

# The importance of interhemispheric transfer for foveal vision: A factor that has been overlooked in theories of visual word recognition and object perception

Marc Brysbaert\*

*Department of Psychology, Royal Holloway, University of London, Egham, Surrey TW20 0EX, UK*

Accepted 5 June 2003

## Abstract

In this special issue of *Brain and Language*, we examine what implications the division between the left and the right brain half has for the recognition of words presented in the center of the visual field. The different articles are a first indication that taking into account the split between the left and the right cerebral hemisphere need not be an inescapable nuisance in models of visual word recognition but may in fact form the clue to the solution of a longstanding problem within this literature. Also, the fact that interhemispheric transfer has implications for foveal word recognition should interest laterality researchers, as it makes their findings more central to normal reading. In this introductory article, I first present a rough picture of the current (lack of) evidence for a bilateral representation of the fovea and the absence of a callosal delay. I then briefly discuss the suggestions made by the different authors on how to integrate the foveal split within current models of visual word recognition.

© 2003 Elsevier Science (USA). All rights reserved.

*Keywords:* Interhemispheric transfer; Macular sparing; Visual word recognition; Foveal split; Symmetry detection; oculomotor control

## 1. Introduction

The brain representation of the visual field can be compared to a big city with a wide river through its center. The left half of the brain receives input from the right visual hemifield (RVF) and the right half from the left visual hemifield (LVF). Both cerebral hemispheres are physically separated from one another by the longitudinal fissure but stay in close contact through a multitude of axons that cross the cleft (through the corpus callosum, the anterior commissure, and via subcortical connections).

Every city planner knows that the presence of a river will have major implications for the organization of a city. No matter how many bridges and tunnels are built, the communication across the river will always be more effortful and take longer than the communication within each city half. Therefore, services will be organized in such a way that interhemispheric transfer is reduced

in favor of intrahemispheric communication. This will be particularly true for those services that require the materials to be transferred a number of times hence and forth before the desired output is reached. Processes that require a lot of forward and backward interactions will preferentially be situated in the same hemisphere.

In this special issue of *Brain and Language*, we examine what implications the division between the left and the right brain half has for the recognition of words presented in the center of the visual field. To some extent, it is surprising that this issue still needs to be brought to the researchers' attention after almost 50 years of intensive research both on laterality and visual word recognition. Why have so few people looked at this question before?

Two arguments have been used why the division of the brain in two halves does not create a challenge for foveally presented words. The first is that the fovea is bilaterally represented, because there is an overlap of the LVF and the RVF along the vertical meridian. That is, before the visual information reaches the brain, it is duplicated and sent to both hemispheres, so that each

\* Fax: +44-1784-434347.

E-mail address: [marc.brysbaert@rhul.ac.uk](mailto:marc.brysbaert@rhul.ac.uk).

brain half can process the information without having to consult the other half. The second argument is that the transfer of visual information between the two cerebral hemispheres is so rapid that it does not limit the interhemispheric communication in a noticeable way. Because of these convictions, a division has grown between laterality researchers and psycholinguists. The former have accepted that in order to make valid claims about laterality, visual stimuli must be presented at least one degree away from the center of the visual field. The latter have happily declared that findings with such parafoveal presentation locations have little bearing on the “true” issue of foveal word recognition.

When some 20 years ago I set out to look at the empirical evidence for these two arguments, I had the firm beliefs that: (a) this information would be easy to find and (b) it would be overwhelmingly convincing, leaving no room for doubt. Much to my surprise (and dismay), however, this was not the case. Evidence in favor of a bilateral representation of the fovea was not to be found in the mainstream handbooks of laterality or physiology, and as a matter of fact such evidence was scarce and unconvincing even in specialized articles. Also, evidence was hard to find that interhemispheric transfer would be as fast as intrahemispheric communication for regions close to the left/right split of the visual field. For these reasons, I have come to view the two arguments in favor of a distinction between foveal and parafoveal word recognition as seductive simplifying assumptions rather than as firm foundations of a coherent theoretical framework. They have allowed researchers of visual word recognition to ignore the vast literature of cerebral asymmetry, and they have allowed laterality researchers to ignore the fine details and controversies within computational models of visual word recognition. There was no gain to be found for either camp in questioning the assumptions. This is also the reason why the few researchers who raised the question failed to have impact. Fortunately, due to some recent developments, both methodologically and theoretically, the situation may be about to change. The different articles in this special issue are a first indication that taking into account the split between the left and the right cerebral hemisphere need not be an inescapable nuisance in models of visual word recognition but may in fact form the clue to the solution of a longstanding problem within this literature. Also, the fact that interhemispheric transfer has implications for foveal word recognition should interest laterality researchers, as it makes their findings more central to normal reading.

In this introductory article, I first present a rough picture of the current (lack of) evidence for a bilateral representation of the fovea and the absence of a callosal delay (see Brysbaert, 1994a, for a review of the older literature; see also Leff, this issue, for a more detailed review of the anatomical evidence). I then briefly discuss

the suggestions made by the different authors on how to integrate the foveal split within current models of visual word recognition.

## **2. Foveal words are not sent to both cerebral hemispheres simultaneously**

The idea that foveally presented words would be sent in parallel to the left and the right hemisphere as two complete copies comes from two observations. The first is that patients with hemianopia (i.e., with a lack of vision in one half of the visual field due to unilateral brain damage) sometimes show sparing of central vision. That is, in the center of the visual field, there is an island of preserved vision in the affected hemifield (this phenomenon is called foveal or macular sparing). A recent example of this argument can be found in Trauzettel-Klosinski and Reinhard (1998). They examined 13 eyes in eight patients and found an overlapping vertical strip of sometimes partial perception in 12 eyes at 0.5° from the midline.

The second argument in favor of a bilateral representation of the fovea comes from a series of studies in which the ganglion cells projecting to one brain half were stained by the injection of horseradish peroxidase in the dorsal lateral geniculate nucleus (Leventhal, Ault, & Vitek, 1988; Stone, Leicester, & Sherman, 1973). If there is a perfect split of the optic fibers, then one would predict that only cells in one half of the retinas are marked (e.g., the temporal hemiretina of the right eye and the nasal hemiretina of the left eye, when the substance has been injected in the nucleus leading to the right cerebral hemisphere). This was not what the researchers found: a limited number of ganglion cells in the “wrong” hemiretinas were stained as well. This was especially true for the ganglion cells surrounding the foveal pit (which itself does not contain ganglion cells) and more so in the nasal hemiretina than in the temporal hemiretina. On the basis of this finding, it has been hypothesized that the crossing of the nasal fibers in the optic chiasm is not complete.

As argued in Brysbaert (1994a), the evidence above only has implications for visual word recognition if three assumptions are met. The first is about the nature of the connections between ganglion cells and receptors, the second about the macular sparing account, and the third about the quality of the cortical representation of the fovea.

The first assumption is that the ganglion cells in the “wrong” hemiretina are connected to receptors in the same half of the retina. The problem with the technique of Stone and Leventhal is that it only marks ganglion cells, which are absent in the fovea. Because the ganglion cells to which the foveal receptors connect are laterally displaced, the fovea appears as a blank spot in

the horseradish peroxidase technique, surrounded by a ring of stained ganglion cells. So, the reason why a number of ganglion cells in the “wrong” hemiretina are marked may simply be that some receptors in the nasal part of the fovea are connected to ganglion cells in the temporal part and vice versa (Schein, 1988). Evidence for this possibility was reported by Tootell, Switkes, Silverman, and Hamilton, 1988 who used a technique that does not depend on retrograde marking of retinal cells by the injection of a substance in the optic tract, but that directly marks brain tissue as a function of how active it was immediately after the injection. Tootell et al. anesthetized monkeys, stabilized the eyes, injected the marker, and presented stimuli at various locations of the visual field. After the stimulation, the brain was sectioned to examine which parts of the striate cortex had responded. In one of the experiments, a stimulus was presented  $0.15^\circ$  away from the vertical meridian. If this part of the retina projects bilaterally, then one should find that the primary visual cortex on each side of the brain was active. However, this was not the case: only the brain half opposite to the stimulated visual field was marked.

The second assumption is that macular sparing is due to bilateral representation of central vision, so that damage to one cerebral hemisphere can be compensated by spared tissue in the other brain half. However, throughout the history of research on macular sparing, there has been an alternative explanation for the phenomenon, which says that central vision occupies a larger area of the visual cortex than peripheral vision and that this area is less likely to be affected by strokes. According to this alternative view, macular sparing would not be due to the fact that a unilateral stroke leaves the contralateral brain tissue unaffected but to the fact that the stroke spares some of the ipsilateral brain tissue responsible for central vision. This alternative explanation is more in line with the findings that macular sparing is not observed in all hemianopic patients (Celesia, Meredith, & Pluff, 1983) and that macular sparing can be observed in patients with bilateral hemianopia (i.e., patients who have bilateral brain damage making vision ineffective both in LVF and RVF). These patients sometimes still show preserved vision in the central part of the visual field (Symonds & MacKenzie, 1957), a phenomenon called tunnel vision. The alternative explanation is also in line with the recently shown correlation between macular sparing and spared ipsilateral brain tissue as revealed by magnetic resonance imaging (Gray, Galetta, Siegal, & Schatz, 1997).

The last assumption that has to be made before one can use the clinical and anatomical findings as evidence for the assumption that foveally presented words are processed simultaneously in both cerebral hemispheres, is that the bilateral brain representation of the fovea (if it exists) is detailed enough to subserve visual word

recognition. Maybe there is some nasotemporal overlap, but the information that comes from the ipsilateral visual field is too crude to enable word recognition (see the study of Fendrich, Wessinger, & Gazzaniga, 1996, discussed below). Maybe the information only consists of low-frequency information that allows the reader to estimate the length of the word blob but that is not detailed enough for letter discrimination. It must not be forgotten that a full bilateral representation of the fovea either requires that the foveal information is duplicated in the retina so that the same information can be sent along two different fibers in the optic nerve, or that the sampling of information in the fovea is dense enough so that the signals can be divided over two different tracts without any apparent loss of visual acuity.

Because the physiological evidence for an overlap of the nasal hemiretina and the temporal hemiretina is slim at best (see also Leff, this issue) and requires quite strong assumptions, the only way to find out whether foveally presented words are indeed bilaterally represented is to look at behavioral data. The early (largely negative) evidence is reviewed in Brysbaert (1994a). Here, I just present three of the most compelling pieces of evidence related to visual word recognition (also see the other articles of the present issue for more references).

In 1993, Corballis and Trudel examined the question of foveal word recognition in split-brain patients. Previous research by Sergent (1987) had suggested that patients like L.B. and N.G. could identify four-letter words presented in the center of the visual field better than predicted by chance. However, Corballis and Trudel noted that the experimental design and the stimulus materials used by Sergent were not well controlled and that in a significant number of cases the words could be identified on the basis of the first or the last letters alone. When the stimuli were corrected for this problem, Corballis and Trudel failed to find evidence for foveal word recognition in L.B., although his performance was good for parafoveal word presentation both in LVF and RVF. Similar results were reported for a second split brain patient, D.K.

Fendrich et al. (1996) tested the existence of a nasotemporal overlap in the split-brain patient J.W. Having previously shown that the split-brain patient V.P. could not compare two small shapes presented  $0.25^\circ$  on either side of the vertical meridian (Fendrich & Gazzaniga, 1989), Fendrich et al. wondered whether J.W. would be able to compare two high contrast, low-frequency gratings (1–8 cycles per degree) that were either horizontally or vertically oriented. This was indeed possible when the gratings were presented  $1^\circ$  from the vertical meridian and for 2s (special equipment was used to stabilize the image on the retina so that the results could not be due to eye movements). Performance was at chance level when stimuli were presented for 200 ms. On the basis of these findings, Fendrich et al. (p. 643)

concluded that each hemisphere has a weak representation of the contralateral hemiretina, which, however, does not allow for a fast recognition of (small) letters.

Finally, Lavidor and Walsh (2003) (see also Lavidor & Walsh, this issue) looked at the effects of unilateral transcranial magnetic stimulation (TMS) on lexical decision times for six-letter words. Transcranial magnetic stimulation transiently disrupts brain functioning. Lavidor and Walsh reasoned that if a foveally presented word is bilaterally represented, then there should be no processing cost associated with the stimulation of the primary visual areas of one cerebral hemisphere (because the information is also present in the other hemisphere). However, this is not what they found. Processing times were significantly prolonged in the conditions with TMS (participants also made more errors). In addition, right hemisphere stimulation was particularly damaging for words with high-frequency beginnings (i.e., words that shared their first letters with many other words, see also Lavidor, Hayes, Shillcock, & Ellis, this issue). Lavidor and Walsh interpreted this effect as a cancellation of the orthographic neighborhood effect usually observed in lexical decision times (i.e., the fact that lexical decision times are shorter for words that resemble many other words than for words that have infrequent letter combinations).

### 3. Interhemispheric transfer takes time even for foveally presented stimuli

If detailed visual information in central vision is not directly transmitted to both cerebral hemispheres, then a second argument can be used (and has been used) to defend the view that the division of the brain in two halves has no implications for foveal word recognition. It is the idea that interhemispheric transfer happens so rapidly that it does not limit word processing in any noticeable way, at least not in individuals with a normally functioning corpus callosum.

Visual word processing involves at least three different stages. First, the features of the letters (the oriented line segments and the curves) must be detected. Second, these features have to activate abstract letter identities (allowing people to appreciate that *BRAIN* and *brain* are the same word), and finally the letter nodes must activate the corresponding word nodes. Given that the corpus callosum not only contains homotopic connections (i.e., connections between areas at the same location and presumably with the same function in the two brain halves) but also heterotopic connections (Cusick & Kaas, 1986; Marzi, 1986), one could envisage interhemispheric transfer in word reading as a transcallosal projection from the feature level in the right hemisphere to the letter level in the left hemisphere. In such a view, the interhemispheric projection would be nothing more

but a slightly longer version of the intrahemispheric projection from features to letters. That is, the information that has to cross the corpus callosum would not need extra synapses; it would simply have to traverse axons that are a few centimeters longer.

Such a heterotopic connection is likely to cause the difference between crossed and uncrossed responses in the Poffenberger paradigm. In this paradigm, unstructured light flashes are presented in LVF or RVF and participants have to press on a button with either the left hand or the right hand as soon as the light appears. The typical finding is that responses take about 2 ms longer when they require interhemispheric transfer (e.g., a left hand response to a light flash in RVF) than when they do not (a left hand response to a light flash in LVF). Importantly, this difference between crossed and uncrossed responses does not differ as a function of the intensity of the light flashes, whether or not the participant is adapted to the darkness of the room, and whether or not catch trials are introduced that require the participant to restrain from responding on a certain percentage of trials (e.g., Brysbaert, 1994b; Ratinckx, Brysbaert, & Vermeulen, 2001). In all conditions, the same 2 ms difference is found, probably because this is the extra time needed to traverse the longer interhemispheric axons.

If interhemispheric communication takes only 2 ms longer than intrahemispheric communication, then it can be argued that this does not create a significant constraint in visual word recognition. Laterality researchers will be very familiar with this argument. After all, since the very beginning of the visual half field (VHF) technique, they have been told that the RVF advantage for word recognition in healthy participants is not due to left hemisphere dominance for verbal processing, but to attentional processes, reading habits, and the fact that word beginnings are more informative than word ends, even though each of these factors has been carefully examined and shown not to be the only cause (even not in combination; see, e.g., Bradshaw & Nettleton, 1983; Bryden, 1982; Brysbaert, Vitu, & Schroyens, 1996).

The idea that interhemispheric transfer does not impose a significant constraint on visual word recognition is defended by Nazir et al. in the present issue. They compare visual word recognition in English and Hebrew readers, and claim that at least part of the VHF difference in visual word recognition is due to reading habits and perceptual learning. Their argument is that in reading, words are primarily fixated between the beginning and the middle of the word because eye movements often undershoot their target location (which is the word center). In addition, words are regularly identified in parafoveal vision, so that they do not need to be fixated in text reading. In a language with left-to-right reading, this means that words are predominantly

processed when they are in the RVF. Because perceptual learning is position specific (i.e., it does not generalize from one retinal location to another), this implies that in languages such as English, French, and Dutch, the left hemiretinas and the associated primary brain structures in the left hemisphere will become more specialized for word recognition than the right hemiretinas. This not only explains the RVF advantage for word identification, but also the finding that centrally fixated words are best processed when they are fixated between the beginning and the middle (the so-called optimal viewing position). Within this view, interhemispheric transfer only plays a marginal role.

The weakness of Nazir et al.'s claim is that it is based on a correlation between landing sites in reading and processing efficiency for words. Although this may indeed point to the possibility that landing sites are the origin of differences in processing efficiency, it could also mean that both phenomena are the outcome of a third, underlying principle. In my understanding, Nazir et al.'s model would need two critical observations before it can dismiss the issue of cerebral dominance in visual word recognition. First, if interhemispheric transfer plays but a marginal role, then the RVF advantage shown in languages with a left-to-right reading direction should be reversed into an equivalent LVF advantage for languages with a right-to-left reading direction. It is not enough that the RVF advantage is attenuated in these languages (because this is predicted by a theory based on left hemisphere dominance for verbal processing; Brysbaert et al., 1996). If the reading direction is the only determinant of VHF differences, then the LVF advantage in languages such as Hebrew, Arabic, and Farsi must be the mirror image of the RVF advantage found in languages such as English, French, and Dutch. Among other things, the LVF advantage must be larger for long words than for short words (Young & Ellis, 1985; Ellis, this issue). The second finding that would be critical evidence in favor of Nazir et al.'s interpretation is that the VHF advantage in a particular language is not different for readers with right hemisphere dominance than for readers with left hemisphere dominance. If the laterality of language functions has no perceptible impact on word recognition, then it does not matter which hemisphere is the more specialized. Only the reading direction matters.

A study involving participants with left hemisphere dominance and right hemisphere dominance was published by Brysbaert (1994a). In this paper, I examined to what extent the word beginning superiority effect in Dutch readers could be due to cerebral asymmetry. The word beginning superiority effect refers to the fact that words are more efficiently processed when participants are allowed to fixate on the first letters than when they are required to fixate on the last letters (see also Fischer, this issue). I wondered to what extent this could be due

to the fact that words fixated on the beginning predominantly fall in the RVF whereas words fixated on the end largely fall in the LVF. To find out, I presented words of 3–9 letters for 160 ms in such a way that participants either fixated on the first, the middle, or the last letters. Participants had to name the words as fast as possible and naming times were registered. Two groups of participants had been selected on the basis of their performance on two VHF tasks. The first task involved fast naming of pictures of symmetrical objects presented in parafoveal vision. This task is known to reveal a RVF advantage in participants with left hemisphere dominance. The second task involved parafoveal clockface reading, a task known to elicit a LVF advantage in unselected participants. The first group of nine participants showed a clear RVF advantage for the picture naming task and a LVF advantage for the clockface reading task. The second group of nine participants showed the reverse pattern (these were selected out of a total of 60 lefthanders).

The results of the study were quite clear: the participants with left hemisphere dominance showed a significantly larger word beginning superiority effect than the participants with right hemisphere dominance, even for words of three letters. The effect was not strong enough to reverse the word beginning superiority effect into a word end superiority effect for the participants with right hemisphere dominance (indicating that cerebral dominance is not the only factor responsible for the word beginning superiority effect observed in unselected samples; Brysbaert et al., 1996), but it was very reliable and consistent (i.e., shown by all participants with a typical cerebral dominance). In addition, the difference was larger for long words than for short words, in line with the previously demonstrated word length effect on VHF asymmetries (Young & Ellis, 1985; see also Ellis, this issue).

Because individuals with atypical brain dominance provide us with priceless information about the influence of cerebral dominance and interhemispheric transfer on visual word recognition, it is clear that more research on this topic is desirable, certainly now that we have brain imaging techniques to determine the laterality of visual word recognition and that we start to know which areas to look at (e.g., Cohen et al., 2002; Knecht et al., 2003). This should allow us to unequivocally diagnose the cerebral dominance of a participant and look at the effects of right hemisphere dominance both on foveal and parafoveal word recognition.

Returning to the issue of foveal word presentation, it may be wondered why interhemispheric transfer could be an important constraint in reading if callosal fibers merely require 2 ms extra conduction time. Two elements are important in the answer to this question. First, the 2 ms estimate is based on the Poffenberger paradigm, in which the stimuli need no visual analysis (they are just

light flashes). There is a constant stream of evidence from visual evoked potentials that as soon as the visual stimulus requires structural analysis, interhemispheric transfer time rises to some 10 ms (e.g., Murray, Foxe, Higgins, Javitt, & Schroeder, 2001). The second element is that a short extra time may not be a burden in a serial, bottom-up model in which visual information is picked up by the receptors and fed forward to the higher-processing centers, but may become an obstacle when information transfer requires multiple interactions between the different levels, for instance because the transfer is based on the creation of a coherence loop between two levels (e.g., McClelland & Rumelhart, 1981; Stone, Vanhoy, & Van Orden, 1997). In such models, a delay or a loss of information quality between two levels multiplies because of the interactions between bottom-up and top-down processes that are required to pass information on from one level to the next.

#### 4. Implications of the split fovea for models of visual word recognition

There is an unwritten law in science that empirical findings fail to have an impact until they are incorporated in a coherent theoretical framework (just like false assumptions can have a long life if they serve a theory well). Therefore, simple demonstrations of a split fovea, interesting as they may be, are unlikely to change much about the current neglect of the topic within models of visual word recognition. Only when it is shown that a word recognition model based on a split fovea is capable of explaining all well-known phenomena in visual word recognition and, in addition, provides answers to some unsolved problems, is the topic likely to get the necessary attention.

One of the major weaknesses of current theories of visual word recognition is that they do not have realistic ideas of the input that must be fed into the model, in particular how the word recognition system encodes the position of the letters in a word (so that it can distinguish between the words “dear” and “read”). In the earliest computational models, the problem was “solved” simply by assuming that there was a different layer of letter nodes for each position in a word. Such models were limited to words of a particular length (McClelland & Rumelhart, 1981) and/or did not allow influences between words of different length (e.g., between “raid” and “braid”; see De Moor & Brysbaert, 2000, for the demonstration of such an effect in humans). Other models encode letter positions by dividing words in trigrams (e.g., Seidenberg & McClelland, 1989). So, the word “read” would be encoded as the trigrams “#re,” “rea,” “ead,” and “ad#.” Still other models (e.g., Plaut, McClelland, Seidenberg, & Patterson, 1996) make a distinction between the word’s onset

(the initial consonants), nucleus (the vowels), and coda (the end-consonants) of monosyllabic words. In such models, there is no transfer of learning possible between the processing of the letter “b” at the beginning of a word and the processing of the letter “b” at the end of a word (Bowers, 2002).

Currently, a number of attempts are made to encode letter positions on a temporal basis (Bowers, 2002; Davis, 1999; Whitney, 2001) in a left-to-right order, at least for languages read that way. Such models are known to have a number of advantages (see in particular Bowers, 2002) and can more easily be extended to words that contain more than one syllable (another restriction of nearly all current computational models). However, as noted by Whitney (2001, this issue) such a left-to-right gradient cannot be taken for granted, but must be the result of active control processes, because the letters that are not directly fixated need more time to activate their representations in the brain. This is due to the well-known drop of visual acuity away from the center of the fovea. For word stimuli, this drop in acuity causes an estimated processing cost of 90 ms per degree of deviation (i.e., 24–30 ms per letter position deviation from the fixation location; Schiepers, 1980; Rayner & Morrison, 1981). The retinal acuity gradient is not a problem for the word part that falls to the right of the fixation location, because it is in agreement with the left–right gradient that is needed for word identification. However, it is a problem for the word part that falls to the left of the fixation location, because here the letters that should be activated first are the ones that are farthest from the fixation location. According to Whitney, this problem can only be solved if two requirements are met. First, the input from the left part of the word must have a steeper activation build-up curve than the input from the right part. Otherwise, the letter information of the final part of the word becomes activated before the information of the initial part becomes activated. The second requirement is that for the left part of the word but not for the right part there is inhibition from letters further from the fixation location on letters closer to the fixation location. Only when these two conditions are met, can the retinal input be converted into a smooth left–right gradient from word beginning to word end. Given the different processes that are needed for the word part left of the fixation location and the word part right of the fixation location, it seemed logical to Whitney to assume that both types of processes took place in different hemispheres. By assuming an interhemispheric transfer time of 9 ms, she was able to simulate the data of both the left hemisphere dominant participants of Brysbaert (1994a) and those of the right hemisphere dominant participants for the different word lengths. In addition, she could simulate a series of letter position effects that have been reported in VHF studies (see also Whitney, this issue).

Because Whitney assumes that the processes needed for the left–right gradient occur before the letter level, this part of her model can be seen as the prerequisite of each word recognition model that is built on the assumption that the letters of a word are processed serially (and indeed of all models that do not assume that the letters close to the fixation location are activated faster than those further away from the fixation location). In addition, she shows that her model can shed new light on the influence different types of word neighbors have in the activation of a target word, an issue that is central to current computational models of visual word recognition.

Shillcock and colleagues propose another model of how the positions of letters in a written word are encoded (Shillcock, Ellison, & Monaghan, 2000; see also Monaghan, Shillcock, & McDonald, this issue). They started from the idea that taking into account the fixation position of the eyes in a word provides more information about the relative positions of the letters than when only information about the first and the last letter is encoded. Information about the letter left of the fixation position and the letter right of the fixation position, together with information of the outer letters, suffices to identify nearly all short words and substantially constrains the identity of longer words. In addition, Shillcock et al. noticed that within this type of model, there is an optimal fixation location between the beginning and the middle of a word, which agrees well with human data (Brysbaert, 1994a; O'Regan & Jacobs, 1992) and with the observation that the eyes in reading preferentially land on this position in words (Rayner, 1998). This could suggest that the preferred landing position is a result of differences in word processing efficiency rather than the origin of these differences (i.e., Nazir's position). Because Shillcock et al.'s work was based on computational models rather than on verbal descriptions, they could directly compare the performance of a split fovea model that converged on a single representation very early (i.e., from the first hidden layer on) with that of a model that largely remained split up to the final stages (dealing with word naming and word meaning). Slightly to their surprise, they observed that a model with divided representations in most layers performed better and simulated more human data than a model with rapid convergence to a unitary representation. On the basis of these findings, they put forward the hypothesis that the two cerebral hemispheres operate largely independently in visual word recognition and that only higher-order information is shared. In addition, their work made them conclude that the right hemisphere word representations are less detailed than the left hemisphere representations, making the split fovea model also applicable to the findings of VHF research with laterally displaced stimuli (see their article in the present issue).

It is interesting to see how a common challenge (explaining how the brain encodes information about the positions of the letters in a word) and a common as-

sumption (that the split between the left and the right brain half provides the solution to this problem) can result in two largely deviating computational models of visual word recognition. (Part of the difference is due to the fact that Whitney uses a localist model, in which words are represented by individual nodes, whereas Shillcock et al. work with a distributed model in which words are represented by partly overlapping distributions of nodes.) More important for the issue of interhemispheric transfer in foveal word recognition, however, is that both models indicate how the existence of a split fovea need not be a nuisance that eventually will have to be integrated in models of visual word recognition, but instead may form a core element in our understanding of human performance.

## 5. Implications of the split fovea for object recognition

Accepting that the need for interhemispheric transfer has implications for visual word recognition, one may wonder whether it also affects other aspects of vision, such as object recognition. A major distinction between words and objects is that the latter are often symmetric along the vertical axis. In such cases, the information of the LVF matches that of the RVF, and there is no real need of interhemispheric transfer in order to recognize the object.

Already at the end of the 19th century, Mach noted that vertical symmetry is more rapidly perceived than is symmetry at other orientations (see, e.g., Wagemans, 1995), and proposed that this resulted from bilateral symmetry in the visual system. More recent interpretations of Mach's hypothesis suggest that the corpus callosum mediates the vertical-symmetry advantage (Herbert & Humphrey, 1996). One reason why such rapid symmetry detection along the vertical meridian evolved, may be that once symmetry is established, there is no need anymore to exchange information between the two hemispheres, so that the amount of interhemispheric transfer can be reduced. In addition, Bradshaw (1989) noticed that the symmetry of an object need not be perfect in order to have the impression of symmetry, and that in such cases the information from the LVF dominates that from the RVF. When the LVF part of a nearly symmetric stimulus (e.g., a face) is duplicated, participants have the impression that end-result resembles the original stimulus more than when the RVF part is duplicated. This agrees with the finding of a LVF advantage for symmetry detection (Brysbaert, 1994c; and unpublished results). So, the brain may have developed a mechanism to rapidly (and roughly) assess whether each brain half has all the necessary information about an object, and to use this information in order to limit the amount of interhemispheric transfer.

When the object is not symmetric, my hunch is that the processes discussed in the present issue for visual

word recognition, also have a bearing on the way in which foveal object recognition has to be thought of.

## 6. Implications of the split fovea for eye movements in reading

My own research on interhemispheric transfer started from the question whether cerebral dominance has implications for the way in which people move their eyes over lines of text in reading. As indicated above, there is a correlation between the fact that English readers tend to land on the beginning of words and the fact that they are likely to be left hemisphere (RVF) dominant for visual word recognition. Given this correlation, it seemed obvious to examine whether the preferred landing position could be due to the fact that readers try to position their eyes in such a way that they can project the largest part of the word directly onto their specialized hemisphere. Since its initial formulation it has become clear that this hypothesis is both wrong (Hebrew readers do not prefer to fixate on the left part of a word, as would have been predicted; see Nazir, Ben-Boutayab, Decoppet, Deutsch, & Frost, this issue) and too simple. The optimal viewing position of a word depends on quite complicated interactions between the distribution of information within the words of a particular language, the decrease of visual acuity and processing speed outside the fovea, the reading direction of the language, and the cerebral dominance of a person (Brysbaert et al., 1996; Shillcock et al., 2000; Whitney, 2001). Luckily, the efforts of Shillcock et al. and Whitney have provided us with the mathematic tools to calculate the optimal viewing position for different types of words with much greater precision. This should allow us in the not too distant future to establish whether languages with right-to-left reading direction indeed refute the hypothesis that in reading the eyes are aimed at the position in words which on average minimizes the processing cost of a word processor with divided input.

Even without the help of mathematical models, a number of predictions about eye movements in reading follow from the split fovea hypothesis. I will highlight two of them here. The first is that the eye movements of a person with a split brain should differ radically from individuals with intact interhemispheric connections. Whereas for the latter it is more interesting to fixate words slightly left of their center, a split brain with left hemisphere dominance can only recognize words that are presented entirely in the RVF (Corballis & Trudel, 1993). Therefore, in such an individual we should find an abnormally high number of fixations on the blank spaces in front of the words or on the first letter of the words. In addition, when words are longer than four letters or so, we should find a high number of refixations within the word because the word length exceeds the region of high-acuity foveal vision. The second predic-

tion is that for any language, people with right hemisphere dominance should on average fixate more to the right than people with left hemisphere dominance. The difference may not be spectacular (because of the trade-off between interhemispheric transfer and the information distribution within words) but it should be demonstrable in an experiment with enough power.

## 7. Conclusion

No city planner can afford to overlook the presence of a wide river in a city. Similarly, the majority of the articles in the present issue of *Brain and Language* argue that our understanding of visual word recognition will not be complete until we understand how the brain has solved the problem of the division between the left and the right brain half. All too long the problem has been swept under the rug, by sticking to the assumptions that foveal information is sent in parallel to the left and the right brain half, or that interhemispheric transfer is fast enough so that we can ignore its necessity in our models of visual perception. Because neither of these assumptions is empirically substantiated, sooner or later they are bound to be questioned and replaced by a more realistic approach. It is my hope that the present issue will be seen as a turning point in this respect.

## Acknowledgments

The preparations of this special issue of *Brain and Language* were supported by a joint activities grant of the British Academy and the CNRS in Lyon (France). I thank Michal Lavidor for the many helpful suggestions on a previous draft of this ms.

## References

- Bowers, J. S. (2002). Challenging the widespread assumption that connectionism and distributed representations go hand-in-hand. *Cognitive Psychology*, 45, 413–445.
- Bradshaw, J. L. (1989). *Hemispheric specialization and psychological function*. Chichester: Wiley.
- Bradshaw, J. L., & Nettleton, N. C. (1983). *Human cerebral asymmetry*. Englewood Cliffs, NJ: Prentice-Hall.
- Bryden, M. P. (1982). *Laterality: Functional asymmetry in the intact brain*. New York: Academic Press.
- Brysbaert, M. (1994a). Interhemispheric transfer and the processing of foveally presented stimuli. *Behavioural Brain Research*, 64, 151–161.
- Brysbaert, M. (1994b). Behavioral estimates of interhemispheric transmission time and the signal detection method: A re-appraisal. *Perception & Psychophysics*, 56, 479–490.
- Brysbaert, M. (1994c). Lateral preferences and visual field asymmetries: Appearances may have been overstated. *Cortex*, 30, 413–429.
- Brysbaert, M., Vitu, F., & Schroyens, W. (1996). The right visual field advantage and the optimal viewing position effect: On the relation

- between foveal and parafoveal word recognition. *Neuropsychology*, 10, 385–395.
- Celesia, G. G., Meredith, J. T., & Pluff, K. (1983). Perimetry, visual evoked potentials and visual evoked spectrum array in homonymous hemianopia. *Electroencephalography and Clinical Neurophysiology*, 56, 16–30.
- Cohen, L., Lehericy, S., Chochon, F., Lemer, C., Rivaud, S., & Dehaene, S. (2002). Language-specific tuning of visual cortex? Functional properties of the Visual Word Form Area. *Brain*, 125, 1054–1069.
- Corballis, M. C., & Trudel, C. I. (1993). Role of the forebrain commissures in interhemispheric integration. *Neuropsychology*, 7, 306–324.
- Cusick, C. G., & Kaas, J. H. (1986). Interhemispheric connections of cortical sensory and motor representations in primates. In F. Leporé, M. Ptito, & H. H. Jaspers (Eds.), *Two hemispheres—one brain: Functions of the corpus callosum* (pp. 83–102). New York: Alan R. Liss.
- Davis, C. (1999). The self-organising lexical acquisition and recognition (SOLAR) model of visual word recognition. Unpublished doctoral dissertation. University of New South Wales.
- De Moor, W., & Brysbaert, M. (2000). Neighbourhood-frequency effects when primes and targets have different lengths. *Psychological Research*, 63, 159–162.
- Ellis, A. W. (this issue). The role of the two cerebral hemispheres in recognising centrally-fixated words: Evidence from effects of word length and neighborhood size. *Brain and Language*.
- Fendrich, R., & Gazzaniga, M. S. (1989). Evidence of foveal splitting in a commissurotomy patient. *Neuropsychologia*, 27, 273–281.
- Fendrich, R., Wessinger, C. M., & Gazzaniga, M. S. (1996). Nasotemporal overlap at the retinal vertical meridian—investigations with a callosotomy patient. *Neuropsychologia*, 34, 637–646.
- Fischer, M. (this issue). Orthographic contributions to perceived word centre. *Brain and Language*.
- Gray, L. G., Galetta, S. L., Siegal, T., & Schatz, N. J. (1997). The central visual field in homonymous hemianopia—evidence from for unilateral foveal representation. *Archives of Neurology*, 54, 312–317.
- Herbert, A. M., & Humphrey, G. K. (1996). Bilateral symmetry detection: Testing a ‘callosal’ hypothesis. *Perception*, 25, 463–480.
- Knecht, S., Jansen, A., Frank, A., van Randenborgh, J., Sommer, J., Kanowski, M., & Heinze, H. J. (2003). How atypical is atypical language dominance? *NeuroImage*, 18, 917–927.
- Lavidor, M., Hayes, A., Shillcock, R., & Ellis, A. W. (this issue). Evaluating a split processing model of visual word recognition: Effects of orthographic neighborhood size. *Brain and Language*.
- Lavidor, M., & Walsh, V. (this issue). Transcranial magnetic stimulation (TMS) as a tool to study the cortical representation of the fovea. *Brain and Language*.
- Lavidor, M., & Walsh, V. (2003). A magnetic stimulation examination of orthographic neighborhood effects in visual word recognition. *Journal of Cognitive Neuroscience*, 15, 354–363.
- Leff, A. P. (this issue). A historical review of the representation of the visual field in primary visual cortex with special reference to the neural mechanisms underlying macular sparing. *Brain and Language*.
- Leventhal, A. G., Ault, S. J., & Vitek, D. J. (1988). The nasotemporal division in primate retina: The neural bases of macular sparing and splitting. *Science*, 240, 66–67.
- Marzi, C. A. (1986). Transfer of visual information after unilateral input to the brain. *Brain and Cognition*, 5, 163–173.
- McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: I. An account of basic findings. *Psychological Review*, 88, 375–407.
- Monaghan, P., Shillcock, R., & McDonald, S. (this issue). Hemispheric asymmetries in the split-fovea model of semantic processing. *Brain and Language*.
- Murray, M. M., Foxe, J. J., Higgins, B. A., Javitt, D. C., & Schroeder, C. E. (2001). Visuo-spatial neural response interactions in early cortical processing during a simple reaction time task: A high-density electrical mapping study. *Neuropsychologia*, 39, 828–844.
- Nazir, T. A., Ben-Boutayab, N., Decoppet, N., Deutsch, A., & Frost, R. (this issue). Reading habits, perceptual learning, and recognition of printed words. *Brain and Language*.
- O’Regan, J. K., & Jacobs, A. M. (1992). Optimal viewing position effect in word recognition: A challenge to current theory. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 185–197.
- Plaut, D. C., McClelland, J. L., Seidenberg, M. S., & Patterson, K. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review*, 103, 56–115.
- Ratinckx, E., Brysbaert, M., & Vermeulen, E. (2001). CRT screens may give rise to biased estimates of interhemispheric transmission time in the Poffenberger paradigm. *Experimental Brain Research*, 136, 413–416.
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, 124, 372–422.
- Rayner, K., & Morrison, R. E. (1981). Eye movements and identifying words in parafoveal vision. *Bulletin of the Psychonomic Society*, 17, 135–138.
- Schiepers, C. (1980). Response latency and accuracy in visual recognition. *Perception & Psychophysics*, 27, 71–81.
- Seidenberg, M. S., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review*, 96, 523–568.
- Shillcock, R., Ellison, T. M., & Monaghan, P. (2000). Eye-fixation behavior, lexical storage, and visual word recognition in a split processing model. *Psychological Review*, 107, 824–851.
- Stone, G. O., Vanhoy, M., & Van Orden, G. C. (1997). Perception is a two-way street: Feedforward and feedback phonology in visual word recognition. *Journal of Memory and Language*, 36, 337–359.
- Stone, J., Leicester, J., & Sherman, S. M. (1973). The naso-temporal division of the monkey’s retina. *Journal of Comparative Neurology*, 150, 333–348.
- Schein, S. J. (1988). Anatomy of macaque fovea and spatial densities of neurons in foveal representation. *Journal of Comparative Neurology*, 269, 479–505.
- Sergent, J. (1987). A new look at the human split brain. *Brain*, 110, 1375–1392.
- Symonds, C., & MacKenzie, I. (1957). Bilateral loss of vision from cerebral infarction. *Brain*, 80, 415–455.
- Tootell, R. B. H., Switkes, E., Silverman, M. S., & Hamilton, S. L. (1988). Functional anatomy of macaque striate cortex: II. Retinotopic organization. *Journal of Neuroscience*, 8, 1531–1568.
- Trauzettel-Klosinski, S., & Reinhard, J. (1998). The vertical field border in hemianopia and its significance for fixation and reading. *Investigative Ophthalmology and Visual Science*, 39, 2177–2186.
- Wagemans, J. (1995). Detection of visual symmetries. *Spatial Vision*, 9, 9–32.
- Whitney, C. (2001). How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin & Review*, 8, 221–243.
- Whitney, C. (this issue). Hemisphere-specific effects in word recognition do not require hemisphere-specific modes of access. *Brain and Language*.
- Young, A. W., & Ellis, A. W. (1985). Different methods of lexical access for words presented in the left and right visual hemifield. *Brain and Language*, 24, 326–358.