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Embedded Words in Visual Word Recognition: Does the Left Hemisphere See the Rain in Brain?

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To examine whether interhemispheric transfer during foveal word recognition entails a discontinuity between the information presented to the left and right of fixation, we presented target words in such a way that participants fixated immediately left or right of an embedded word (as in *gr*apple, bull*et*) or in the middle of an embedded word (*grapp*le, bu*llet*). Categorization responses to target words were faster and more accurate in a congruent condition (in which the embedded word was associated with the same response; e.g., Does *bullet* refer to an item of clothing?) than in an incongruent condition (e.g., Does *bullet* refer to a type of animal?). However, the magnitude of this effect did not vary as a function of position of fixation, relative to the embedded word, as might be expected if information from the 2 visual fields was initially split over the cerebral hemispheres and integrated only late in the word identification process. Equivalent results were observed in Experiment 1 (long stimulus duration) and Experiment 2 (in which stimulus duration was 200 ms; i.e., less than the time required to initiate a refixation).

Keywords: split fovea, embedded word recognition, semantic categorization

A question that has interested researchers of reading in recent years concerns the distinct contribution made by the two halves of the brain to the process of visual word recognition. Psycholinguists traditionally have assumed that the anatomical divide between the left and right hemispheres does not have implications for foveal word recognition, because all information in the central part of the visual field is projected simultaneously to both hemispheres. However, this assumption has been strongly challenged by anatomical and behavioral evidence suggesting that the language-dominant hemisphere does not initially receive all of the letters in the ipsilateral foveal field but must instead rely on inputs from the nondominant hemisphere (Brysbaert, 2004; Ellis & Brysbaert, 2010). In the present article we report an experiment that sought to test the implications of interhemispheric communication for visual word recognition. Before describing this experiment, we review some evidence relating to interhemispheric communication in reading.

One of the most compelling sources of evidence for the role of interhemispheric communication during visual word recognition is the finding that the optimal viewing position (OVP) is influenced by the cerebral dominance of the participant (Brysbaert, 1994; Hunter, Brysbaert, & Knecht, 2007). Previous research has shown that, for the majority of readers, written words are processed most efficiently when they are fixated between the beginning and the middle (Brysbaert & Nazir, 2005; O'Regan & Jacobs, 1992). The OVP is also the preferred viewing position in natural reading (Rayner, 1998). Research has indicated that there are four factors contributing to the OVP effect (Brysbaert & Nazir, 2005). The first is the rapid drop of visual acuity outside the fixation position. As a result, words are recognized faster when they are fixated in the middle (with all letters falling in central vision) than when they are fixated at the extremes. The left–right asymmetry of the OVP curve is the result of three more variables, the first of which is the reading direction. The OVP is further to the left in languages read from left to right than in languages read from right to left. The second factor causing an asymmetry in the OVP curve is the fact that the initial letters of a word seem to carry more information than the last letters about the identity of the word, possibly because it is easier to identify spoken words with informative beginnings (Shillcock, Ellison, & Monaghan, 2000). Finally, there is a contribution of language laterality: Participants with right hemisphere dominance have their OVP more toward the right than do participants with left hemisphere dominance (Brysbaert, 1994; Hunter et al., 2007; see Figure 1).

The finding of different OVP curves for right-dominant and left-dominant participants is at odds with the assumption of a bilaterally projecting fovea. If both hemispheres have immediate access to all information in the fovea (usually assumed to cover the central 3 degrees of the visual field), it should not make a difference which hemisphere is doing the language processing. Still, as can be seen in Figure 1, Hunter et al. (2007) found that participants with speech production controlled by the left hemisphere were more efficient after fixations on the first letters of the words (making most of the word fall in the right visual hemifield) than participants with speech production in the right hemisphere, who were relatively more efficient after fixations on the last letters of the words (making most of the word fall in the left visual hemi-

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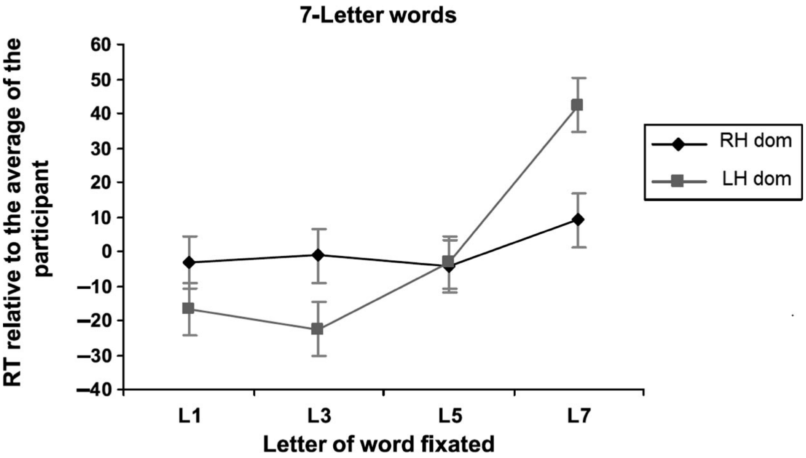

Figure 1. The optimal viewing position (OVP) curves of left-handed participants with left and right hemisphere dominance (as assessed by means of an fMRI study and a word generation task). The participants were asked to name seven-letter words presented in such a way that participants looked at the first letter of the word, the third, the fifth, or the last. Left hemisphere (LH) dominant participants showed the typical *J*-shaped OVP curve, with fastest responses when they were fixating left of the word center. Right dominant (RH) participants showed a much flatter curve, because for them the asymmetric information distribution within words and the reading direction favored the word beginning, whereas the brain dominance favored fixations on the word end. Error bars represent standard errors. RT = reaction time. From "Foveal Word Reading Requires Interhemispheric Communication," by Z. R. Hunter, M. Brysbaert, and S. Knecht, 2007, *Journal of Cognitive Neuroscience, 19,* p. 1384. Copyright 2007 by the Massachusetts Institute of Technology. Reprinted with permission.

field). In addition, Hunter and Brysbaert (2008a) observed that the asymmetry of the OVP curve correlated perfectly with the visual hemifield advantage found for parafoveal word recognition, an effect frequently used to assess cerebral dominance (Hunter & Brysbaert, 2008b; see also Brysbaert, Vitu, & Schroyens, 1996).

If interhemispheric communication is required for foveal word recognition, the logical next question is whether this has implications for word recognition theories. Thus far, most computational modelers of visual word recognition have disregarded this issue without feeling a need to address it empirically. Is this justified? Or are we overlooking an essential element in visual word recognition?

One reason why the need for interhemispheric communication in foveal word recognition might not be important for computational models is that this communication is part of the processes occurring prior to word recognition itself. Most models of visual word recognition start from the assumption that the input consists of abstract letter identities. These are letter representations that have been stripped of their specific font and case. One could assume that the interhemispheric transfer is part of the translation processes from the visual input to the abstract letter identifiers. Within such an *early-integration account*, interhemispheric integration is taken care of before word processing itself begins. This type of account can be found in Whitney's (2001) SERIOL model. According to this model, the input to the word processing system consists of a left-to-right sequence of letter representations and the activation of each letter position is suppressed until its turn is reached. The inhibition is particularly strong for letters presented to the right of the fixation position. Otherwise, these letters would start to feed into the model well before the information of the first letters has arrived. In the SERIOL model there is no discontinuity between the information initially sent to the left hemisphere and the information initially sent to the right hemisphere, because word processing does not start until all information has been integrated in the dominant hemisphere. In the model the difference in the OVP for readers with left versus right hemispheric dominance is entirely due to the time it takes before the information has been united in the dominant hemisphere. The more information initially sent to the nondominant hemisphere, the longer it takes before word recognition can commence. The SOLAR model (Davis, 1999) also incorporates an early-integration account, in which word identification does not commence until all of the letters are assembled in the dominant hemisphere. Davis (1999) further suggested that letter-by-letter reading in alexia could result when cortical damage led to delayed interhemispheric transfer of letter identity information.

In contrast, if the information from the hemifields is not integrated prior to word recognition, the initial divide of information over the left and the right brain halves likely has implications for the way in which written words are recognized. Such a *late-integration account* has been defended by Shillcock et al. (2000). According to their split-fovea model, each hemisphere starts word processing on the basis of the letters it has received, and the outputs of both hemispheres are integrated at a later stage. As a result, word processing is different when a word is fixated on the first, the middle, or the last letter. As Shillcock, McDonald, and Monaghan (2003) formulated it, "The initial division of a fixated word between the two hemispheres goes on to condition the normal reading of that word; there is no early, seamless integration of the contents of the visual cortex in the two hemispheres" (p. 503). Each hemisphere starts processing autonomously, and "interhemispheric communication is based on some of the output of that processing, such as partial semantic activation of words" (p. 503). According to Shillcock et al.'s (2000) model, the OVP effect is due to differences in the efficiency of visual word recognition according to the amount of information initially received by each hemisphere and the effectiveness of the division of labor between the hemispheres.

To empirically assess the potential impact of interhemispheric integration on visual word recognition, we must examine whether there are processing discontinuities between information presented to the left of the fixation position and information presented to the right of the fixation position. Such an approach was reported by Van der Haegen, Brysbaert, and Davis (2009). They started from the finding that words are primed more when two of their letters are transposed (e.g., *jugde-JUDGE*) than when the corresponding letters are replaced by different letters (*junpe-JUDGE*; Perea & Lupker, 2003, 2004).Van der Haegen et al. (2009) reasoned that for a late integration theory it would be more detrimental when the two transposed letters are sent to different hemispheres (i.e., *jug**de,* where the * indicates the position of fixation) than when they are projected to the same hemisphere (e.g., *ju*gde*). The input *jug** to the right hemisphere is as incompatible with the target word *judge* as the input *jun**; similarly, the input **de* to the left hemisphere is not more informative than the input **pe.* In contrast, the input *ju** is compatible with the target word *judge*, and the input **gde* is more informative than the input **npe* if letter positions are not coded in a strict manner (as suggested by the transposed letter priming effect).

Van der Haegen et al. (2009) systematically varied the positions of the transposed letters and the participants' fixation positions. However, they failed to find an extra drop in the priming effect when the participants were viewing between the two transposed letters compared to when the participants were viewing to the left or to the right of the transposed letters. There was an increase of priming as the distance between the transposed letters and the viewing position grew (arguably because letter position coding is less precise away from the viewing position), but there was no effect specific to the split of the transposed letters across the hemispheres. Van der Haegen et al. (2009) concluded that their findings were more in line with an early-integration account (no processing discontinuity at the fixation location) than with a late-integration account.

The present studies were further attempts to test the late-integration account, by making use of an even stronger manipulation. Our starting point was the semantic competition effect for embedded subset words reported by Bowers, Davis, and Hanley (2005). They found that participants needed more time to indicate that the word *warm* did not refer to a body part than to indicate that the word *gaunt* did not refer to a body part, whereas the reverse pattern was obtained when participants were asked to indicate whether these words referred to a family relative. Bowers et al. (2005) had predicted this pattern of results on the basis of the semantic properties of the words embedded within the target stimuli. Thus, the meaning of the embedded word *arm* in *warm* is incongruent with the "no" response to the question "Is this a body part?" Similarly, there is an incongruence between the meaning of the embedded word *aunt* in *gaunt* and the "no" response to the question "Is this a relative?" The incongruence results in longer reaction times and more mistakes.

If there is a discontinuity between the information presented to the left of the fixation and the information presented to the right of the fixation, one would predict that the interference effect of the embedded word will be stronger when the complete word is presented to one hemisphere (as in *w*arm*) than when the word is divided over the left and the right hemisphere (as in *wa*rm*). In order to make sure that the effect was not confounded by the viewing position, we systematically manipulated the position of the embedded word within the carrier word and the fixation position of the participant in the carrier word. Participants were asked to make semantic categorizations to target stimuli that contained embedded words at the beginning (e.g., *bullet, dogma*) or at the end (e.g., *swine, grapple*). In addition, participants were asked to fixate in such a way that either the embedded word was entirely presented to one visual hemifield (as in *bull*et, dog*ma, s*wine,* or *gr*apple*) or the embedded word was split over both hemifields (as in *bu*llet, do*gma, swin*e,* or *grapp*le*).

Finding a stronger congruency effect in the condition where the embedded word is sent entirely to one hemisphere than when it is distributed over both hemispheres would be powerful evidence for a late-integration account of interhemispheric communication in visual word recognition. Not finding such a difference would be consistent with models that do not consider interhemispheric integration an important aspect in visual word recognition.

Experiment 1

Method

Participants. The participants were 41 volunteers from Royal Holloway, University of London. Participants had normal or corrected-to-normal vision and were right-handed native speakers of English. They were offered £5.00 in exchange for their time.

Stimuli and design. Three variables were factorially manipulated in the experimental design: embedding position (left or right), fixation position (left or right), and congruency (congruent or incongruent). The first factor, embedding position, refers to whether the subset word was embedded in the initial (e.g., *bus*t) or the final (e.g., c*lamp*) part of the word. We selected 80 words that contained embedded words, 40 of which were initial subsets and 40 of which were final subsets. Embedded words were three to five letters long, and carrier words were one, two, or three letters longer. The embedded word comprised more than half of the total letters in all cases. All embedded words were considerably more frequent than the carrier words (mean CELEX frequency for embedded words = 90 per million; for carrier words = 5 per million; Baayen, Piepenbrock, & van Rijn, 1993). The initial and final embedded items were matched, with N-Watch software (Davis, 2005), on length, frequency of carrier, frequency of embedded word, and *N* of the carrier word (see Table 1). Eighty words were used as fillers. These fillers were exemplars of the semantic categories chosen for the embedded words and were matched in length to the carrier words (see the Appendix for a full list of targets).

The second factor, fixation position, was varied by manipulating the position of the word relative to a fixed fixation location. Participants were instructed to fixate between two vertical lines that were presented above and below the line where the target word would appear. The target word was subsequently presented

Table 1
Stimulus Characteristics for Targets and Embedded Words

Position of embedding	Initial embedding	Final embedding	Analysis of variance
Target length (no. letters)	3.63	3.78	*F*(1, 79) = 1.09, *ns*
Target frequency (per million)	90.15	83.27	*F*(1, 79) = 0.10, *ns*
Target *N*	11.78	10.83	*F*(1, 79) = 0.51, *ns*
Carrier frequency (per million)	5.21	5.20	*F*(1, 79) = 0.00, *ns*
Carrier length (no. letters)	5.18	5.30	*F*(1, 79) = 0.35, *ns*

in such a way that the fixation position was to the left of the word's center on half of the trials and to the right of center on the other half of the trials. The precise position was chosen so that (on half of the trials) the embedded word was the only part of the stimulus on one side of the fixation point (e.g., this was the case when participants were asked to fixate between the *r* and *a* of *gr*apple* or between the *n* and *e* of *corn*ea*); on the remaining trials the fixation position was in a symmetrical position to the other side of fixation (e.g., between the *p* and *l* of *grapp*le* or the *o* and *r* of *co*rnea*). Filler trials were presented in the same manner.

The third factor, congruency, refers to whether the correct response to the carrier word was congruent with the response that would be correct for the subset. The embedded words were assigned to 40 semantic categories (item of clothing, type of fruit, etc.; see the Appendix for the full list of semantic categories). The critical trials were those in which the embedded subset was a member of the semantic category that formed the basis of participants' responses, so that there was an incongruency between the correct response to the carrier word (which was always "no") and the response that would be correct for the embedded word (e.g., "Is gunk a weapon?"). On congruent trials, the embedded subset was not a member of the semantic category, and hence the correct response to the carrier word was congruent with the response that would be correct for the subset (e.g., "Is gunk a vehicle?"). Each block of semantic categorizations also included a number of filler items that demanded a "yes" response. Congruency (congruent or incongruent) and fixation position (left or right of word center) were rotated over four experimental lists such that each carrier word target (containing either initial or finally embedded words) was seen by all participants.

Procedure. Stimulus presentation and data recording were controlled by the DMDX software (Forster & Forster, 2003) running on a Pentium III personal computer. Stimuli were presented in white letters on a black background, in 12-point Courier New (a fixed width font). Participants were seated 60 cm away from the screen. At this distance, a 6-letter word covered a visual angle of 2.67°.

Participants were presented with a semantic categorization question at the beginning of a block of trials (e.g., "Which of the following words are examples of animals?"). Subsequent words were categorized using a two-button response box, with a "yes" decision corresponding to a right-hand button press.

Participants were asked to fixate the area between the two vertically aligned lines that were presented at the onset of each trial for 70 screen refreshes (1,162 ms). Then the words were presented for a maximum of 70 screen refreshes or until the participant responded, while the vertical lines remained visible. Participants were asked to respond as fast and accurately as possible. Following their response, participants were given feedback to remind them of the current semantic category and ensure attentiveness. Participants pressed the spacebar after each trial to move to the next item or block of trials. Each participant was presented with a different random order of semantic categories and items.

To make sure that the participants were fixating between the two vertical lines at the onset of the stimulus word, we presented a digit instead of a word at random intervals for 80 ms, directly followed by a backward mask (a # symbol). Participants had to categorize the digit as being greater than or less than 5. They were told that their data would be discarded if they made more than 30% errors. Digit trials (24/180 trials) were not signaled in advance and were presented at random throughout the experiment to ensure compliance with the fixation instructions (for a similar procedure, see Van der Haegen et al., 2009).

Results

The performance on the digit task was examined in order to check that participants had maintained an accurate fixation on the correct screen location. Participants were excluded if their error rates on the digit trials exceeded 30%. This criterion led to exclusion of two participants. In addition, three items were excluded from the analysis: Two of them had error rates of greater than 30% (*pants* and *picket*), and one of them turned out to be incongruent at both viewing positions (*c*owl* vs. *cow*l*).

Data were analyzed both by participants and by items using four-factor analyses of variance (ANOVAs). The analysis by participants treated congruency (two levels), embedding position (two levels), and fixation position (two levels) as repeated factors and list (four levels) as an unrepeated factor. The analysis by items treated congruency and fixation position as repeated factors and embedding position and list as unrepeated factors. Latency and error data by participants are shown in Table 2.

Table 2
Reaction Times, in Ms, and Errors (%) in Experiment 1 as a Function of Embedding Position and Fixation Position

Condition	Example	Incongruent	Congruent	Effect
Left embedded, fixation left	b*eard	792 (6.7)	743 (2.8)	49 (3.9)
Left embedded, fixation right	bear*d	772 (5.4)	760 (4.5)	12 (0.9)
Right embedded, fixation left	c*inch	782 (4.9)	746 (2.8)	36 (2.1)
Right embedded, fixation right	cinc*h	771 (5.6)	753 (2.6)	18 (3.0)

The ANOVAs on the "no" response latency data showed a main effect of congruency: categorizations were slower for the incongruent condition than for the congruent condition, $F_1(1, 35) = 21.15, p < .001$; $F_2(1, 69) = 7.75, p < .01$; minimum $F'(1, 102) = 5.66, p < .05$; F_1 95% CI [0.16, 0.42 *SD* units]; F_2 95% CI [0.10, 0.60 *SD* units]. There was an interaction between congruency and fixation position that was significant by participants but not by items, $F_1(1, 35) = 5.23, p < .05$; $F_2(1, 69) = 2.06$, *ns*; minimum $F'(1, 102) = 1.48$, *ns*; F_1 95% CI [0.02, 0.28 *SD* units]; F_2 95% CI [−0.16, 0.19 *SD* units]. This marginal interaction reflected the fact that there was a numerically larger congruency effect for words that were fixated to the left of center than for words that were fixated to the right of center. No other results reached significance either by participants or by items. In particular, there was no evidence at all for the predicted three-way interaction among congruency, fixation position, and embedding position, $F_1(1, 35) = 0.61$, *ns*; $F_2(1, 69) = 0.52$, *ns*; minimum $F'(1, 102) = 0.28$, *ns*; F_1 95% CI [−0.08, 0.19 *SD* units]; F_2 95% CI [−0.26, 0.53 *SD* units].

The errors analysis showed a main effect of congruency: More errors were made in the incongruent condition than in the congruent condition, $F_1(1, 35) = 8.48, p < .001$; $F_2(1, 69) = 8.51, p < .001$; minimum $F'(1, 102) = 4.25, p < .05$; F_1 95% CI [0.11, 0.56 *SD* units]; F_2 95% CI [0.11, 0.58 *SD* units]. No other effects reached significance in the error analyses.

For completeness, we also analyzed the effect of fixation position on responses to filler trials (demanding a "yes" response). Note that the filler stimuli were not selected to contain embedded words, and thus congruency and embedding position were not included in this analysis. Also note that we did not manipulate the fixation position within individual words. Instead, half of the filler words were fixated on the beginning and half on the end, so that the F_2 analysis is a between-items comparison (both conditions were matched on length and frequency). Left fixations on the target words resulted in significantly faster and less error prone reaction times (RTs) than did right fixations: left fixation mean RT = 632 ms, right fixation mean RT = 669 ms; $t_1(38) = 5.53$, $p < .001$, 95% CI [0.37, 0.81 *SD* units], $t_2(77) = 2.52$, $p < .02$, 95% CI [0.02, 0.94 *SD* units]; left fixation mean error = 4.9%, right fixation mean error = 8.6%; $t_1(38) = 4.41$, $p < .001$, 95% CI [0.37, 0. 98 *SD* units], $t_2(77) = 1.70$, $p > .05$, 95% CI [−0.01, 0.13 *SD* units].

Discussion

Experiment 1 showed that semantic categorization responses were slowed by the presence of an incongruent embedded word, independent of whether the embedded word was sent entirely to one hemisphere or whether it was initially divided over both hemispheres. As indicated in the Introduction, this finding is in line with the early-integration account of the split-fovea theory. According to this account, all letter information is integrated in the dominant hemisphere before word processing starts. As a result, no discontinuity is predicted between the information presented to the left of the fixation position and the information presented to the right of the fixation position.

A potential criticism of the above interpretation is that the relatively long presentation duration of the target words may have encouraged participants to refixate while preparing their categorization response.[1] This might in turn have affected our ability to observe the predicted three way interaction of congruency, embedding, and fixation. In order to check that the long target duration used in Experiment 1 did not introduce unwanted biases, we repeated the experiment using a target duration of 200 ms. This presentation time is long enough for participants to see the word clearly and short enough to prevent eye movements with foveally presented stimuli (Walker & McSorley, 2006).

Experiment 2

Method

Participants. The participants were 45 volunteers from Royal Holloway, University of London. Participants had normal or corrected-to-normal vision and were right-handed native speakers of English. They were offered £5.00 in exchange for their time.

Stimuli and design. The stimuli and design were identical to those described in Experiment 1.

Procedure. The only difference in procedure from Experiment 1 was the reduction of the target duration to 200 ms.

Results

The exclusion criteria used in Experiment 1 were also applied to the data collected in Experiment 2, leading to the exclusion of five participants who did not satisfy the accuracy criterion performance in the digit task. In addition, two items were excluded from the analysis, one because it had an error rate greater than 30% (*picket*) and the other because it was incongruent at both viewing positions (*cowl*; see Experiment 1). Data were analyzed as described in Experiment 1; reaction time and error data are shown in Table 3.

As in Experiment 1, the ANOVAs on the "no" response latency data showed a main effect of congruency, with slower categorization responses in the incongruent than in the congruent condition, $F_1(1, 36) = 22.06, p < .001$; $F_2(1, 70) = 5.02, p < .05$; minimum $F'(1, 96) = 4.09, p < .05$; F_1 95% CI [0.14, 0.38 *SD* units]; F_2 95% CI [0.03, 0.58 *SD* units]. There was a main effect of embedding that was significant by participants but not by items, $F_1(1, 36) = 5.48, p < .05$; $F_2(1, 70) = 1.63$, *ns*; minimum $F'(1, 101) = 1.26$, *ns*; F_1 95% CI [0.02, 0.27 *SD* units]; F_2 95% CI [−0.10, 0.46 *SD* units]. This reflected the fact there were longer response times to target words containing left-embedded words.

As in Experiment 1, no other results reached significance either by participants or by items. In particular, the results of Experiment 2 confirmed that there was no evidence for a three-way interaction among congruency, fixation position, and embedding position using a shorter target duration, $F_1(1, 36) = 0.25$, *ns*; $F_2(1, 69) = 0.52$, *ns*; minimum F' (1, 101) = 0.17, *ns*; F_1 95% CI [−0.19, 0.12 *SD* units]; F_2 95% CI [−0.34, 0.31 *SD* units].

The errors analysis showed that there was a main effect of congruency, $F_1(1, 36) = 7.51, p < .01$; $F_2(1, 70) = 5.41$; minimum F' (1, 101) = 3.14, $p < .01$; F_1 95% CI [0.07, 0.51 *SD* units]; F_2 95% CI [0.04, 0.58 *SD* units], such that a larger number of errors were made in the incongruent condition. In addition, there was a main effect of embedding, $F_1(1, 36) = 17.97, p < .001$;

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[1] This possibility was suggested by Carol Whitney.

Table 3
Reaction Times, in Ms, and Errors (%) in Experiment 2 as a Function of Embedding Position and Fixation Position

Condition	Example	Incongruent	Congruent	Effect
Left embedded, fixation left	b*eard	776 (12.1)	751 (7.0)	25 (5.6)
Left embedded, fixation right	bear*d	795 (9.3)	774 (4.9)	21 (4.3)
Right embedded, fixation left	c*inch	771 (6.0)	748 (5.0)	23 (1.0)
Right embedded, fixation right	cinc*h	776 (5.5)	740 (4.5)	36 (1.0)

$F_2(1, 70) = 5.8$, $p < .001$; minimum F' $(1, 101) = 4.38$, $p < .05$; F_1 95% CI [0.16, 0.46 *SD* units]; F_2 95% CI [0.06, 0.62], with a larger number of categorization errors made with targets containing left-embedded words. No other effects reached significance by participants or by items in the errors analyses.

The effect of fixation position on responses to filler trials (demanding a "yes" response) were analyzed as described in Experiment 1. Left fixations on the target words resulted in faster reaction times than did right fixations, an effect that was significant by participants but not by items, and there were no difference in error rates between left and right fixations (left fixation mean RT = 631 ms, right fixation mean RT = 658 ms; $t_1(39) = 3.75$, $p < .001$, 95% CI [0.27, 0.91 *SD* units], $t_2(77) = 1.42$, *ns*, 95% CI [−0.07, 0.12 *SD* units]; left fixation mean error = 7.5%, right fixation mean error = 7.6 %; $t_1(38) = 0.46$, *ns*, 95% CI [−0.67, 0.30 *SD* units], $t_2(77) = 1.70$, *ns*, 95% CI [−0.47, 0.49 *SD* units].

To further investigate the commonalities and differences between Experiments 1 and 2, we ran a combined analysis of the critical items (see Tables 2 and 3). This analysis confirmed the clear main effect of congruency, both on RTs and error rates, which did not differ significantly between the experiments. The analysis also pointed to a higher error rate in Experiment 2 than in Experiment 1: $F_1(1, 71) = 3.65$, $p = .06$; $F_2(1, 69) = 8.19$, $p < .01$. Finally, there was a main effect of embedding, $F_1(1, 71) = 17.73$, $p < .001$; and $F_2(1, 69) = 5.05$, $p < .05$, with more errors made to left-embedded words than to right-embedded words. No other effects reached significance in both F_1 and F_2.

Discussion

The main finding of Experiment 2 was that the congruency effect remained the same when the stimulus presentation was limited to 200 ms. As in Experiment 1, this congruency effect was not smaller when the embedded word was split across visual fields (and thus, according to split fovea theory, distributed over the hemispheres) than when the embedded word was in one visual field (i.e., sent to a single hemisphere). If anything, there was a trend in the opposite direction (30.5 ms vs. 22 ms), as also found in Experiment 1 (see Table 2). The only real difference produced by the shorter presentation time was an increase in errors (6.8% in Experiment 2 vs. 4.4% in Experiment 1). Errors were particularly high for the left-embedded words in Experiment 2, and this was true both in the congruent and the incongruent condition. The responses to these items also tended to be slower. The fact that brief presentation times increase the impact of information presented to the left of the fixation position has been noticed before by Van der Haegen et al. (2009, p. 117) and has been related to left–right seriality in word recognition. If words are processed from beginning to end, limited presentation duration is more likely to cut short information processing at the end of the word than at the beginning.

General Discussion

In the present studies we tested whether the need for interhemispheric transfer in foveal word recognition entails a processing discontinuity between the information presented to the left of the fixation position and the information presented to the right of the fixation position. We tested this by presenting embedded words in carrier words so that they were either displayed entirely to one hemisphere (*bull*et, gr*apple*) or split across hemispheres (*bu*llet, grapp*le*). In previous research, Bowers et al. (2005) had shown that embedded words interfere with a semantic decision if the meaning of the embedded word contradicts the required semantic response. We reasoned that an information discontinuity between information sent to different cerebral hemispheres would entail a smaller interference effect when the information of the embedded word is split (as in *bu*llet*) than when it is sent completely to one hemisphere (as in *bull*et*).

Our results replicated those of Bowers et al. (2005; see also Nation & Cocksey, 2009, for a replication with beginning readers). Participants were 25–30 ms slower to indicate that *bullet* is not an animal than that it is not a flower. However, there was no evidence that this effect was larger in the conditions where the participants fixated next to the embedded word (as in *gr*apple, bull*et*) than in the conditions where the participants fixated in the middle of the embedded word (*grapp*le, bu*llet*). Evidence for such an interaction would have provided clear support that there was independent hemispheric recognition of the embedded word. If anything, the trend went in the opposite direction: There was more interference when participants were looking at the embedded word than when they were looking before or after the embedded word (33.5 vs. 24 ms in Experiment 1; 30.5 vs. 22 ms in Experiment 2), in line with the observation that visual acuity is sharpest at the fixation position and drops rapidly outside this point. These findings are evidently more in line with an early-integration account (Davis, 1999; Whitney, 2001) than with a late-integration account (Shillcock et al., 2000).

A criticism by proponents of the late integration account might be that we failed to find the expected three-way interaction among congruency, fixation position, and embedding position because each hemisphere treated the letters it received as a subset of a longer word. That is, the two hemispheres engaged in sublexical processing rather than treating their initial inputs letters as potential lexical candidates. In the case of the stimulus *c*inch,* the left hemisphere searched for words ending in *inch* that were longer than four letters and not for the word *inch* itself.[2] A problem with this account, however, is how it could explain the fact that we found a healthy inhibition effect of the embedded word, both when it was presented to a single hemisphere (*c*inch*) and when it was distributed over the hemispheres (*cinc*h*).

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[2] This possibility was suggested to us by Padraic Monaghan.

A further criticism might be that participants failed to adhere to the fixation requirements and that this prevented us from seeing the smaller interference effect when participants fixated in the middle of the embedded word than when they fixated to the left or to the right of it. This criticism also seems very unlikely to us. First, the OVP effect is exactly the same when fixations are controlled with digits, as was done here, and when fixations are controlled with an eye tracker (Van der Haegen, Drieghe, & Brysbaert, 2010). Second, we failed to find any difference in interference effect between Experiment 1 (free vision) and Experiment 2 (limited stimulus exposure). Third, for the filler items, which required the usual "yes" response, we saw the expected faster decision times after fixations on the word beginning than after fixations on the word end (Experiment 1: 632 vs. 669 ms; Experiment 2: 631 vs. 658 ms).[3] Finally, the effect we observed was an interference effect, not a facilitation effect. It is difficult to see why participants would have moved their eyes if on half of the trials they would have experienced less interference by following the instructions.

It is interesting that, in both Experiment 1 and Experiment 2, the semantic interference effect was the same for beginning and final embedded subsets (e.g., for *hat* in *hatch* and *apple* in *grapple*; Experiment 1: 30.5 ms vs. 27 ms, Experiment 2: 23 ms vs. 29.5 ms). Exactly the same equivalence was reported by Bowers et al. (2005). The presence of semantic interference effects for final subsets poses a problem for traditional models of orthographic input coding, which assume strict coding of letter position (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Grainger & Jacobs, 1996). In such models, *apple* and *grapple* do not share any common letter units, and hence there is no reason to expect participants to be slower to decide that *grapple* is not a type of fruit than to make some other categorization that does not give rise to a conflicting response (e.g., "Is this an item of clothing?"). Newer models of orthographic input coding (e.g., Davis, 1999, in press; Grainger & Whitney, 2004), by contrast, are sensitive to relative rather than absolute position and predict the automatic activation of final-embedded subsets.

Nevertheless, although the semantic interference effect did not differ as a function of embedding position, the data did show more errors overall to targets containing left-embedded words than to targets containing right-embedded words. This pattern is consistent with studies using the lexical decision task, which have fairly consistently shown greater interference effects for beginning than for final-embedded subsets (Davis, Perea, & Acha, 2009; Davis & Taft, 2005). The asymmetry may reflect the particular importance of the initial letters in word identification (e.g., White, Johnson, Liversedge, & Rayner, 2008).

In summary, our results, together with those of Van der Haegen et al. (2009), indicate that modelers of visual word recognition are warranted in their assumption that their computational models need not explicitly integrate the need for interhemispheric communication. As assumed by Davis (1999) and Whitney (2001), this communication takes place before word processing proper starts and is part of the translation of the raw input into an ordered sequence of abstract letter identities that activate the stored word representations. Even though the viewing position makes word processing more or less efficient (see the Introduction), it does not fundamentally alter the way in which the words are processed. When a word is viewed at nonoptimal positions, it simply takes longer for all the letters to arrive in the dominant hemisphere.

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[3] In this respect it should be noted that the manipulation of fixation position in the present experiment was quite small and was associated with some variability (due to variations in the size of the carrier and embedded words); in the majority of cases there were only one or two letter positions separating the left and right fixation positions (e.g., *ha*tch* vs. *hat*ch*; *b*ust* vs. *bus*t*). Thus, we would not expect to observe especially large effects of fixation position per se.

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(*Appendix follows*)

Appendix

Stimuli Used for Experiments 1 and 2

Table A1

Items Used for "No" Response Trials

Target	Embedding	Incongruent category	Congruent category
beard	left	animal	number
cowl[b]	left	animal	vehicle
lambast	left	animal	type of fuel
bullet	left	animal	flower
dogma	left	animal	apparel
pigmy	left	animal	tree
zillion	right	animal	drink
scat	right	animal	geological feature
brat	right	animal	musical instrument
fury	left	animal body part	vehicle
hornet	left	animal body part	relative
bagel	left	apparel	animal
booth	left	apparel	household item
chat	right	apparel	animal
wring	right	apparel	relative
hippo	left	body part	drink
facet	left	body part	number
hearth	left	body part	metal
lunge	left	body part	geological feature
richest	right	body part	tool
spear	right	body part	living thing
tulip	right	body part	weapon
snail	right	body part	type of conflict
swarm	right	body part	human settlement
bred	right	colour	geological feature
feast	right	direction	apparel
fewest	right	direction	body part
teak	left	drink	body part
swine	right	drink	body part
prose	right	flower	household item
grapple	right	fruit	part of speech
seam	left	geological feature	type of dance
chill	right	geological feature	relative
driver	right	geological feature	illness
frock	right	geological feature	light source
pants[a]	left	household item	direction
clamp	right	household item	relative
depot	right	household item	body part
grope	right	household item	type of rule
caveat	left	human dwelling	fruit
scamp	right	human settlement	body part
scold	right	illness	animal
dice	right	is it cold	unit of time
ascent	right	kind of money	human dwelling
plateau	left	kitchen utensil	apparel
sung	left	light source	vehicle
ambush	right	living thing	is it cold
tint	left	metal	vegetable
plead	right	metal	unit of weight
bellow	left	musical instrument	geological feature
tench	left	number	part of building
canine	right	number	money

(*Appendix continues*)

Table A1 (*continued*)

Target	Embedding	Incongruent category	Congruent category
wallop	left	part of building	animal body part
sword	right	part of speech	animal
twine	left	relative	animal
unclean	left	relative	household item
bison	right	relative	body part
gaunt	right	relative	direction
picket[b]	left	tool	body part
dollop	left	toy	animal
ballet	left	toy	vehicle
napalm	right	tree	colour
ward	left	type of conflict	metal
feline	right	type of dance	body part
gash	left	type of fuel	apparel
broil	right	type of fuel	type of music
node	left	type of gesture	kind of money
guidance	right	type of music	animal
claw	right	type of rule	kitchen utensil
cinch	right	unit of distance	animal body part
simile	right	unit of distance	household item
yearn	left	unit of time	unit of distance
futon	right	unit of weight	animal
cornea	left	vegetable	type of fuel
bust	left	vehicle	unit of distance
planet	left	vehicle	toy
tankard	left	vehicle	type of gesture
vane	left	vehicle	toy
cargo	left	vehicle	animal
gunk	left	weapon	vehicle

[a] This item was removed from Experiment 1. [b] These items were removed from Experiments 1 and 2.

Table A2
Targets Used for the "Yes" Responses (Filler Trials)

Target	Category
baboon	animal
deer	animal
donkey	animal
eagle	animal
ferret	animal
gecko	animal
giraffe	animal
hamster	animal
sheep	animal
tiger	animal
turtle	animal
crest	animal body part
talon	animal body part
bangle	apparel
garter	apparel
glove	apparel
scarf	apparel
ankle	body part
colon	body part
knee	body part
knuckle	body part
navel	body part

(*Appendix continues*)

Table A2 (*continued*)

Target	Category
nostril	body part
pancreas	body part
shin	body part
tonsil	body part
maroon	colour
left	direction
north	direction
beer	drink
cider	drink
daisy	flower
pear	fruit
delta	geological feature
glacier	geological feature
volcano	geological feature
iron	household item
kettle	household item
sink	household item
soap	household item
vase	household item
tent	human dwelling
hamlet	human settlement
mumps	illness
sorbet	is it cold
euro	kind of money
ladle	kitchen utensil
candle	light source
fungus	living thing
copper	metal
flute	musical instrument
seven	number
twelve	number
roof	part of building
phrase	part of speech
cousin	relative
nephew	relative
niece	relative
sibling	relative
shovel	tool
balloon	toy
teddy	toy
willow	tree
fight	type of conflict
salsa	type of dance
coal	type of fuel
petrol	type of fuel
wink	type of gesture
jazz	type of music
order	type of rule
fathom	unit of distance
metre	unit of distance
decade	unit of time
gram	unit of weight
carrot	vegetable
bike	vehicle
coach	vehicle
scooter	vehicle
tram	vehicle
rifle	weapon

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