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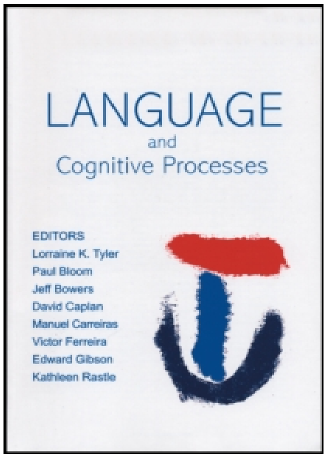

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Theoretical analysis of interhemispheric transfer costs in visual word recognition

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Theoretical analysis of interhemispheric transfer costs in visual word recognition

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It is becoming increasingly clear that interhemispheric transfer is an important factor in visual word recognition. One of the two computational models of visual word recognition that includes this aspect, the SERIOL model, is tested on the basis of recently obtained behavioural word naming data. Optimal viewing position (OVP) data were collected from participants with left hemisphere language dominance, right hemisphere language dominance, and bilateral language representation (as determined by fMRI). We employ a mathematical model, which is based on some of the underlying assumptions of SERIOL, to investigate the model's ability to predict our results. We show that this mathematical model, which makes use of the original parameters, is able to perfectly predict the differences in the OVP curves observed in the three groups of participants.

INTRODUCTION

Recent developments have confronted researchers once again with the importance of the input code in their computational models. In particular, the coding of letter position information has proven to be a difficult issue to solve. For a long time, the slot-based position coding scheme formed the basis of computational models (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; McClelland & Rumelhart, 1981). In this coding scheme, each letter position is represented by a different bank of letters. So, a distinction is made between letters in the first letter position of the word, the second, the

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third, and so on. In DRC, for instance, the word 'trap' is encoded as 't' in the first slot, 'r' in the second slot, 'a' in the third, 'p' in the fourth, and blank in the remaining four slots. An alternative encoding scheme was presented by Seidenberg and McCelland (1989). In their model the position of letters was encoded by means of wickelgraphs, triplets of letters. So, the word 'trap' was encoded through activation of the wickelgraphs '_tr', 'tra', 'rap', and 'ap_'. Because this encoding scheme turned out to be problematic for the naming of non-words, Plaut, McClelland, Seidenberg, and Patterson (1996) replaced it by a scheme in which a distinction was made between the onset (starting consonants), the nucleus (vowel), and the coda (end consonants) of a syllable. So, 'trap' was represented as 'tr' in the onset representations, 'a' in the nucleus representations, and 'p' in the coda representations.

The most devastating finding for the above models was the observation that visual words can be recognised fluently despite the fact that some of the inner letters are transposed. Processing of the target word 'COURT' is primed nearly as well by the prime 'jugde' as by the prime 'judge' (Perea & Lupker, 2003). The present special issue of *Language and Cognitive Processes* includes several attempts to find new encoding principles that allow the input 'jugde' to activate the word 'judge'. Our article deals primarily with the SERIOL model (Whitney, 2001).

According to Whitney (2001), two main 'problems' must be overcome before retinal input can activate word representations: The first is the fact that due to the decrease of visual acuity outside the fixation location, information close to the fixation location has a higher activation level than information further away. So, the retinal information of a word fixated in the centre has a higher activity for the middle letters than for the beginning and the end letters. This does not agree with the finding that the first letters of words are more important for word recognition than the inner letters, as shown by the 'jugde/judge'-experiments ('ujdge' does not prime 'COURT', Perea & Lupker, 2003). Therefore Whitney's SERIOL model assumes that an activation gradient that continually decreases from the word beginning to the word end is a necessary prerequisite for the encoding of letter order. An inversion process is needed to convert the retinal acuity gradient into a locational gradient that agrees with the behavioural data indicating the importance of the first letters of a word in the recognition process.

The second problem is that there is very little evidence for a bilateral representation of foveal vision, such that interhemispheric communication needs to occur at some processing stage in order to integrate information from the left and right visual half-fields. The SERIOL model incorporates this by introducing an interhemispheric transfer parameter, which accounts for the process of initially transferring all the information of a foveally presented word into the hemisphere that is dominant for language processing.

The present article deals in particular with this latter component and looks at how new empirical data can attest for the use of the interhemispheric transfer parameter, as defined in the SERIOL model. To do so, we introduce the optimal viewing position (OVP) design for word recognition and review how a mathematical model based on the principles of SERIOL was used to account for past OVP data (Brysbaert, 1994). We then go on to further test the validity of this mathematical model by investigating if it can also account for new OVP data obtained recently. Further, we consider if a model that includes interhemispheric transfer, but not the inversion cost parameter, could account for the new OVP data as well.

OVP DESIGN FOR WORD RECOGNITION

It is well known that visual information in the left visual half-field is sent to the right hemisphere and that information in the right visual half-field is sent to the left cerebral hemisphere. There is much more uncertainty of what happens at the centre of the visual field, where the left and the right visual hemifields meet. In general, it has been assumed that there is a small streak of overlap, from which information is sent simultaneously to the left and to the right hemisphere. The extent of this overlap has been estimated to be between 1 and 3 degrees of visual angle. Reviews of the literature, however, found very little empirical evidence for this assumption (Brysbaert, 1994, 2004; Lavidor & Walsh, 2004).

Brysbaert (1994) argued that the discussion about whether or not interhemispheric transfer has functional consequences for foveal word recognition can be settled quite easily on the basis of empirical data. All that is needed is to compare a group of participants with right hemisphere language dominance to a group of participants with left hemisphere language dominance. Although language is lateralised to the left in most individuals (Knecht et al., 2000; Pujol, Deus, Losilla & Capdevila, 1999; Szaflarski et al., 2002), there is a small percentage of people with right hemisphere language dominance. Comparing the performance of left and right language dominant individuals in a foveal word recognition task would reveal to what extent higher cognitive processes such as reading rely on interhemispheric transfer and information integration.

To investigate this issue, Brysbaert (1994) made use of the Optimal Viewing Position (OVP) effect (O'Regan & Jacobs, 1992). The OVP effect is obtained by asking participants to read words after initial fixation on the first, the second, …, or the last letter. This is achieved by displaying words briefly between two vertically aligned lines that define the fixation space. By shifting the position of the words relative to the fixation location, it is possible to measure response times for fixations on different letter positions in a word (Figure 1 shows an example). Brysbaert (1994) hypothesised that if foveal vision is split (i.e., information in foveal vision is not transferred simultaneously to both cerebral hemispheres), then for the majority of people, who are left dominant for language processing, it should be easier to process a word after fixation on the first letter than after fixation on the last letter, known as the 'word-beginning superiority effect'. The reason for this is that a fixation on the first letter of a word makes the whole word fall in the right visual field, whereas a fixation on the last letter makes the whole word fall in the left visual field. In contrast, the few people with right hemisphere dominance (5% of the right-handed, and 15–25% of the left-handed) would be at an advantage for fixations on the last letter and would experience an interhemispheric transfer cost for fixations on the first letter.

Brysbaert's (1994) results were in line with his hypothesis, as left dominant participants in his study showed a stronger word-beginning superiority effect than right dominant participants, but the effect was less strong than anticipated. The right dominant participants did not show the expected word-end superiority effect, in particular not for words longer than 4 letters. They just showed a less strong word-beginning superiority effect (see Figure 2). This is due to the influence of additional factors, including left-to-right reading direction, asymmetries in the information distribution within words (Efron, 1990) and lexical constraints (e.g., Clark & O'Regan,

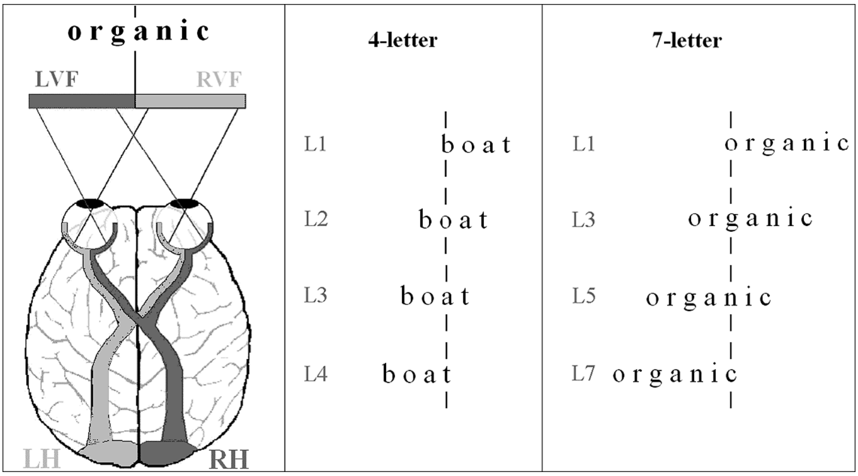

Figure 1. Display of four- and seven-letter words in the OVP design. Four-letter words are fixated on each letter (L1-L4), seven-letter words on every other letter (L1, L3, L5, L7). Typically response times towards a word are fastest when participants fixate letters within the first half of a word (see OVP curves in Figure 2).

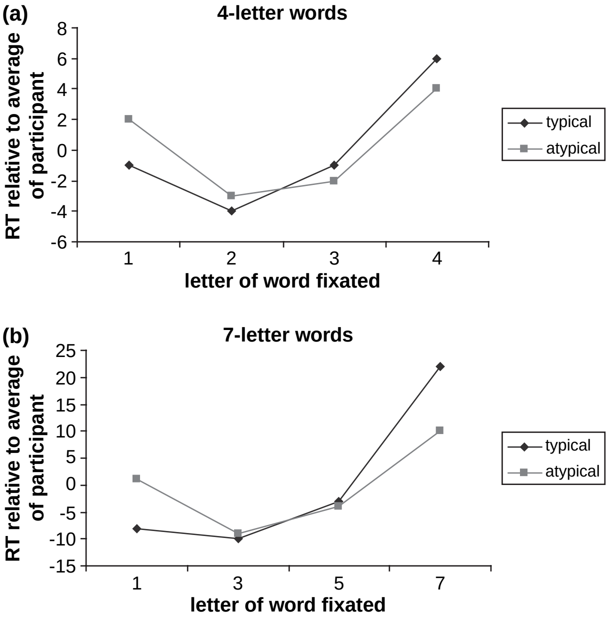

Figure 2. Naming latencies for four- and seven-letter words as a function of cerebral dominance and fixation location, based on Brysbaert (1994). The data of both groups have been standardised by calculating the deviation of the naming latency to the mean of the participant. In this way, the non-significant difference in overall naming latency between the groups has been partialled out (see Brysbaert, 1994 for the raw naming latencies).

1999; Stevens & Grainger, 2003), which are known to contribute to this effect, particularly for long words.

Whitney (2001) argued that the data of Brysbaert (1994) could be explained if one acknowledges that the cost for interhemispheric transfer is only one of the factors that contribute to the word-beginning superiority effect in participants with left hemisphere dominance (see also Brysbaert & Nazir, 2005). Whitney (2001) showed that her model could account for the differences in the OVP curves reported by Brysbaert (1994) by assuming a higher inversion cost of the acuity gradient in the subdominant hemisphere, combined with an interhemispheric transfer cost of 9 ms (see also Whitney, 2004; Whitney & Lavidor, 2004, 2005).

A similar conclusion was reached independently by Shillcock, Ellison, and Monaghan (2000). These authors started from the problem of how the brain keeps track of the letter positions in a word (e.g., to distinguish SALT from SLAT; see Peressotti and Grainger (1999) for another approach that uses eye fixation position as an anchor point for position coding). Their solution was that the fixation location provides the brain with an extra anchor regarding the letter positions (in addition to the word beginning and the word end). They also ventured that each hemisphere rather independently activates word candidates that agree with the input it receives and integrates this information with that of the other hemisphere only at a relatively late stage. Finally, they assumed that the encoding is coarser in the subdominant hemisphere than in the dominant hemisphere. On the basis of these assumptions, Shillcock et al. were able to simulate the OVP curves of Brysbaert (1994). Importantly, in this model, interhemispheric communication does not take place before the word processing 'as such' starts (as in the SERIOL model) but is part of the processing itself. However, both models are based on the splitting of visual input across the midline and incorporate the need for interhemispheric transfer.

A weakness of Brysbaert's (1994) findings was that the laterality of the participants had been assessed in a suboptimal way with the use of visual half-field tasks. In recent years, it has become possible to assess language dominance in healthy participants much more reliably by making use of blood-flow measurements (e.g., Knecht et al., 2000).

Therefore we recently ran a new set of experiments, to obtain OVP data from participants whose language dominance we could be 100% sure of. We assessed the laterality of 10 left-handed participants using fMRI (see Hunter, Brysbaert, & Knecht, 2007). We used a mental word generation task that is known to produce marked language lateralisation in the scanner setting (Knecht et al., 2003). Participants were asked to generate words starting with a particular letter (e.g., 'R'). We then looked at the BOLD response in a predefined region of interest (ROI), containing BA 44 and BA 45 (Broca's area), in the left and right hemisphere to determine individual dominance patterns. In this study, we found that two of the participants we examined, had nearly exclusive activity in the right hemisphere (i.e., were right dominant for word generation), two others had bilateral activity, and the remaining six showed strong activity in the left hemisphere. These 10 participants further took part in an OVP word naming experiment similar in design to the experiment run by Brysbaert (1994) (see Figure 1). The task was to name English nouns of four- and seven-letter length, which were presented on screen for 180 ms each, as fast as possible (see Hunter, Brysbaert, & Knecht, 2007).

Table 1 shows the extent of activation for each participant in the ROI within the left and right hemisphere for the fMRI experiment and the naming latencies for four- and seven-letter words after fixation on the first letter and fixation on the last letter for the OVP task. Similar to Brysbaert (1994) nearly all our participants showed a word-beginning superiority effect, except for those participants with right language dominance when they were naming short words of four letters.

TABLE 1

Voxel count in ROI in the left and right hemisphere, fMRI based laterality indices (LI) and naming latencies when fixating the first and the last letters for four- and seven-letter words are given for each participant.

		MNI Coordinates		*MNI Coordinates*		*4-letter OVP*		*7-letter OVP*	
	Active Voxels Left ROI	*x, y, z*	*Active Voxels Right ROI*	*x, y, z*	*fMRI_LI*	*First Letter*	*Last Letter*	*First Letter*	*Last Letter*
Sub_10	11378	−51 +15 +24	0		1	420.33	450.44	425.25	450.17
Sub_07	7021	−51 +13 +24	110	+59 +13 +36	0.97	455.58	485.07	461.15	561.61
Sub_02	8953	−51 +16 +22	128	+49 +17 +29	0.95	496.84	505.84	480.94	545.86
			100	+43 +5 +31					
Sub_03	5812	−52 +15 +25	169	+49 +16 +5	0.945	445.86	454.32	467.17	513.52
Sub_08	9469	−52 +13 +22	2213	+55 +10 +14	0.62	506.7	515.2	514	564.68
Sub_09	7054	−50 +17 +26	1606	+56 +19 +29	0.603	510.16	520.31	502.42	548.81
			137	+45 +18 +9					
Sub_01	5265	−49 +12 +27	2399	+59 +11 +17	0.37	484.67	496.69	495.53	514.78
Sub_04	2940	−50 +10 +22	3029	+54 +15 +10	−0.19	448.39	454.67	479.89	501.46
			1214	+51 +7 +32					
			100	+54 +33 +2					
Sub_06	1076	−52 +14 +12	7206	+52 +17 +22	−0.66	541.56	531.24	538.43	558
	238	−42 +11 +31							
	144	−51 +12 +44							
Sub_05	143	−44 +3 +31	8250	+52 +16 +22	−0.966	490.69	485.06	482.46	487.56

In this paper, we go on to investigate to what extent a mathematical model that is based on some of the principles of the SERIOL model can account for the pattern of results we observed in this new study. In particular we aim to verify the importance of interhemispheric transfer as a parameter in this and related models of word reading.

EMPLOYING A MATHEMATICAL MODEL BASED ON SERIOL

Principles of the model

As indicated above, the SERIOL model includes two components that transform the retinal input into a code that is able to activate word representations. The first is an inversion of the retinal acuity gradient, such that the activity of the beginning letters of a word is higher than the activity of the end letters. This transformation is in particularly necessary for that part of the word that is presented to the left of the fixation location (at least for languages read from left to right). In the part presented to the right of the fixation location, the activity levels of the different letters coincide with the requirement that the activity of the first letters is higher than the activity of the last letters. In the extreme case, a fixation on the first letter induces a perfect correspondence between the retinal acuity gradient and the required differences in activity levels: The activation level of the first letter is higher than the activation level of the second letter, which is higher than the activation level of the third letter, and so on. In contrast, a fixation on the last letter results in a complete contradiction between the retinal acuity gradient and the required activation gradient, because now the activation of the last letter is higher than the activation of the second last letter, and so on. So, an inversion of the retinal activity levels is needed for all the letters that fall to the left of the fixation location.

The second component of the model is the requirement of information transfer from the non-dominant hemisphere to the dominant one. For a person with left hemisphere dominance, this will be needed when the person fixates the last letter. For a person with right hemisphere dominance this is required when the person fixates the first letter.

Whitney (as described in detail in Whitney, 2001, *Appendix B*) provided a simple mathematical model that captured the above two components (in addition to two other components that are not discussed here, namely the base processing time for a word and the time cost of phonological assembly). The following criteria were taken into account:

a. Letters occurring in the hemifield ipsilateral to the dominant hemisphere have to undergo callosal transfer; the time cost is independent of the number of letters. This cost is either 0 (no letters to transfer) or a positive constant, which Whitney (2001) estimated to be 9 ms on the basis of the data reported in Brysbaert (1994) (Figure 2).

b. Letters occurring in the LVF will induce a cost because the retinal acuity gradient must be inverted. The inversion cost increases with the number of letters for which the activation level has to be inverted. Furthermore, on the basis of Brysbaert (1994), Whitney assumed that the cost of the acuity gradient inversion is higher if the inversion has to happen in the non-dominant hemisphere than when it occurs in the dominant hemisphere.

Whitney's resulting model looked as follows:

$$\text{cost}\ (N, T) = \max\ (0, E\ (T) \times ((N - A)^2 + B)) \qquad (1)$$

where N is the number of letters and T indicates whether or not callosal transfer is needed (T = 1 and T = 0 respectively). E(T) specifies the relative cost per letter that needs inversion in the dominant and the non-dominant hemisphere. E(T) = 1, if T = 0; E(T) = C, if T = 1, where C is a real constant > 1.0. A and B are integer constants. The max function prevents the cost from becoming negative.

Modelling the data amounts to assigning values to the parameters A, B, and C. Because a model is particularly interesting if the values remain constant across studies (rather than having to be estimated anew each time in order to obtain a reasonable fit), we opted to consider the values defined in Whitney (2001) upon Brysbaert (1994) data as fixed. According to these fixed values E(T) = 1 in the dominant hemisphere and E(T) = 1.7 in the non-dominant hemisphere. A and B were estimated in Whitney (2001) to be A = 3 and B = 4.

Table 2 displays the predicted values of the model for four-letter and seven-letter words for the different laterality groups. For instance, right dominant participants incur the following costs for four-letter words:

fixation first letter: callosal transfer = 9 ms, inversion cost = 0
fixation last letter: callosal transfer = 0, inversion cost = $1\text{x}((4–3)^2 + 4) = 5$

Therefore, naming times are predicted to be 4 ms faster for fixations on the last letter than for fixations on the first letter. For left dominant participants, the costs for 4-letter words are:

fixation first letter: callosal transfer = 0 ms, inversion cost = 0
fixation last letter: callosal transfer = 9, inversion cost = $1.7 \times ((4–3)^2 + 4) = 8.5$

Therefore, the model predicts 17.5 ms longer naming times for fixation on the last letter than for fixation on the first letter. Assuming that for the

TABLE 2
Predicted values and actual difference scores of the SERIOL model.

	Predicted model values		*Actual difference scores*	
	4-letter	*7-letter*	*4-letter*	*7-letter*
RD	−4	11	−8	12
BI	5	20	9	20
LD	17	42	16	55

Columns 2 and 3 show the predicted values of the SERIOL model for differences in naming latencies between fixation on the last letter and fixation on the first letter for four- and seven-letter words in participants with different patterns of language dominance (RD = right dominant, BI = bilateral representation, LD = left dominant). Estimates are based on the parameter values from Whitney (2001) upon the basis of the data from Brysbaert (1994). Columns 4 and 5 show the actual differences observed between RT for fixation on the last letter and RT for fixation on the first letter for the different language laterality groups and the different word lengths tested.

bilateral participants there are no differences in callosal transfer costs and inversion costs between the hemispheres, a time cost of 5 ms due to inversion is predicted for fixations on the last letter. Table 2 also shows the results for analogous calculations for seven-letter words.

Fit of the model to the new data

Next, we compare the predictions of the model to the values we obtained for our participants in our new set of experiments (see Table 1). The group, to which a participant belonged, was determined by looking for which cell of Table 2 (columns 2 and 3) the squared difference between the model data and the actual data was minimal, using equation 2:

$$(\text{4-let\_Model} - \text{4-let\_Part})^2 + (\text{7-let\_Model} - \text{7-let\_Part})^2 \qquad (2)$$

Drawing upon model data and experimental data participants are classed as RD, BI, or LD. The allocation was as follows: Participants 5, 6 = RD, participants 1, 4 = BI and participants 2, 3, 7, 8, 9, 10 = LD.

The goodness of fit of the model to the actual data can also be assessed by looking at the obtained values of the participants in the different groups. For instance, the two RD participants showed a difference between *RT for fixation on the last letter* and *RT for fixation on the first letter* for 4-letter words of –5.6 ms and –10.3 ms respectively (see Table 1), giving an average of –8. The remaining data, calculated in similar manner, are given in Table 2 (columns 4 and 5), which shows the average of the differences for RD, BI, and LD groups for four- and seven-letter words in.

A comparison of the actual difference scores to the predicted difference scores (Table 2) reveals how close the fit is and how well we can discriminate between the three groups on the basis of the SERIOL model: We get exactly the same clustering on the basis of the word naming latencies as we had on the basis of the brain imaging data (see Table 1). This is also illustrated in Figure 3. When the individual difference scores for the four- and the seven-letter words are plotted against each other, we see three distinct clusters appearing that also contain the model's predictions.

Does the SERIOL model explain anything more than Brysbaert (1994)?

Another interesting question is whether the mathematical model based on SERIOL provides a better fit to our new data than the original Brysbaert (1994) subject data. A criticism against the previously shown analysis might be that the SERIOL based approach is nothing but a good fit of

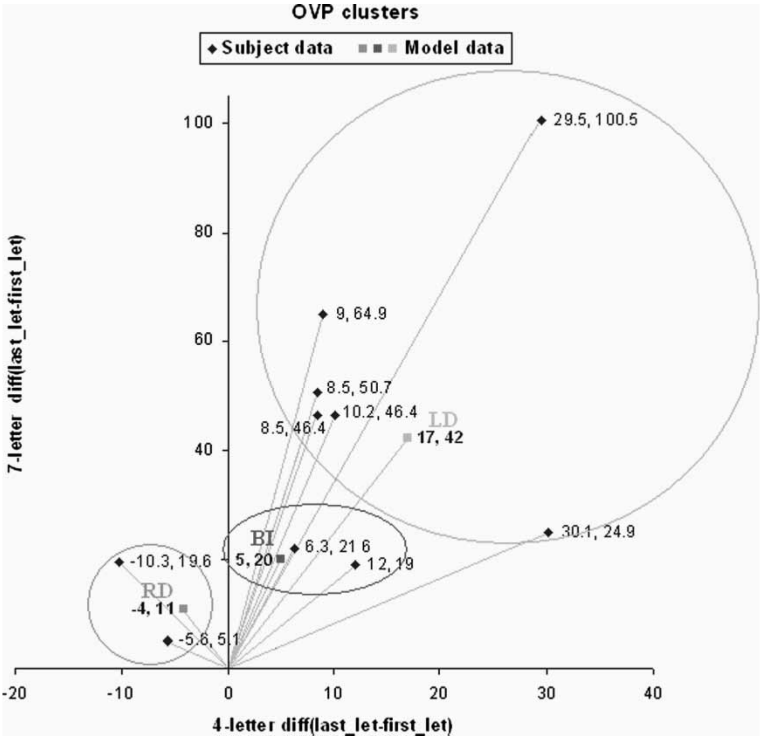

Figure 3. Scatter plot of the difference scores between RTs for fixations on the last and the first letters of four- and seven-letter words for the participants listed in Table 1. Three clusters can be discriminated, distinguishing the left dominant group, the bilateral group, and the right dominant group. The predictions of the SERIOL model for these three groups also fall within their cluster.

Brysbaert (1994) and that Brysbaert (1994) is a good fit of the present data. In that case, the model itself would not add anything.

To investigate this, we calculated the values that would be predicted for RD, LD, and BI groups based on the original Brysbaert (1994) average subject data. To do so, we assumed that the typical group was indeed left dominant and the atypical group was indeed right dominant for language (although, as mentioned earlier, Brysbaert (1994) only assessed this via behavioural measures). The numbers for the bilateral group were then assigned halfway between the values for the right dominant and left dominant groups. The values that would be predicted for RD, LD, and BI groups upon the original Brysbaert (1994) data are given in Table 3 (again looking at RT for fixation on the last letter, and RT for fixation on the first letter, for four- and seven-letter words).

The so formed predictions for RD, LD, and BI performance were compared with the values of the participants in our new experiment. Participants were then allocated to each laterality group depending on which pair of values minimised function (2). The allocation of participants calculated upon the original Brysbaert (1994) average subject data was as follows: Participant 5 = RD, participants 1, 4, 6 = BI and participants 2, 3, 7, 8, 9, 10 = LD.

Comparing the allocation based on the original Brysbaert (1994) data to the allocation based upon the values predicted by the model, shows us that one right dominant participant (Participant 6) is classified wrongly as bilateral. A comparison between the actual difference scores (Table 2) and the scores based on the original Brysbaert (1994) average subject data (Table 3) reveals that the original Brysbaert (1994) data can not provide as good a fit to our current data as the values predicted by the mathematical model based on SERIOL.

One reason why the model does a better job at classifying our current data is that the constraints of the model compensate for the noisiness of the original data. In the Brysbaert (1994) data the division into left dominant

TABLE 3
Values predicted upon the original Brysbaert (1994) average subject data for differences in naming latencies between fixation on the last letter and fixation on the first letter for four- and seven-letter words.

	4-letter	*7-letter*
RD	2	9
BI	4.5	20
LD	7	30

BI values have been assigned half way between RD and LD participants.

and right dominant groups was not necessarily correct, as some right dominant participants might have actually been bilateral. Looking at Whitney (2001) we see that the SERIOL model tended to overestimate the effect sizes of Brysbaert (1994), forcing in particular the non-left hemisphere dominant participants to be more extreme in the model than in the actual data. Because the model was this time round applied to participants that are in fact right or left dominant, the same parameters yield a better fit. This is further support for the assumptions of the model and shows that the mathematical model does indeed add something new.

An alternative approach using interhemispheric transfer

In the previous sections we described how well the SERIOL model, as defined in 2001, fits the new data we gathered. This adds credit to the model. However, it does not imply that the choices made in the SERIOL model are the only ones that can be made. For instance, rather than incorporating an inversion cost, we may think of a perception cost which occurs when a word is not fixated at the optimal viewing position. It is well known that the initial letters are highly predictive of word identity (e.g., O'Regan, 1990), considerably more so than the final letters. It is therefore possible to posit a perception cost model, in which the disadvantage of fixating on the last letter, relative to the first letter, is the consequence of poorer perception of the letters that are most predictive of word identity.[1]

The informativeness of the foveal area (I) can be defined as follows:

$$I = 1 - (\text{dist}*k) \tag{3}$$

where *dist* is the fixation distance from the first letter (i.e., $\text{dist} = 0$ when fixating on the first letter, $\text{dist} = 3$ when fixating on the final letter of a four-letter word, $\text{dist} = 6$ when fixating on the final letter of a seven-letter word). If we further suppose that the initial letters are perceived more poorly by the non-dominant hemisphere, by a factor of h, then the perception cost is:

$$\text{Cost}\ (N) = N^2 * (1 - I*h) \tag{4}$$

where N is the number of letters (as in equation 1), and I is defined as in (3) above.

By estimating the values of the different parameters, we get a model that fits the empirical data as well as the SERIOL model does. This is the case when k is set to .15 (representing cost per letter distant from the most predictive letter), h is set to .5 for letters that are projected to the non-dominant hemisphere and to 1 for letters that are projected to the dominant hemisphere (i.e., the non-dominant hemisphere is only half as good at

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[1] The authors would like to thank Colin Davis for suggesting this approach (see Stevens & Grainger (2003) for empirical support regarding the mechanisms of the perception cost model).

TABLE 4
Values predicted when using a parameter that represents perception cost (rather than inversion cost), for differences in naming latencies between fixation on the last letter and fixation on the first letter for four- and seven-letter words in participants with RD, BI, or LD language representations.

	4-letter	*7-letter*
RD	−8	13
BI	4	22
LD	19	54

perceiving letters), and when the hemispheric transfer time is set to 7 ms (and added to the perception cost term computed in (4), to give a total cost). Table 4 shows the predicted values we obtain with these parameters for the difference between RT for fixation on the last letter and RT for fixation on the first letter for four- and seven-letter words for the three different laterality groups.

If we now allocate participants to RD, BI, or LD groups based upon the predicted values (again looking at which pair of values minimises function (2)), we obtain an identical distribution as when using the SERIOL based approach (participants 5, 6 = RD, participants 1, 4 = BI and participants 2, 3, 7, 8, 9, 10 = LD) and hence a very good fit to our data. We may be able in the future to distinguish this alternative perception cost approach from the SERIOL model by considering not just fixations on the exterior letters, but also fixations on medial letters.

DISCUSSION

One weakness of theoretical modelling accounts is that model parameters are often estimated in such a manner as to maximise the fit of the model to the empirical data upon which the model is defined. Therefore, there is a legitimate concern whether the model truly captures some aspect of human processing, or whether it is simply the best fit to the results that have been obtained in one particular study. The best way to counter this criticism is to see whether the model can account for the data of other paradigms and whether it can account for the data of new experiments that address the same issue. The present article examined the latter (see, e.g., Whitney & Lavidor, 2004, for an example of the former).

The data of the present study differed in several aspects from the data in Brysbaert (1994). For instance, the present data were based on English words, whereas Brysbaert (1994) looked at the naming of Dutch words. Also, the two studies used completely different techniques to assess language lateralisation (patterns of neural activation in a word generation task vs. differences between stimulus recognition in the left and right visual half-field). Still, the SERIOL model, which had been fitted to the data from Brysbaert (1994), provided a near perfect match to the new data. This is important news, not only for the SERIOL model, but also for the existence of interhemispheric communication and its behavioural implications in central word recognition. These findings stand in strong opposition to the claims made by some researchers that cerebral asymmetry and interhemispheric transfer have a minimal functional impact on visual word recognition in foveal vision (e.g., Dehaene, Cohen, Sigman, & Vinckier, 2005).

Researchers have been slow to incorporate the need for interhemispheric communication in their models of visual word recognition. Brysbaert (2004) argued that this was because they did not have any incentive to do so. The advantages of the inclusion were not clear and by ignoring the issue researchers could keep the vast (and sometimes messy) literature of laterality out of their models. Only recently have researchers started to discover that the existence of brain asymmetries and interhemispheric transfer in central word recognition do shed new light on issues such as the encoding of letter positions (Shillcock et al., 2000), the different impact of word beginning and word end neighbours in visual word recognition (Lavidor & Walsh, 2004), the stronger effect of word length for fixations on the last half of the word than for fixations on the first half (Ellis, 2004), the integration of words in the ongoing sentence context (Coney & Judge, 2006), and eye movements in dyslexics (Kelly, Jones, McDonald, & Shillcock, 2004).

Thus far, two different views have been proposed about how to integrate interhemispheric communication in computational models of visual word recognition. The first is the SERIOL model that we have been drawing on in this article. To some extent, this is the less intrusive model concerning the impact of interhemispheric communication, because the basic claim is that interhemispheric transfer occurs at the front end, before word recognition proper starts. Word recognition will not commence until the first letters have enough computational energy to activate the word representations. Therefore, the need for interhemispheric transfer only affects the total processing time and, importantly, has an impact on the differences in processing time as a function of the fixation location, but the transfer process does not really influence word processing itself. A word is recognised in the same way whether it is fixated on the first letter or on the last letter. The requirement of interhemispheric transfer is a feature that can be integrated (and in our view should be integrated) in nearly every existing model of visual word recognition without really changing any of the underlying assumptions.

Our data do not imply that the assumptions underlying the SERIOL model are the only ones that can account for the OVP effect. Simulations with an alternative perception cost model that does not include an acuity gradient inversion indeed show that such a model equally well accounts for the empirical data, as long as it includes parameters for interhemispheric transfer cost and a difference in processing efficiency between the dominant and the non-dominant hemisphere. Although the differences between the SERIOL and the perception cost model may seem trivial in terms of mathematical modelling, they do have important consequences for the architecture of the computational models upon which these mathematical approximations are based (see Davis & Bowers, 2006, for an in-depth discussion). What our findings show is that the alternatives to the SERIOL model are not full accounts of human visual word processing as long as they do not include differences in processing efficiency between hemispheres and the need for interhemispheric communication.

A more radical view of the role of interhemispheric transfer in visual word recognition has been presented by Shillcock and colleagues (2000). In their split-fovea model, word recognition is fundamentally different after fixation on the first letter, the middle letter, or the last letter. Fixation on the first letter makes the whole word fall in the right visual half-field, so that the word will be processed almost exclusively by the left hemisphere. In contrast, fixation on the last letter will result in the right hemisphere taking the main burden for word recognition. Fixation on the middle of a word sends partial information to both brain halves, which independently activate word candidates that only in a relatively late processing stage compete with one another. Although in this article we do not address the power of the split-fovea model to account for our data, we have little doubt that it will be able to do so. An attractive aspect of the split-fovea model, relative to the SERIOL model, is that it does not assume word processing to wait until the activation level of the first letter reaches a particular threshold.

The only way in which the SERIOL and the split-fovea model can be separated is by looking at the effect of the fixation location for different types of words. For the SERIOL model, the information distribution within a word does not make a difference, whereas it does in the split-fovea model. Therefore, experiments looking at the processing of specific words as a function of the fixation location rather than at the overall performance over tens of unselected words may be able to decide between the two models. Some preliminary evidence in favour of the split-fovea model was recently reported by Knevitt (2007). She reasoned that transposed letters in a word would be particularly harmful if they were sent to different hemispheres. So, she predicted that it would be more difficult to recognise the 'word' tgier (as tiger) after fixation between the second and the third letter than after fixation between the third and the fourth letter, whereas the opposite would be true for the recognition of the 'word' tiegr. To examine this hypothesis she asked participants to indicate whether briefly presented words (presentation time = 250 ms) referred to objects that were larger or smaller than a shoebox.

Participants were told that the words could be misspelled and that they were to ignore these misspellings. Knevitt observed a 20 ms penalty in semantic decision times when participants had to fixate words in such a way that the transposed letters were sent to different hemispheres (i.e., tg-ier and tie-gr) than when they were sent to the same hemisphere (i.e., tgi-er and ti-egr). Further experiments will have to show whether this initial evidence in favour of the split-fovea model is also found in other paradigms.

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