than on ensuring that the fixations required by the paradigm actually take place. In short, if precise fixation of a specified location is inappropriate for word recognition research, the logic underlying a substantial amount of SFT research is fundamentally flawed. The second problem is that if, as Whitney and Lavidor (2005) suggest, precise fixation is not possible without experimental control but ensuring precise fixation disrupts word recognition, it is not clear how the consistent, precise fixation of specific inter-letter spaces proposed by SFT can be a normal component of word recognition. If Whitney and Lavidor are correct. the fixation requirements of SFT would impair the recognition of words rather than reflect the role of precisely located fixations that naturally occur with sufficient regularity to define the split-fovea process in word recognition (e.g., Shillcock et al., 2000; Shillcock & McDonald 2005).

Problems concerning the accuracy with which previous research is reported are not restricted to the issue of fixation ability. When encountering reviews of previous findings in articles promoting SFT, readers may easily form the impression that previous research indicates with considerable clarity that there is no functional overlap between the two visual hemifields and that this is clearly consistent with SFT. For example, many articles in this area (e.g., Brysbaert, 1994; Hsiao et al., 2006, 2007; Lavidor & Ellis, 2003; Lavidor & Walsh, 2003; Lavidor & Walsh, 2004a; Lavidor & Walsh, 2004b; Lavidor et al., 2001, 2003, 2004) cite an early study by Harvey (1978) in which visual targets were presented to the left and right of a central fixation point at reported eccentricities of between 0.25 and 4.00 degrees of visual angle. Reaction times were faster for targets presented in the hemifield ipsilateral to the response hand and this "uncrossed advantage" remained essentially unchanged for targets presented 0.25 degrees from the fixation point. Harvey's findings are consistently reported in articles supporting SFT as evidence that the unilateral projection of visual information to the contralateral hemisphere continues right up to the point of fixation and so provides evidence against bilateral projection around the point of fixation. However, even taken at face value, Harvey's findings offer no comment on the existence of a region of bilateral projection 0.5 degrees wide centred around the point of fixation. Such an overlap would be substantial for normal word recognition, where at least 4 letters may occupy 1 degree of visual angle (e.g., Rayner & Pollatsek, 1989) and would be notably inconsistent with the fundamental assumption of SFT that the hemispheric processing of words is split precisely at the point of fixation (i.e., such that even adjacent letters in a word project to different hemispheres). However, in line with the problems of more recent research in this area, the absence of objective monitoring or control of the actual locations of fixations made in Harvey's experiment casts further doubt on the validity of these findings for assessing SFT (see discussions in previous sections).

Three other studies (Haun, 1978; Lines, 1984; Lines & Milner, 1983) using a similar approach to Harvey (1978) are usually also cited in the same articles as support for split-foveal processing but, despite their use in these articles, these studies also provide no support for the foveal split posited by SFT. In each study, visual targets were presented to the left and right of a fixation point at reported eccentricities of between 0.50 and 4.00 degrees of visual angle. Haun (1978) found hemifield superiorities, and Lines (1984) and Lines and Milner (1983) found uncrossed advantages, that

remained essentially unchanged across all eccentricities, including stimuli presented 0.50 degrees from the designated fixation point. But even this smallest eccentricity would allow a substantial region of bilateral projection (1 degree wide) centred around the point of fixation (assuming accurate fixation) and so these findings also make no comment on a split in hemispheric processing at the point of fixation.⁴ However, in addition to this inconsistency, the studies by Haun, Lines, and Lines and Milner, as in the study by Harvey, all attempted to control fixation location by using only instructions and so the actual retinal locations of stimuli presented in these experiments are themselves in considerable doubt.⁵

A study by Portin and Hari (1999) is also frequently cited as support for SFT (e.g., Hsiao et al., 2006, 2007; Lavidor & Ellis, 2003; Lavidor et al., 2004; Lavidor & Walsh, 2003) but, on inspection, this study also provides no support for the notion that processing is split at the point of fixation. Portin and Hari investigated hemispheric responses to luminance stimuli presented at various eccentricities and reported finding contralateral activation even for stimuli presented 0 degrees from a central fixation point. This finding is presented in articles supporting SFT as evidence that the foveal region at the point of fixation is represented only unilaterally, in the contralateral hemisphere. However, the semicircular stimuli used in this study were so large that even when their medial edge was presented adjacent to the fixation point they extended 5.5 degrees into either the left or right hemifield and so well into extrafoveal retinal areas where unilateral projections are well established (see also previous sections and Footnote 4). Consequently, although Portin and Hari obtained evidence of contralateral hemispheric activation by these stimuli, neither the stimuli nor the authors provide any indication that this evidence indicates a processing split at the point of fixation.

Previous research conducted using commissurotomy ("splitbrain") patients and in the area of hemianopia (loss of vision in one visual hemifield due to unilateral damage to the primary visual cortex) and macular sparing (residual sight in the central part of the affected visual hemifield) often provides little that is relevant to the specific claims of SFT because the focus of this previous research is not the notion that the visual field of each fovea is divided precisely at its vertical midline. However, numerous articles supporting SFT (e.g., Brysbaert, 1994, 2004; Ellis et al., 2005; Hsiao & Shillcock, 2005; Hsiao et al., 2006, 2007; Hunter et al., 2007; Lavidor & Ellis, 2003; Lavidor et al., 2001, 2003; Lavidor & Walsh, 2003; Lavidor & Walsh, 2004a; Lavidor et al., 2004) cite the findings of Fendrich and Gazzaniga (1989) in which the ability to compare stimuli presented in different visual hemifields was studied with a commissurotomy patient. Fendrich and Gazzaniga found that cross-hemifield comparisons were nearly at chance when stimuli were presented 0.25 degrees away from fixation and this is reported in articles

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⁴ A further complicating factor in studies of this type is determining the retinal location of the information in each stimulus that is actually responsible for the effects observed. For example, Haun (1978) reports that stimuli were presented 0.50 degrees from fixation but this was the location of the outer edges of these stimuli and the width of stimuli actually extended from 0.21 degrees (inner edge) to 0.50 degrees (outer edge) on either side of the fixation point. Consequently, depending on the location of the information in these stimuli (symmetrical uppercase letters) that participants used to perform the task, a wide range of regions of bilateral projection (up to about 1 degree wide) would be consistent with the findings of these studies. However, even making the most conservative assumption that participants in the study by Haun used only information from the inner edges of stimuli, this would still allow a substantial region of bilateral projection of about .42 degrees wide around the point of fixation.

⁵ In a similar, follow-up experiment, Haun (1978) acknowledged the problems of not controlling fixation location but still made the unsubstantiated claim that stimuli were presented 5.2 min from each participant's point of fixation; a level of accuracy resembling the functional limits of modern eye-tracking systems.

supporting SFT as evidence against bilateral projection (note that the obvious possibility of an area of bilateral overlap of 0.50 degrees wide is not addressed in these articles). However, although readers of these articles are often invited to see also Fendrich et al. (1996), the actual findings of this later study involving two of the same authors are generally not reported. In fact, on closer inspection of Fendrich et al.'s study, their findings are entirely consistent with an area of bilateral projection of up to 1 degree either side of fixation. Inspired by considerations over the earlier findings of Fendrich and Gazzaniga, Fendrich et al. found that a callosotomy patient could accurately compare spatial-frequency gratings (not an easy task) shown for 2s in separate visual hemifields even though the medial edges of these stimuli were 1 degree from fixation but not when these stimuli were presented for only 200 ms or when their medial edges were 2 degrees from the vertical midline. Moreover, performance was most accurate for spatial frequencies of 2 and 4 cycles per degree and least accurate for 1 and 8 cycles per degree. which resembles normal spatial frequency sensitivity. As Fendrich et al. conclude, these findings indicate a substantial region of bilateral projection around the point of fixation (of approximately 2 degrees wide; a similar conclusion is drawn by Gazzaniga, 2000), and this is clearly inconsistent with the claims of SFT. While the precise nature and functioning of the overlap in normal readers remains to be fully determined, the role of this information in word recognition and its general inconsistency with the claims of SFT should not simply be ignored.

Others (e.g., Brysbaert, 1994, 2004; Hunter et al., 2007; see also Martin et al., 2007) have cited in support of SFT a study by Corballis and Trudel (1993) in which commissurotomy patients made lexical decisions for 4-letter words and nonwords presented either entirely to the left or to the right of a central fixation point, or straddling the fixation point so that two letters appeared to the left and two to the right. The findings showed performance above 90% correct for stimuli presented to the right, poorer performance (about 73% and 82% correct) for stimuli presented to the left, and the poorest levels of all (about 57% correct) for stimuli presented centrally. At first sight, these findings may suggest that the particularly poor performance observed with central presentations indicates a split at the point of fixation which sent the two halves of each word to separate (unconnected) hemispheres with disastrous effects (as SFT may propose). However, as is so often the case, a closer look at the original study reveals crucial information. In particular, the letter strings used by Corballis and Trudel were abnormally sized and subtended a horizontal visual angle of approximately 4 degrees (even adjacent letters were spaced 1.20 degrees apart, centre to centre). Thus, when these over-sized strings were presented centrally, each string extended about 2 degrees each side of fixation into extrafoveal retinal regions where unilateral projections may have inspired the disruptive effects observed. Indeed, under the same display conditions, normal participants failed to show any differences in accuracy across left, right, and central presentations, and only marginal effects for reaction times, suggesting that the displays used were not well suited to eliciting well-established patterns of hemispheric asymmetry. As Corballis and Trudel point out, although other researchers (e.g., Sperry, Gazzaniga, & Bogen, 1969) have suggested that, when words are fixated centrally by commissurotomy patients, each half is processed in a separate hemisphere, these suggestions "may have given a false impression of the degree of perceptual disunity between the divided hemispheres" (p. 321). In short, the study by Corballis and Trudel is not a source of great support for SFT.

Many articles supporting SFT also cite a study by Sugishita et al. (1994) in arguments against bilateral projection around the point of fixation (e.g., Ellis et al., 2005; Lavidor & Ellis, 2003; Lavidor & Walsh, 2003; Lavidor & Walsh, 2004a; Lavidor et al., 2001, 2003,

2004; Martin et al., 2007; Whitney, 2004) although closer scrutiny of this study indicates a rather different interpretation. Sugishita et al. presented word and letter stimuli in and around the right foveae of two commissurotomy patients. Since both patients required direct presentation to left hemisphere processes to read these stimuli aloud, Sugishita et al. reasoned that stimuli presented to the right hemiretina of the right eye should not project to the left hemisphere (and so be read aloud) unless bilateral projections existed. The findings revealed bilateral projections that extended to just under 0.6 degrees from the foveal centre. As Sugishita et al. point out, their findings are not conclusive and further information is necessary to assess the full width of bilateral overlap, but the indication yet again is that a substantial area of bilateral projection (>1 degree) exists around the point of fixation in humans and, therefore, that these findings are inconsistent with the claims of SFT. Indeed, despite this study being widely (and erroneously) cited as support for SFT. Sugishita et al.'s view that fixation errors are common in studies where fixation is critical and that, due to errors in fixation, stimuli "should be presented at least 2.0 degrees right or left of the foveal center to ensure adequate lateralisation of the stimulus to one hemisphere" (p. 414) does not get reported in articles supporting SFT.

In a similar vein, but in a study rarely cited by advocates of SFT, Trauzettel-Klosinski and Reinhard (1998) used a scanning laser ophthalmoscope to project dots directly on to the retina of patients suffering from hemianopia and who showed macular sparing. Dots were presented at various eccentricities, the closest 0.5 degrees from fixation. Trauzettel-Klosinski and Reinhard found that participants could detect dots presented in the affected hemiretina at 0.5 degrees in 12 of the 13 eyes examined, indicating an area of bilateral overlap extending approximately 0.5 degrees to each side of fixation (i.e., 1 degree wide in total). This finding is clearly highly relevant to assessing the fundamental claims of SFT but is largely neglected in that literature (although Lavidor & Walsh, 2003; Lavidor & Walsh, 2004a, do cite this study as providing support for bilateral projections). In a follow-up study, Reinhard and Trauzettel-Klosinski (2003) used the same technique but investigated patients showing hemianopia without macular sparing and found evidence of bilateral overlap extending approximately 0.5 degrees each side of fixation (i.e., 1 degree wide in total) in 34 of the 36 eyes examined. Twenty-two eyes showed that this overlap may have been smaller at fixation although, as the authors point out, issues concerning accuracy of measurement make this unclear. Clearly, even an overlap of just 0.5 degrees either side of fixation (i.e., 1 degree wide in total) would correspond to at least four letters in normal reading (e.g., Rayner & Pollatsek, 1989) projecting bilaterally to both hemispheres, which is inconsistent with the fundamental claim of SFT that processing of words is split so precisely that when a particular inter-letter space in a word is fixated, all letters to the left and right of this space are subjected to different processes because they project unilaterally to different hemispheres.

Finally in this section, the reporting of a study by Gray, Galetta, Siegal, and Schatz (1997) in many articles supporting SFT (e.g., Hsiao & Shillcock, 2005; Hsiao et al., 2006, 2007; Lavidor & Ellis, 2003; Lavidor et al., 2004; Lavidor & Walsh, 2003; Lavidor & Walsh, 2004b; Martin et al., 2007) highlights a general source of error when citing the findings of previous research as support for the notion that human foveae are split at the midline. As an example, Lavidor and Ellis (2003) report that "Gray et al. (1997) concluded that the foveal region is unilaterally represented in the primary human visual cortex" (p. 70). However, for many researchers (including Gray et al., 1997), the term *fovea* refers to an area some distance away from the foveal midline, occupying an area between 3 and 5 degrees towards the periphery. In contrast, the area straddling the foveal midline and, therefore, the area of interest to

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proponents of SFT, is referred to as the *foveola*, and has a diameter of 1-2 degrees (e.g., Gray et al., 1997). Thus, when Gray et al. refer to "unilateral foveal representation" in their article describing clinical visual assessment, they are referring to projections from an area at least 3 degrees away from the foveal midline (see also Gray, Galetta, & Schatz, 1998; Wellings, 1998) and not to an area straddling the point of fixation. Indeed, Gray et al. (1997) clearly acknowledge anatomical evidence indicating bilateral representation of the central 1–2 degrees of the foveola, and make the pertinent point about clinical assessment that "testing the central 1-2 degrees foveolar field is extremely difficult because the foveolar field falls within the fixation target on campimeters and perimeters" (p. 312) and, not surprisingly, make it clear that "bilateral representation of foveal vision is the focus of our report" (p. 315). Thus, although other researchers (including advocates of SFT) use the term fovea to include the area straddling the foveal midline, the misreporting of the study and findings of Grav et al. in articles supporting SFT indicates the dangers associated with different terminologies used by anatomists, clinicians, and cognitive psychologists that must be addressed if the findings of previous research are to be interpreted and reported accurately. In fact, contrary to the claims made by proponents of SFT, the study and findings of Gray et al. are of no relevance to the notion that a split in foveal processing occurs at the point of fixation and offer no support whatsoever for the role of split-fovea processing in word recognition.

These inaccuracies and misapprehensions in reporting previous research serve to demonstrate the misleading way in which previous research has often been reported as support for some of the fundamental claims of SFT. However, the previous research articles we have covered in this section, although numerous and oft-cited in the SFT literature, are not intended to provide either an exhaustive list of such problems or a comprehensive assessment of all the research that could possibly be relevant to the debate concerning split-fovea processing. The inaccuracies and misapprehensions we have reported, nevertheless, should serve as an important indication of the problems that exist over the validity of the interpretations of previous research that are presented widely in the SFT literature. As ever, and as we all tell our students, go to the original sources if you want the full story.

4. A checklist for conducting SFT research

It should be apparent from our assessment of SFT research that experimentation in this area suffers from fundamental methodological shortcomings. As a consequence, the contribution made by this research so far to an understanding of the relevance of SFT to hemispheric asymmetries and word recognition is not clear. It may be tempting to some to try to ignore the issues we have raised but, for most, that would clearly not be in the best interests of scientific rigour and would leave open numerous issues concerning the validity of SFT. Consequently, our recommendation is that future SFT research should adhere to some basic methodological principles if the contribution of this theory to our understanding of hemispheric asymmetries and word recognition is to be fully revealed. We shall present just three of these methodological principles here although there are bound to be many more issues that should be addressed for a particular experiment to reach an acceptable level of scientific rigour. Nevertheless, we hope that the issues we have raised throughout this article act as a general alert to researchers to produce better and more appropriate experimentation.

4.1. Use an eye-tracker

SFT places considerable emphasis on the role of fixation location when addressing hemispheric processing and word recognition.

Consequently, because of the likelihood that accurate fixations will not take place on even the majority of trials in an experiment and because of the distorting influences that occur when fixation accuracy is not ensured, SFT research must include effective eyetracking procedures. Without this technological involvement, the extensive arguments that advocates of the theory present concerning the precise location of fixations within words and their effect on hemispheric processing and word recognition will be weakened greatly and may even be highly misleading. In the vast majority of paradigms used in SFT research, where participants are required to fixate a particular, pre-cued location when a stimulus is presented, the eye-tracking requirements are relatively simple, although they still require technical expertise and care if they are to be implemented effectively and optimally. Specifically, researchers should use a fixation-contingent stimulus display in which an eye-tracking device is linked to a computer which controls the displays of each stimulus. In this way, the output of the eve-tracker can signal to the display computer when the required location is being fixated on the display screen and, therefore, when stimulus presentation would be appropriate (for more descriptions of this procedure, see Jordan et al., 1998, 2000, 2003a,b, 2008; Jordan, Paterson, Kurtev, & Xu, in press-c; Jordan & Patching, 2006; Patching & Jordan, 1998). If necessary, this fixation-contingent procedure can be simplified for participants by using a "fixation window" technique (Jordan & Patching, 2006) in which small adjustments to the location of stimuli can be implemented in the display to compensate for corresponding small shifts in fixation away from the required location. In this way, stimuli can be presented accurately relative to participants' fixations but without requiring participants to hold their fixation on a single location. However, and as we have indicated earlier in this article, whatever fixation-contingent technique is adopted for future SFT research, researchers should not assume that any eye-tracker will reproduce the claims of the manufacturer. These claims are often just theoretical maximum levels of performance and not the levels that may be achieved in practice (i.e., when used in an experiment). Thus, accurate head restraint, eye-tracker anchoring, calibration, and measuring (e.g., using an artificial eye) are imperative for SFT researchers to maximise the accuracy with which fixations are monitored and controlled in their experiments, and for these researchers (and readers of subsequent articles on the topic) to be aware of the constraints of the equipment and procedures employed. Of course, if it transpires that word recognition is unaffected by the accuracy with which designated within-word fixation locations are actually fixated, this in itself would cast considerable doubt on the role of precise fixation location in word recognition that lies at the heart of SFT.

4.2. Use appropriately sized stimuli

A fundamental component of SFT is the notion that foveal information presented either side of the point of fixation projects unilaterally to different, contralateral hemispheres. Consequently, researchers have often manipulated the positions of stimuli around the point of fixation in attempts to reveal asymmetries in hemispheric processing within foveal vision. However, as we have pointed out earlier in this article, conclusions from such studies are compromised greatly if stimuli stray outside foveal vision, into areas which are known to have unilateral projections to the contralateral hemisphere and which, therefore, may provide a division in processing which could be misconstrued as a split in hemispheric processing at the point of fixation. Generally speaking, therefore, if researchers wish to reveal a split in foveal processing at the point of fixation (and this is a fundamental goal of SFT research), the clarity of any findings are likely to be increased greatly by using stimuli that fit entirely within foveal vision. Obviously, the precise require-

ments of any experiment will vary, and presenting stimuli that also extend beyond foveal vision may be a sensible and critical condition for a particular research question. But researchers should be aware of the confounding influences of inadvertently presenting stimuli outside the fovea and then arguing that the effects produced by information presented either side of fixation are due to a split in foveal processing at the point of fixation. Estimates of the size of foveal vision vary but the indications are that presenting stimuli to within 1 degree either side of fixation would be safe. Indeed, from the findings of Jordan et al. (2008; see also Jordan, Paterson, & Kurtev, 2009) where stimuli were presented to the left or right of fixation at a range of foveal locations with outer edges 0.70, 0.80, and 0.90 degrees from fixation, word recognition showed no evidence of being affected by a split in hemispheric processing at any of these locations.

4.3. Use an appropriate task

As in any study in which overt responses to lateralised displays are used to investigate hemispheric asymmetries, the clarity of the findings of SFT research will be greater if confounding systematic asymmetries in hemispheric processing are removed from any response task required of participants. As we have indicated, a task such as naming which, for most individuals, is a response that can be generated by just one hemisphere, may distort the pattern of effects produced when information is presented to the left and right of fixation. Nevertheless, tasks (e.g., lexical decision, forced choice) which require a simple manual response (e.g., a button press) can be conducted using either hand (and, therefore, either hemisphere) and so, with appropriate counterbalancing between left and right hands, can provide a useful means of addressing confounding systematic hemispheric asymmetries in responding. However, other task confounds may exist and researchers should be aware of these when designing experiments and interpreting their findings. For example, one issue often ignored in SFT research is that participants may be more able to guess a word's identity when the highly informative beginnings of words are closer to the point of fixation. Thus, although a processing advantage may be observed in SFT research when most or all of the letters in a word are presented to the right of fixation, this benefit may occur simply because the beginnings of words can be seen more easily than when most or all of the letters in a word are presented to the left of fixation, and this imbalance may produce spurious indications of a LH processing advantage at the point of fixation (as SFT would predict). Tasks such as naming, lexical decision, and full-report may be particularly susceptible to this confound. However, one task (the Reicher-Wheeler task; see Reicher, 1969) can overcome this problem by using a forced choice between two alternatives (e.g., read, road) that differ in ways that cannot be identified from any part of the stimulus other than the critical location (in this example, letter position 2). Thus, although this crucial aspect of the Reicher-Wheeler task has not always been fully understood (e.g., see Lavidor & Bailey, 2005), the benefit of the task for studies of SFT is that it offers a means of measuring performance without contamination by sophisticated guesswork based on asymmetries in the visibility of partial word information (e.g., see Jordan et al., 1998, 2000, 2003a, 2003b; Reuter-Lorenz & Baynes, 1992) and so may provide a more rigorous (and, therefore, compelling) test of split-foveal processing in word recognition, if it exists.

In sum, SFT provides an interesting view of the processes involved in word recognition from retina to cortex, but research in this area is notable for the shortcomings in practice and errors of fact that it contains. We have highlighted a number of the shortcomings and errors that exist in the published literature but others are likely to exist, and it is unlikely that all will be absent from all future articles written in support of SFT. The message, therefore, is that readers should consider carefully what they read in this area of research. Unfortunately, nature and the science conducted to unravel its complexities are rarely as clear-cut as SFT appears to propose, and nature has a habit of not cooperating with the simple precision that researchers sometimes wish to impose on its exposition.

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