

# Brain Activation for Lexical Decision and Reading Aloud: Two Sides of the Same Coin?

Manuel Carreiras<sup>1,2</sup>, Andrea Mechelli<sup>3</sup>, Adelina Estévez<sup>1</sup>,  
and Cathy J. Price<sup>4</sup>

## Abstract

■ This functional magnetic resonance imaging study compared the neuronal implementation of word and pseudoword processing during two commonly used word recognition tasks: lexical decision and reading aloud. In the lexical decision task, participants made a finger-press response to indicate whether a visually presented letter string is a word or a pseudoword (e.g., “paple”). In the reading-aloud task, participants read aloud visually presented words and pseudowords. The same sets of words and pseudowords were used for both tasks. This enabled us to look for the effects of task (lexical decision vs. reading aloud), lexicality (words vs. nonwords), and the interaction of lexicality with task. We found very similar patterns of activation for lexical decision and reading aloud in areas associated with word recognition and lexical retrieval (e.g., left fusiform gyrus, posterior temporal cortex, pars opercularis, and

bilateral insulae), but task differences were observed bilaterally in sensorimotor areas. Lexical decision increased activation in areas associated with decision making and finger tapping (bilateral postcentral gyri, supplementary motor area, and right cerebellum), whereas reading aloud increased activation in areas associated with articulation and hearing the sound of the spoken response (bilateral precentral gyri, superior temporal gyri, and posterior cerebellum). The effect of lexicality (pseudoword vs. words) was also remarkably consistent across tasks. Nevertheless, increased activation for pseudowords relative to words was greater in the left precentral cortex for reading than lexical decision, and greater in the right inferior frontal cortex for lexical decision than reading. We attribute these effects to differences in the demands on speech production and decision-making processes, respectively. ■

## INTRODUCTION

Reading is a remarkable skill that only humans have achieved. Understanding the cognitive steps involved has required some ingenious techniques based on reaction times. The most popular of these tasks are lexical decision and reading aloud: The lexical decision task requires participants to determine whether a letter string is a word or a nonword, whereas the reading-aloud task requires the participant to pronounce the letter string. Lexical decision and reading aloud have been the major driving force in gathering empirical evidence for developing computational models of lexical processing (see Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Grainger & Jacobs, 1996; Plaut, McClelland, Seidenberg, & Patterson, 1996; Coltheart, Curtis, Atkins, & Haller, 1993; Seidenberg & McClelland, 1989).

In the lexical decision task, participants are presented with strings of letters and asked to decide as rapidly as possible whether the letter constitutes a word or not. In a typical experiment, half of the items are words (e.g.,

*table, dog*) and half are “nonwords” (e.g., *pable, dnom*). Usually, the participant is asked to press one button for words and another for nonwords. The main dependent variable is response time (the time elapsed between the presentation of the stimulus and the response), but accuracy is also of interest. The basic assumption behind this technique is that to decide whether a given letter string is a word or not, participants need to check whether it corresponds to a lexical representation. Hence, the time required to make a lexical decision to a word stimulus gives us an estimation of how this string is represented in the lexical network and/or the operations needed to access to the lexical representation. However, the total response time is also affected by some early encoding processes and some late response processes responsible for the motor response (Ratcliff, Gomez, & McKoon, 2004). Furthermore, given that the lexical decision task is a word/nonword discrimination task, it has been criticized on the basis that the decision processes may play an important role in the obtained response time, for instance, the choice of the nonword foils modulates the magnitude of many lexical effects (Carreiras, Perea, & Grainger, 1997; Balota & Chumbley, 1984).

<sup>1</sup>Universidad de La Laguna, Tenerife, Spain, <sup>2</sup>Institute of Cognitive Neuroscience, London, <sup>3</sup>King’s College, London, <sup>4</sup>Institute of Neurology, London

In the reading-aloud task, the participant has to pronounce aloud as quickly as possible the sounds associated with a presented stimulus. The main dependent variable is again response time (i.e., the amount of time elapsing between presentation of the stimulus and the onset of the participant's vocalization). However, the advantage of reading aloud over lexical decision is that reading aloud does not require any overt discrimination about the stimulus, even when the stimuli include both words and pseudowords. It is well known that words are named faster than nonwords, which allows reading-aloud time to be used as an index of lexical access time (e.g., Fredericksen & Kroll, 1976; Forster & Chambers, 1973), although a number of other factors can influence reading-aloud speed (Carreiras et al., 1997; Paap, McDonald, Schvaneveldt, & Noel, 1987).

Unfortunately, response times are always measured within the distorting lenses of the particular task used. To overcome this problem, most current studies use a multitask approach (e.g., a combination of lexical decision and reading aloud) to study word recognition processes because the comparison among different tasks permits a more comprehensive analysis of the core processes underlying lexical access (Carreiras et al., 1997). The performance in these two tasks clearly relates to core shared basic processes involved in visual word recognition (see Carreiras et al., 1997; Grainger & Jacobs, 1996, for the idea of functional overlap). However, each task also promotes the use of particular input–output processes. For instance, the reading-aloud task requires the activation of articulatory phonologic codes, whereas such processes are not necessarily required in the lexical decision task.

Functional imaging studies have started to investigate the biological basis of visual word recognition during both reading aloud (e.g., Binder, Medler, Deasi, Conant, & Liebenthal, 2005; Heim et al., 2005; Mechelli et al., 2005; Price et al., 2003; Turkeltaub, Eden, Jones, & Zeffiro, 2002; Fiez, Balota, Raichle, & Petersen, 1999; Hagoort et al., 1999, among others) and lexical decision (Katz et al., 2005; Ischebeck et al., 2004;<sup>1</sup> Binder et al., 2003; Fiebach, Friederici, Müller, & von Cramon, 2002; Mummery, Shallice, & Price, 1999; Price et al., 1994), with some of these studies also investigating the effects of word type, that is, lexicality (words vs. pseudowords), lexical frequency, and spelling regularity (words with regular or irregular spelling to sound relationships). A review of the literature (Price & Mechelli, 2005) suggests that the effect of word type on brain activation is stronger during lexical decision (e.g., Binder et al., 2003; Fiebach et al., 2002) than covert or overt reading aloud (Mechelli et al., 2005; Joubert et al., 2004; Mechelli, Gorno-Tempini, & Price, 2003; Fiez et al., 1999; Hagoort et al., 1999). If this is true, lexicality effects might be stronger during lexical decision because words and pseudowords require different responses during lexical

decision (Yes, it's a word vs. No, it's not a word). Indeed, the longer response times to pseudowords than words during lexical decision has been attributed to the time taken to check the response (Perea, Rosa, & Gómez, 2005; Ziegler, Jacobs, & Kuppel, 2001; Forster, 1976) or to an extended temporal deadline for pseudowords if a word has not been recognized (Grainger & Jacobs, 1996; Coltheart, Davelaar, Jonasson, & Besner, 1977). During reading aloud by contrast, increased response times for pseudowords relative to words have been attributed to the absence of semantics or lexical orthographic-to-phonologic mappings.

The task-dependent nature of lexicality effects may be even more striking in a language with a shallow orthography such as Spanish. Low-frequency words and pseudowords may be processed similarly as both may engage in mandatory phonologic sublexical processes during reading aloud, and can be read without deep lexical processing, whereas in the lexical decision task, more lexical processing is needed to decide whether a particular string of letters is a word or not. Such different task demands may reflect a differential pattern of activation for pseudowords and words in the two tasks. To date, however, the task-dependent nature of lexicality effects on blood-oxygen-level-dependent (BOLD) signal may have been confounded by different procedures (e.g., block designs vs. event-related designs), different materials, and different languages. To our knowledge, only one previous functional magnetic resonance imaging (fMRI) study has directly compared the neuronal implementation of reading aloud and lexical decision with the same group of participants (Katz et al., 2005). However, this study did not manipulate lexicality during the reading-aloud task, which presented only a limited number of words and no pseudowords. Therefore, although a similarity in the activation pattern for lexical decision and reading aloud is noted, no formal task comparison is reported, nor was it possible to examine the effect of task on lexicality. In contrast, the fMRI study we report below recorded hemodynamic responses to words and pseudowords during reading aloud and lexical decision to ascertain the common and unique activation patterns for each task, stimulus type, and how the effect of stimulus type varies with task.

## METHODS

### Participants

A total of 36 right-handed volunteers (23 women and 13 men) participated in the study. All were native speakers of Spanish, aged between 22 and 46 years, and gave informed consent as stipulated by ethics approval from the National Hospital for Neurology and Neurosurgery and the Institute of Neurology Joint Research Ethics Committee.

## Experimental Design

The experiment manipulated task (reading aloud and lexical decision) and word type (words and pseudowords) in a  $2 \times 2$  factorial design. Two task-specific baseline conditions were also included to reduce activation from nonlexical sensorimotor processing. There were two versions of the same experiment (Version A and Version B). Both used Spanish words from a Spanish standard corpus (Sebastián, Martí, Carreiras, & Cuetos, 2000) and pseudowords with a 1:1 ratio and matched for word length and number of orthographic neighbors (i.e., the number of words that can be created by changing one letter of the stimulus item). In Version A, all the stimuli (112 words and 112 pseudowords) had four or five letters and the pseudowords were created by substituting one or two letters from existing Spanish words without changing syllabic structure or the number of orthographic neighbors. In Version B, the word and pseudoword length was increased (7–11 letters) and the number of stimuli increased (224 words, 224 pseudowords). Half the pseudowords were created by substituting one or two letters (as in Version A) and the other half were created by changing the position of two nonadjacent letters. The reason we used two types of pseudowords was to address whether position and identity of letters produced differential brain activation, as this is a critical issue for the coding schema of computational models. However, in the analyses reported in this article, we only included the pseudowords with substituted letters, so that pseudowords were comparable in the two experiments. Therefore, the main difference between Versions A and B was the word length of the stimuli.

Recent research has shown that pseudowords created by transposing letters are very effective at activating the lexical representation of their base words.

Sixteen subjects (10 women) participated in two experimental runs of Version A, and 20 subjects (13 women) participated in four experimental runs of Version B (double the number of runs because of double the number of stimuli). Within all experimental runs, there were 16 blocks of intermixed words and pseudowords (henceforth lexical blocks) which alternated with 16 blocks of unfamiliar false fonts (matched to the letter strings for number of components and component size), henceforth referred to as baseline blocks. Within the false font blocks, seven stimuli were presented one after the other at a rate of 1 per 1.8 sec. Within the lexical blocks, 14 stimuli were presented (also at a rate of 1 per 1.8 sec), with seven words randomly intermixed with seven pseudowords.

The task manipulation (reading aloud or lexical decision) was counterbalanced within run. One task was performed during the first and the last 8 blocks of the run, whereas the other task was performed during the other 16 blocks in the middle of the run. The assignment of the two tasks to blocks of items was counter-

balanced within participants across runs because, in the second half of the experiment (Run 2 for Version A and Runs 3 and 4 for Version B), the same stimuli were presented again, but with a different task. In Version B, the two different types of pseudowords were blocked and counterbalanced within the experimental run.

## Procedure

Each trial started with the fixation point—a cross in the middle of the screen—that lasted for 1300 msec and then the corresponding stimuli for 500 msec. Immediately before each block, a brief instruction—the Spanish words *LEE* (“read”) for the reading-aloud task or *¿PALABRA?* (“word?”) for the lexical decision task—was displayed for 2500 msec to remind the participants of the task for each particular block. In addition, for each participant, these brief instructions together with the corresponding stimuli of the block were presented in red for one task and in black for the other task. The assignment of the colors to the two tasks was counterbalanced across participants.

In the reading-aloud task, participants were instructed to read each stimulus, whispering their sounds into a microphone. During the corresponding baseline blocks, participants whispered the Spanish word *FALSO* (“false”) to partially control for articulatory processes. In the lexical decision task, subjects were instructed to make finger press responses to indicate whether the letter string was a real word or not. During the corresponding baseline blocks, participants made a keypad response to indicate that the stimulus was not a word. Accuracy was recorded in the reading-aloud tasks. Dubious cases were scored as errors. Accuracy and response time were recorded in the lexical decision task.

## Data Acquisition

A Siemens 1.5-T scanner was used to acquire T2\*-weighted echo-planar images with BOLD contrast. Each echo-planar image comprised 35 axial slices of 2 mm thickness with 1 mm slice interval and  $3 \times 3$  mm in-plane resolution. Volumes were acquired with an effective repetition time (TR) of 3.15 sec/volume and the first six (dummy) volumes of each run were discarded to allow for T1 equilibration effects. A total of 216 volume images were taken in each run. After the two functional runs, a T1-weighted anatomical volume image was acquired from all participants.

## Data Analysis

Data were analyzed with statistical parametric mapping (SPM2: Wellcome Department of Imaging Neuroscience, London, UK; [www.fil.ion.ucl.ac.uk](http://www.fil.ion.ucl.ac.uk)), running under

Matlab 6.5.1 (Mathworks, Sherbon, MA, USA). All volumes from each participant were realigned and unwarped (Jesper et al., 2001), adjusting for residual motion-related signal changes. The functional images were spatially normalized (Friston, Ashburner, et al., 1995) to a standard MNI-305 template using nonlinear basis functions. Functional data were spatially smoothed with a 6-mm full-width half-maximum isotropic Gaussian kernel to compensate for residual variability after spatial normalization and to permit application of Gaussian random-field theory for corrected statistical inference (Friston, Holmes, et al., 1995).

### Statistical Analysis

At the first level, data were analyzed in a subject-specific fashion, with six event types of interest (words, pseudowords, and baseline for both reading aloud and lexical decision). In Version B, pseudowords with a letter position change but no substituted letters were modeled separately and excluded from the contrasts that entered the group-level analysis. Each stimulus onset was convolved with a synthetic hemodynamic response function using high-pass filtering with a cutoff period of 128 sec. For each participant, the following contrasts were computed:

1. Lexical decision on words relative to false fonts
2. Lexical decision on pseudowords relative to false fonts
3. Reading aloud words relative to saying “false” to false fonts
4. Reading aloud pseudowords relative to saying “false” to false fonts
5. Reading aloud vs. lexical decision on words
6. Reading aloud vs. lexical decision on pseudowords
7. Words vs. pseudowords during reading aloud
8. Words vs. pseudowords during lexical decision

The following second-level ANOVAs were then computed:

ANOVA 1: Reading aloud and lexical decision relative to task-specific baselines (Contrasts 1, 2, 3, 4). This analysis allowed us to find effects that were (a) common to lexical decision and reading aloud (Contrasts 1, 2, 3, 4) and (b) greater for lexical decision (Contrasts 1 and 2 > 3 and 4) or reading aloud (Contrasts 3 and 4 > 1 and 2) after baseline differences had been removed.

ANOVA 2: Direct comparison of lexical decision and reading aloud (Contrasts 5 and 6).

ANOVA 3: Lexicality effects (Contrasts 7 and 8). To determine whether lexicality effects were due to increases or decreases relative to task-specific baselines, we also report the effects of Contrasts 1–4 from ANOVA 1 in the regions identified in Contrasts 7 and 8.

These second-level ANOVAs included data from all 36 subjects, after preliminary analyses revealed that subject group (Version A vs. Version B) did not interact with either task or lexicality. Unless otherwise indicated, we report and discuss regions that showed significant effects at  $p < .05$  (corrected for multiple comparisons).

## RESULTS

### Behavioral Data

#### Accuracy

The percentage of errors was 2.2% for reading aloud and 3.9% for lexical decision (see Table 1). There was no significant effect of lexicality during lexical decision [ $F(1,35) = 1.24$ ,  $MSe = 7.2$ ,  $p > .1$ ]; however, during reading aloud, words were pronounced more accurately than pseudowords [ $F(1,35) = 21.28$ ,  $MSe = 13.6$ ,  $p < .001$ ].

#### Latency Analysis

This was only possible for lexical decision because of the well-known technical difficulties recording voice onset times in scanner noise. For lexical decision, incorrect responses were excluded along with reaction times more than 2.0 standard deviations above or below the mean for each participant in each condition. The ANOVAs based on lexicality (words vs. pseudowords) showed that words were responded to faster than pseudowords [ $F(1,35) = 46.5$ ,  $MSe = 1905$ ,  $p < .0001$ ].

### fMRI Data

#### ANOVA 1a

Activation that was common to lexical decision and reading aloud relative to task-specific baselines was left lateralized in superior and inferior temporal, inferior frontal, precentral, and parietal regions and bilateral in occipital, anterior insula, putamen, cerebellar, and sup-

**Table 1.** Means (Standard Deviations) in milliseconds and Percentage of Errors (in italics) for Lexical Decision and Reading Aloud Times

	Words	Pseudowords
<i>Lexical Decision</i>		
Latency	755 (98)	825 (119)
Errors	3.6 (3.4)	4.3 (4.8)
<i>Reading Aloud</i>		
Errors	0.22 (0.4)	4.2 (5.4)

plementary motor area (SMA) regions (see Table 2A and Figure 1, for details).

#### ANOVA 1b

Differential effects for lexical decision and reading aloud, after accounting for task-specific baselines, were observed in bilateral superior temporal areas for reading aloud relative to saying “falso” to false fonts, and in the left postcentral gyrus and right anterior insula for lexical decision relative to pressing the no response to false fonts (see Table 2B).

#### ANOVA 2

When sensorimotor processes were not controlled, lexical decision increased activation relative to reading aloud in bilateral motor and frontal regions associated with finger pressing responses, whereas reading aloud increased activation relative to lexical decision in bilateral motor and temporal areas associated with articulation and hearing the sound of the spoken response (see Table 3A and B, and Figure 2, for details).

#### ANOVA 3

Pseudowords increased the activation relative to words during both tasks in pre-SMA/SMA, right inferior frontal, and left precentral areas. The effect in the right inferior frontal was greater during lexical decision ( $z = 3.1$ ,  $p < .001$  for Lexicality by Task interaction) and the effect in the left precentral was greater during reading aloud ( $z = 3.5$ ,  $p < .001$  for Lexicality by Task interaction). The contrast Words > Pseudowords revealed a greater deactivation for pseudowords than words in bilateral temporo-parietal and left superior frontal areas and the posterior cingulate. These deactivations were consistent across tasks (see Table 4A and B and Figure 3, for details).

## DISCUSSION

The main findings of the present experiment can be summarized as follows: (1) The lexical decision and reading aloud produced very similar patterns of activation in brain regions associated with word recognition and lexical retrieval. (2) Differences between word and pseudoword processing were also remarkably consistent across task. Nevertheless, (3) task-dependent activation was observed in areas associated with sensorimotor processing and (4) differences between word and pseudoword processing were modulated by task demands.

Both lexical decision and reading aloud activated the distributed network of brain areas that have previously

been associated with orthographic, semantic, and phonologic processing of written words (see Demonet, Thierry, & Cardebat, 2005; Price & Mechelli, 2005; Jobard, Crivello, & Tzourio-Mazoyer, 2003; Bookheimer, 2002; Turkeltaub et al., 2002, for reviews). This suggests that both our tasks captured common cognitive processes (orthographic, phonologic, and lexico-semantic) involved in visual word processing. Although semantic and phonologic processes are not mandatory during a lexical decision, many previous studies have demonstrated that they become increasingly involved when the choice of nonwords includes word-like pronounceable pseudowords as used in our study (Van Orden, 1987, when a rose is a rows; Edwards, Pexman, Goodyear, & Chambers, 2005; Gibbs & Van Orden, 1998; Pugh, Rexer, & Katz, 1994; Stone & Van Orden, 1993). There remain, however, obvious differences between reading and lexical decision. Reading involves overt articulation of phonology and lexical decision requires different key-presses to indicate a YES or NO response. It is therefore not surprising that the direct comparison of activation during our reading and lexical decision tasks highlighted task-dependent activation in sensorimotor areas. Reading increased activation in bilateral premotor, cerebellum, and superior temporal regions previously associated with articulation and hearing the sound of the spoken response (see Price et al., 2003). Lexical decision increased activation in bilateral postcentral, left parietal, SMA, and right cerebellum regions associated with finger press responses (Gordon, Lee, Flament, Ugurbil, & Ebner, 1998). In addition, there were differences in visual processing regions: Reading aloud increased activation in the medial extrastriate cortex and lexical decision increased activation in a lateral region of the right inferior occipital lobe. These task-dependent visual effects were unexpected given that the same stimuli and presentation rate were used for both tasks. They may have emerged because of different functional connectivity between visual and motor regions. Indeed, the task-dependent activation in visual areas disappeared when reading and lexical decision were compared to visual and motor processing during their task-specific baselines. In summary, our lexical decision and reading-aloud tasks activated the same set of brain regions with differential effects limited to sensorimotor processing regions.

Lexicality had effects both on the behavioral responses and on brain activation. The lexical decision task showed that pseudowords were classified more slowly—but not significantly less accurately—than words. There were no differences in the reading-aloud task due to the fact that the number of errors was almost negligible. With respect to brain activation, pseudowords increased activation in the pre-SMA/SMA, right inferior frontal, and left precentral areas relative to words while decreasing activation in bilateral temporo-parietal, posterior cingulate, and medial superior frontal regions. These effects have

**Table 2.** Common and Differential Tasks Effects Relative to Task-specific Baselines

<i>Location</i>	<i>x</i>	<i>y</i>	<i>z</i>	<i>LD&amp;R &gt; FF</i>	<i>LD &gt; FF</i>	<i>R &gt; FF</i>
Left middle occipital gyrus	-28	-92	-4	6.3	5.3	4.5
Right cuneus	14	-78	16	5.6	5.0	4.6
Left fusiform gyrus						
posterior	-40	-66	-12	6.5	6.1	4.6
anterior	-42	-42	-20	7.4	7.4*	5.0
Left superior temporal cortex						
posterior	-52	-40	12	6.6	5.1	6.1
	-62	-34	4	7.4	5.1	7.5*
	-62	-14	6	7.1	3.1	7.5*
anterior	-52	10	-14	7.0	4.3	6.0*
Left inferior frontal gyrus	-44	24	-6	7.3	5.5	6.8*
	-54	12	0	7.6	5.7	7.3*
Bilateral anterior insulae	-36	24	0	7.5	7.4	5.7
	34	18	4	6.5	7.0*	3.4
Left supramarginal gyrus	-44	-34	46	7.5	7.5*	5.2
Left intraparietal sulcus	-24	-62	36	5.6	4.0	5.2
	-20	-68	44	5.2	3.8	4.4
	-26	-52	48	6.2	5.7	4.4
Left precentral gyrus						
ventral	-60	-18	28	6.9	6.1	5.0
	-48	6	32	7.7	6.9	7.6
	-54	0	42	8.0	7.5	8.2
	-46	-6	54	7.7	7.1	7.0
dorsal	-26	-8	56	6.0	6.5	3.8
Bilateral SMA/Pre-SMA	-4	4	58	8.0	7.7	7.1
	8	6	56	7.4	6.9	5.0
	8	18	44	6.6	7.0*	3.6
Bilateral cerebellum	-2	-78	-26	7.7	7.4	6.5
	6	-74	-20	7.7	7.5	6.3
	25	-68	-24	7.7	7.2	6.5
	-28	-62	-24	5.8	5.2	5.0
Bilateral putamen	-24	-6	6	7.6	6.5	5.7
	-26	2	-4	6.3	5.4*	3.9
	-20	6	4	6.2	5.1	5.1
	26	10	4	5.6	5.4*	3.6

**Table 2.** (continued)

*B. Differential Task Effects after Accounting for Task-specific Baselines*

Location	Coordinates			Z Scores		
	<i>x</i>	<i>y</i>	<i>z</i>	<i>LD vs. R</i>	<i>LD &gt; FF</i>	<i>R &gt; FF</i>
<i>[LD-FF] &gt; [R-FF]</i>						
Left postcentral gyrus	<b>-50</b>	<b>-22</b>	<b>54</b>	<b>5.3</b>	<b>7.5</b>	<i>ns</i>
Right anterior insula	<b>34</b>	<b>18</b>	<b>4</b>	<b>5.8</b>	<b>7.0</b>	3.4
<i>[R-FF] &gt; [LD-FF]</i>						
Bilateral superior temporal gyri	<b>-62</b>	<b>-14</b>	<b>6</b>	<b>6.4</b>	3.1	<b>7.5</b>
	<b>-62</b>	<b>-34</b>	<b>4</b>	<b>4.9</b>	<b>5.1</b>	<b>7.5</b>
	<b>56</b>	<b>-28</b>	<b>0</b>	<b>4.9</b>	<i>ns</i>	<b>6.9</b>

Z scores significant at  $p < .05$  (corrected for multiple comparisons) are reported in **bold**.

*ns* = not significant if did not reach at least the uncorrected threshold criteria of height  $p < .001$ ; LD = lexical decision; R = reading aloud; FF = false fonts; LD&R > FF = common activation of lexical decision and reading aloud; LD > FF = activation of lexical decision more than false fonts; R > FF = activation of reading aloud more than false fonts; LD > R = activation of lexical decision more than reading aloud and false fonts; R > LD = activation of reading aloud more than lexical decision and false fonts.

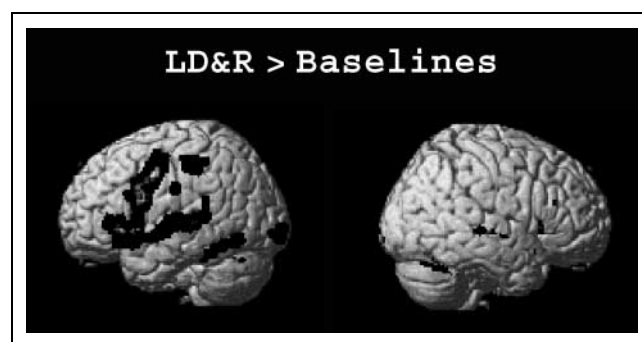
\*Where there is a differential effect of task at  $p < .001$  uncorrected.

also been reported in several previous studies (e.g., Binder et al., 2003, 2005; Mechelli et al., 2003, 2005; Ischebeck et al., 2004; Xu et al., 2001; Paulesu et al., 2000; Fiez et al., 1999; Hagoort et al., 1999; Herbster et al., 1997; Price, Wise, & Frackowiak, 1996). In addition, however, our experimental design allows us to segregate these lexicality effects into those that are modulated by task and those that are task-independent. Thus, we show for the first time that the effects in the right inferior frontal and left precentral gyrus are modulated by task, but the effects in the SMA, temporo-parietal, and cingulate regions are task-independent.

The task-dependent lexicality effects allow us to distinguish between the contribution of the left and right frontal regions during pseudoword processing. For example, during lexical decision, subjects must consider whether a letter string is a word and inhibit word

responses to word-like pseudowords. This rejection process increases activation in the right inferior frontal cortex on the border between the pars opercularis and the pars triangularis. Consistent with the rejection process, a recent review paper has recently linked the right pars opercularis to cognitive inhibition (Aron, Robbins, & Poldrack, 2004). In contrast, when pseudowords are read aloud, a phonologic solution needs to be established without support from semantic information. In this context, there is greater activation for pseudowords in the left precentral cortex, an area that has already been linked to nonsemantic phonologic retrieval (Mechelli et al., 2005). Our results therefore provide a neat and consistent association between cognitive models and anatomical effects.

Task-independent lexicality effects were observed in the SMA (where activation was higher for pseudowords than for words or fixation) and the posterior cingulate and temporo-parietal areas (where deactivation relative to fixation was greater for pseudowords than for words). Increased SMA activation for pseudoword processing has previously been related to different computational demands on the segment-by-segment assembly of articulatory programs (see Hagoort et al., 1999). This conclusion was based on the authors' observation that syllable frequency was lower in their pseudowords than words. However, in our study, we observed increased SMA activation for pseudowords despite matching the syllable frequency of our pseudowords and words. Moreover, we have previously shown that SMA/pre-SMA activation is modulated by lexical frequency rather than by syllable frequency (see Carreiras et al., 2006). Likewise, the increased deactivation for pseudowords in the bilateral temporo-parietal, medial frontal, and



**Figure 1.** Surface rendering of the brain. Activation of lexical decision to words and pseudowords compared to deciding “no” to false fonts and of reading aloud words and pseudowords compared to responding “false” to false fonts. All contrasts depicted at  $p < .05$ , corrected.

**Table 3.** Direct Comparisons between the Two Tasks

Location	Coordinates			Z Scores		
	<i>x</i>	<i>y</i>	<i>z</i>	All	Words	Pseudo
<i>A. Direct comparison of lexical decision to reading aloud</i>						
Bilateral postcentral gyri	<b>60</b>	<b>-20</b>	<b>46</b>	<b>5.8</b>	<b>5.3</b>	<b>5.0</b>
	<i>-52</i>	<i>-28</i>	<i>48</i>	<i>7.5</i>	<i>7.7</i>	<i>6.8</i>
	<i>-64</i>	<i>-26</i>	<i>28</i>	<i>5.9</i>	<i>5.6</i>	<i>5.0</i>
Left intraparietal sulcus	<i>-54</i>	<i>-22</i>	<i>18</i>	<i>6.1</i>	<i>4.9</i>	<i>6.0</i>
	<i>-34</i>	<i>-32</i>	<i>52</i>	<i>6.7</i>	<i>6.5</i>	<i>5.6</i>
Right cerebellum	<b>24</b>	<b>-50</b>	<b>-26</b>	<b>7.0</b>	<b>6.9</b>	<b>5.8</b>
	<i>2</i>	<i>-48</i>	<i>-32</i>	<i>5.6</i>	<i>6.9</i>	<i>3.0</i>
SMA	<i>-4</i>	<i>-12</i>	<i>54</i>	<i>6.1</i>	<i>5.5</i>	<i>5.0</i>
Right inferior occipital cortex	<b>30</b>	<b>-98</b>	<b>-10</b>	<b>5.6</b>	4.8	<b>4.9</b>
Gyrus rectus	<b>6</b>	<b>8</b>	<b>-12</b>	<b>6.1</b>	4.4	<b>6.5</b>
	<i>14</i>	<i>12</i>	<i>-16</i>	<i>5.6</i>	3.4	<i>6.6</i>
	<i>-6</i>	<i>6</i>	<i>-12</i>	<i>5.9</i>	4.0	<i>5.6</i>
<i>B. Direct comparison of reading aloud to lexical decision</i>						
Bilateral superior temporal gyri	<b>-66</b>	<b>-30</b>	<b>2</b>	<b>7.6</b>	<b>6.4</b>	<b>7.4</b>
	<i>-54</i>	<i>-18</i>	<i>0</i>	<i>5.6</i>	4.4	<i>5.4</i>
	<i>-52</i>	<i>-12</i>	<i>2</i>	<i>6.4</i>	<b>5.0</b>	<b>5.1</b>
	<i>54</i>	<i>-36</i>	<i>6</i>	<i>5.9</i>	<b>5.6</b>	<b>5.0</b>
	<i>50</i>	<i>-26</i>	<i>2</i>	<i>6.1</i>	4.8	<b>5.8</b>
	<i>52</i>	<i>-12</i>	<i>0</i>	<i>7.5</i>	<b>5.6</b>	<b>6.1</b>
Bilateral precentral gyri	<b>56</b>	<b>12</b>	<b>-14</b>	<b>5.1</b>	4.1	<b>4.7</b>
	<b>-58</b>	<b>-4</b>	<b>20</b>	<b>7.6</b>	<b>7.3</b>	<b>7.5</b>
	<i>-44</i>	<i>-14</i>	<i>36</i>	<i>7.9</i>	<i>7.7</i>	<b>7.8</b>
	<i>-52</i>	<i>-8</i>	<i>46</i>	<i>5.5</i>	<b>4.9</b>	<b>4.9</b>
	<i>56</i>	<i>-4</i>	<i>24</i>	<i>7.7</i>	<b>6.8</b>	<b>7.3</b>
	<i>46</i>	<i>-12</i>	<i>36</i>	<i>7.7</i>	<i>7.4</i>	<i>7.7</i>
Bilateral cerebellum	<b>-12</b>	<b>-60</b>	<b>-20</b>	<b>7.5</b>	<b>5.3</b>	<b>7.6</b>
	<b>16</b>	<b>-70</b>	<b>-16</b>	<b>7.0</b>	<b>6.0</b>	<b>6.8</b>
Medial extrastriate	<b>-8</b>	<b>-94</b>	<b>0</b>	<b>5.8</b>	<b>5.1</b>	<b>5.3</b>
	<b>0</b>	<b>-84</b>	<b>12</b>	<b>5.4</b>	<b>5.0</b>	<b>5.0</b>

Z scores significant at  $p < .05$  (corrected for multiple comparisons) are reported in **bold**.

Z scores are reported in *italics* when they do not reach the threshold  $p < .001$ , uncorrected for height. All = refer to words and pseudowords together.

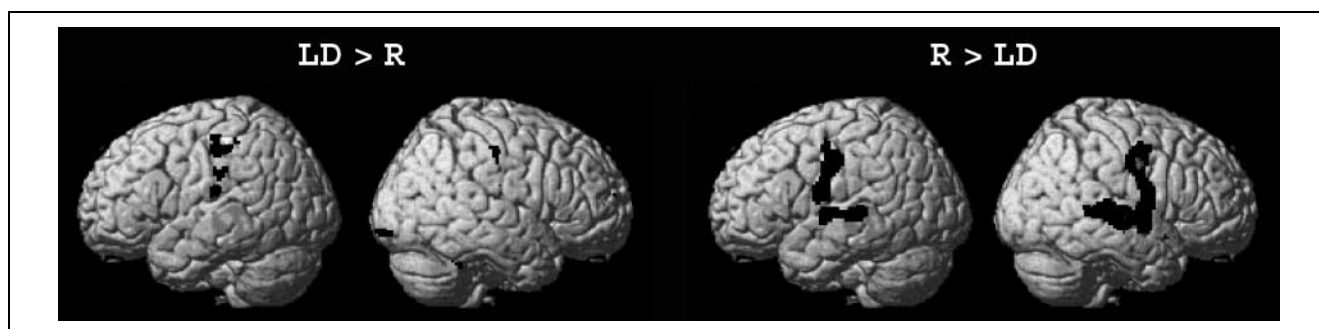
posterior cingulate regions is likely to arise at the level of lexical computations. Previous studies, for example, have interpreted deactivation of bilateral temporoparietal regions during pseudoword processing in terms of diminished semantic processes (e.g., Binder et al., 2003, 2005; Ischebeck et al., 2004). It is therefore possible that as lexico-semantic processing decreases, there are compensatory increases in SMA/pre-SMA activation. It could also be argued that higher SMA activation for pseudowords was caused by conflict monitoring (see Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004). For example, during lexical decision, our word-like pseudowords may evoke a conflict between the incorrect response (“yes, it’s a word”) and the correct response (“no, it’s not a word”). However, conflict monitoring does not explain why SMA activation was also higher for pseudowords than for words during reading aloud.

Despite detecting a range of lexicality effects, we did not find increased activation for pseudowords in the left frontal operculum or the left posterior inferior temporal lobe, as previously described (see Mechelli et al., 2003, for review). There are three possible explanations for these null effects. First, contrary to the majority of previous studies of English readers, our study involved Spanish participants reading Spanish. The critical difference here is that spelling-to-sound relationships are consistent in Spanish but inconsistent in English. Consequently, words may be read more like pseudowords in Spanish than in English. Second, activation for pseudowords also depends on the linguistic experience of the subjects. For example, Paulesu et al. (2000) compared pseudoword reading in English and Italian subjects and found greater left posterior inferior temporal activation in English subjects and greater left posterior superior temporal activation in Italian subjects. Third, many of the word and pseudoword differences reported in previous studies may reflect strategic differences introduced by block designs. In our study, words and pseudowords were fully randomized, thereby removing the possibility that subjects could predict the next response. Future studies, comparing word and pseudoword processing in different orthographies, subject groups, and stimulus orders are needed to test these hypotheses further.

### Implications

There have been several concerns about the utility of the lexical decision and the reading-aloud tasks as measures of the processes underlying lexical access. As stated in the Introduction, one major problem with the lexical decision task is that it is not only a word identification task, but rather, a discrimination task in which participants are required to discriminate words from pseudowords. Thus, participants may rely on a number of available sources of information to make the





**Figure 2.** Surface rendering of the brain. *LD > R*: activation of lexical decision as compared to reading aloud. *R > LD*: activation of reading aloud as compared to lexical decision. All contrasts depicted at  $p < .05$ , corrected.

word/pseudoword discriminations. For instance, words that have many similarly spelled words may be responded to faster than words with no similarly spelled words, whereas pseudowords with many similarly spelled words may be responded to slower than pseudowords with no similarly spelled words (see Andrews, 1997, for a review of “neighborhood” effects). In addition,

the magnitude of a number of lexical effects is modulated by the “wordlikeness” of the pseudoword foils (Stone & van Oden, 1993). Regarding the reading-aloud task, the manipulated variables (e.g., orthographic neighborhood) could have an impact on either recognition process and/or on processes after recognition tied to the output of the response. In addition, it may be

**Table 4.** Lexicality Effects: Direct Comparisons

*A. Lexicality Effects: Direct Comparison of Pseudowords to Words*

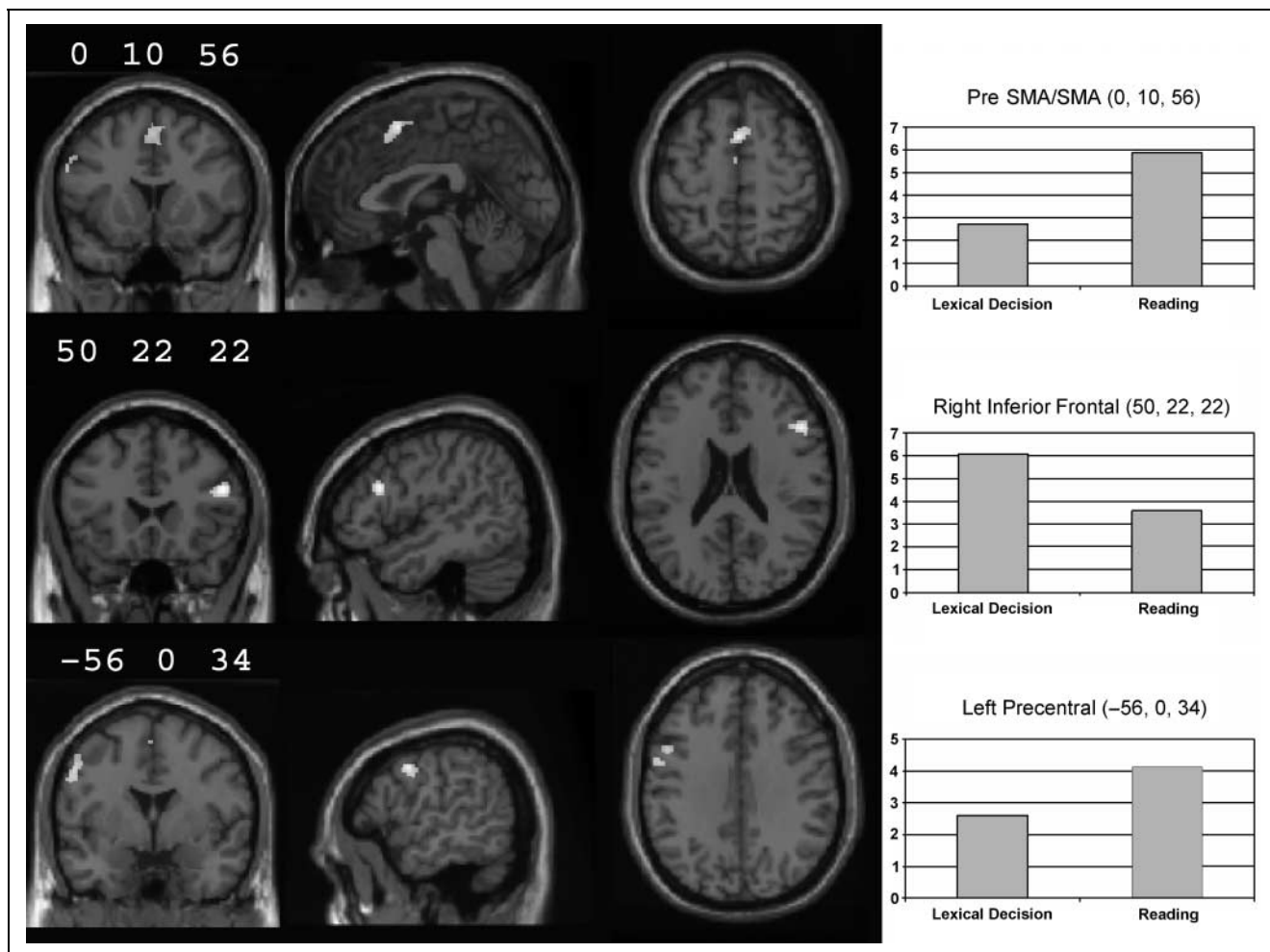
<i>Location</i>	<i>Coordinates</i>			<i>Pseudowords &gt; Words</i>			<i>Pseudowords &gt; FF</i>			<i>Interaction</i>
	<i>x</i>	<i>y</i>	<i>z</i>	<i>Z Scores</i>			<i>Z Scores</i>			
				<i>All</i>	<i>LD</i>	<i>Read</i>	<i>All</i>	<i>LD</i>	<i>Read</i>	
Pre-SMA/SMA	<b>0</b>	<b>10</b>	<b>56</b>	<b>5.1</b>	<i>3.0</i>	<i>4.7</i>	<b>7.7</b>	<b>6.8</b>	<b>7.0</b>	
	<b>6</b>	<b>18</b>	<b>44</b>	<i>4.1</i>	<i>3.7</i>	<i>3.0</i>	<b>6.1</b>	<b>6.5</b>	<i>3.9</i>	
	<b>-2</b>	<b>-4</b>	<b>60</b>	<i>3.5</i>	<i>2.6</i>	<i>1.8</i>	<b>5.3</b>	<b>5.3</b>	<i>1.9</i>	
Right inferior frontal	<b>50</b>	<b>22</b>	<b>22</b>	<b>5.6</b>	<b>5.3</b>	<i>3.8</i>	<i>4.2</i>	<b>5.2</b>	<i>2.3</i>	<b>3.1</b>
<i>Left precentral gyrus</i>	<b>-50</b>	<b>-4</b>	<b>50</b>	<i>4.7</i>	<i>3.4</i>	<i>3.7</i>	<i>3.6</i>	<b>5.6</b>	<b>7.4</b>	
	<b>-56</b>	<b>0</b>	<b>34</b>	<i>4.2</i>	<i>2.8</i>	<b>4.9</b>	<i>3.4</i>	<i>4.7</i>	<b>6.1</b>	<b>3.5</b>
	<b>-46</b>	<b>8</b>	<b>28</b>	<i>4.0</i>	<i>2.4</i>	<i>3.9</i>	<b>7.6</b>	<b>5.9</b>	<b>7.3</b>	

*B. Lexicality Effects: Direct Comparison of Words to Pseudowords*

<i>Location</i>	<i>Coordinates</i>			<i>Words &gt; Pseudowords</i>			<i>FF &gt; Pseudowords</i>		
	<i>x</i>	<i>y</i>	<i>z</i>	<i>Z Scores</i>			<i>Z Scores</i>		
				<i>All</i>	<i>LD</i>	<i>Read</i>	<i>All</i>	<i>LD</i>	<i>Read</i>
Bilateral temporo-parietal	<b>54</b>	<b>-70</b>	<b>20</b>	<b>5.3</b>	<i>4.5</i>	<i>3.1</i>	<b>7.4</b>	<b>5.6</b>	<b>6.5</b>
	<b>-46</b>	<b>-74</b>	<b>38</b>	<i>4.9</i>	<i>3.9</i>	<i>3.7</i>	<b>7.7</b>	<b>7.3</b>	<b>6.0</b>
	<b>-52</b>	<b>-68</b>	<b>16</b>	<i>4.6</i>	<i>2.8</i>	<i>4.8</i>	<b>7.6</b>	<b>6.1</b>	<b>5.6</b>
Posterior cingulate	<b>-6</b>	<b>-46</b>	<b>32</b>	<i>4.9</i>	<i>4.6</i>	<i>3.9</i>	<b>6.5</b>	<b>5.6</b>	<i>4.3</i>
Medial superior frontal	<b>-2</b>	<b>58</b>	<b>4</b>	<i>4.8</i>	<i>3.5</i>	<i>3.9</i>	<b>7.3</b>	<b>6.6</b>	<b>5.8</b>

Z scores significant at  $p < .05$  (corrected for multiple comparisons) are reported in **bold**.

Z scores are reported in *italics* when they do not reach the threshold  $p < .001$ , uncorrected for height. FF = false fonts; All = refer to words and pseudowords together.



**Figure 3.** Sagittal coronal and axial sections, and graphs of contrast estimates. Voxels colored in white depict activation for pseudowords as compared to words. These effects are due to increases of activation of the pseudowords as compared to the false font baselines (see Table 4 for details). All contrasts depicted at  $p < .001$ , uncorrected. Graphs show the increase of activation of pseudowords relative to words in lexical decision and in reading above the false font baseline of each task.

possible to name a word, especially in languages with shallow orthographies, without accessing the lexicon (e.g., Tahossi & Laghi, 1992; but see Perea & Carreiras, 1998). In the present study, the important result to stress is that the two tasks elicited an increase of activation of common brain areas, corresponding to the activation identified in other studies for tasks that involved language processing. Nonetheless, the activation in these common areas is greater for one task in some areas and for the other task in other areas. In addition, effects of lexicality were mostly similar for lexical decision and reading aloud in the present study, although the activation in different regions was modulated by task. This suggests that both tasks are tapping mostly on the same or similar “core” processes of the visual word recognition processing.

### Conclusion

In summary, there is a large experimental psychology literature dealing with the recognition of printed words.

Lexical decision and reading aloud are typically used to understand how individual words are comprehended. Here we have shown that these two tasks mostly tap into the same core cognitive processes of visual word recognition, as revealed by the common activation in areas that have been linked with language processing. Nevertheless, we also found task-dependent effects that demonstrate increased activation in speech production areas for reading and increased activation in decision making and manual responses for lexical decision. These findings also help to interpret previously reported activation differences between pseudowords and words.

### Acknowledgments

This work was funded by the Wellcome Trust. M. C. was funded by grants BSO2003-01135 and SEJ2004-07680-C02-02/PSIC from the Ministry of Education and Science, and grant PR2004-0563 from the Secretaría de Estado de Educación y Universidades (Spain). A. M. was supported by grant MH64445 from the National Institute of Health (USA). M. C. thanks the

Institute of Cognitive Neuroscience, University College of London, where he was a visitor while the work was carried out.

Reprint requests should be sent to Manuel Carreiras, Departamento de Psicología Cognitiva, Campus de Guajara, Universidad de La Laguna, 38205-Tenerife (Spain), or via e-mail: mcarreir@ull.es or www.neurocog.ull.es.

## Note

1. They have used a “phonological lexical decision task.”

## REFERENCES

- Andrews, S. (1997). The effects of orthographic similarity on lexical retrieval: Resolving neighborhood conflicts. *Psychological Bulletin and Review*, 4, 439–461.
- Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences*, 8, 170–177.
- Balota, D. A., & Chumbley, J. I. (1984). Are lexical decisions a good measure of lexical access? The role of word frequency in the neglected decision stage. *Journal of Experimental Psychology: Human Perception and Performance*, 10, 340–357.
- Binder, J. R., McKiernan, K. A., Parsons, M. E., Westbury, C. F., Possing, E. T., Kaufman, J. N., et al. (2003). Neural correlates of lexical access during visual word recognition. *Journal of Cognitive Neuroscience*, 15, 372–393.
- Binder, J. R., Medler, D. A., Deasi, R., Conant, L. L., & Liebenthal, E. (2005). Some neurophysiological constraints on models of word naming. *NeuroImage*, 27, 677–693.
- Bookheimer, S. (2002). Functional MRI of language: New approaches to understanding the cortical organization of semantic processing. *Annual Review of Neuroscience*, 25, 151–188.
- Carreiras, M., Mechelli, A., & Price, C. J. (2006). The effect of word and syllable frequency on activation during lexical decision and reading aloud. *Human Brain Mapping*, 27, 963–972.
- Carreiras, M., Perea, M., & Grainger, J. (1997). Effects of orthographic neighborhood in visual word recognition: Cross-task comparisons. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 23, 857–871.
- Coltheart, M., Curtis, B., Atkins, P., & Haller, M. (1993). Models of reading aloud: Dual-route and parallel distributed-processing approaches. *Psychological Review*, 100, 589–608.
- Coltheart, M., Davelaar, E., Jonasson, J. F., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), *Attention and performance VI* (pp. 535–555). Hillsdale, NJ: Erlbaum.
- Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, 108, 204–256.
- Demonet, J. F., Thierry, G., & Cardebat, D. (2005). Renewal of the neurophysiology of language: Functional neuroimaging. *Physiological Review*, 85, 49–95.
- Edwards, J. D., Pexman, P. M., Goodyear, B. G., & Chambers, C. G. (2005). An fMRI investigation of strategies for word recognition. *Cognitive Brain Research*, 24, 648–662.
- Fiebach, C. J., Friederici, A. D., Müller, K., & von Cramon, D. Y. (2002). fMRI evidence for dual routes to the mental lexicon in visual word recognition. *Journal of Cognitive Neuroscience*, 14, 11–23.
- Fiez, J. A., Balota, D. A., Raichle, M. E., & Petersen, S. E. (1999). Effects of lexicality, frequency, and spelling-to-sound consistency on the functional anatomy of reading. *Neuron*, 24, 205–218.
- Forster, K. I. (1976). Accessing the mental lexicon. In R. J. Wales & E. W. Walker (Eds.), *New approaches to language mechanisms*. Amsterdam: North-Holland.
- Forster, K. I., & Chambers, S. M. (1973). Lexical access and naming time. *Journal of Verbal Learning and Verbal Behavior*, 12, 627–635.
- Frederiksen, J. R., & Kroll, J. F. (1976). Spelling and sound: Approaches to the internal lexicon. *Journal of Experimental Psychology: Human Perception and Performance*, 2, 361–379.
- Friston, K. J., Ashburner, J., Frith, C. D., Poline, J. B., Heather, J. D., & Frackowiak, R. S. J. (1995). Spatial registration and normalization of images. *Human Brain Mapping*, 2, 1–25.
- Friston, K. J., Holmes, A., Worsley, K. J., Poline, J.-B., Frith, C. D., & Frackowiak, R. S. J. (1995). Statistical parametric maps in functional imaging: A general linear approach. *Human Brain Mapping*, 2, 189–210.
- Gibbs, P., & Van Orden, G. C. (1998). Pathway selection’s utility for control of word recognition. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 1162–1187.
- Gordon, A. M., Lee, J. H., Flament, D., Ugurbil, K., & Ebner, T. J. (1998). Functional magnetic resonance imaging of motor, sensory, and posterior parietal cortical areas during performance of sequential typing movements. *Experimental Brain Research*, 121, 153–155.
- Grainger, J., & Jacobs, A. M. (1996). Orthographic processing in visual word recognition: A multiple read-out model. *Psychological Review*, 22, 696–713.
- Hagoort, P., Brown, C., Indefrey, P., Herzog, H., Steinmetz, H., & Seitz, R. (1999). The neural circuitry involved in the reading of German words and pseudowords: A PET study. *Journal of Cognitive Neuroscience*, 11, 383–398.
- Herbster, A. N., Mintun, M. A., Nebes, R. D., & Becker, J. T. (1997). Regional cerebral blood flow during word and nonword reading. *Human Brain Mapping*, 5, 84–92.
- Heim, S., Alter, K., Ischebeck, A. K., Amunts, K., Eickhoff, S. B., Mohlberg, H., et al. (2005). The role of the left Brodmann’s areas 44 and 45 in reading words and pseudowords. *Cognitive Brain Research*, 25, 982–993.
- Ischebeck, A., Indefrey, P., Usui, N., Nose, I., Hellwig, F., & Taira, M. (2004). Reading in a regular orthography: An fMRI study investigating the role of visual familiarity. *Journal of Cognitive Neuroscience*, 16, 727–741.
- Jesper, L. R., Andersson, J. L. R., Hutton, C., Ashburner, J., Turner, R., & Friston, K. (2001). Modeling geometric deformations in EPI time series. *NeuroImage*, 13, 903–919.
- Jobard, G., Crivello, F., & Tzourio-Mazoyer, N. (2003). Evaluation of the dual route theory of reading: A meta-analysis of 35 neuroimaging studies. *NeuroImage*, 20, 693–712.
- Joubert, S., Beauregard, M., Walter, N., Bourgouin, P., Beaudoin, G., Leroux, J. M., et al. (2004). Neural correlates of lexical and sublexical processes in reading. *Brain and Language*, 89, 9–20.
- Katz, L., Lee, C. H., Tabor, W., Frost, S. J., Mencl, W. E., Sandak, R., et al. (2005). Behavioral and neurobiological effects on printed word repetition in lexical decision and naming. *Neuropsychologia*, 43, 2068–2083.
- Mechelli, A., Crinion, J., Long, S., Friston, K. J., Lambon-Ralph, M. A., Patterson, K., et al. (2005). Dissociating reading processes on the basis of neuronal interactions. *Journal of Cognitive Neuroscience*, 17, 1753–1765.
- Mechelli, A., Gorno-Tempini, M. L., & Price, C. J. (2003). Neuroimaging studies of word and pseudoword reading: Consistencies, inconsistencies, and limitations. *Journal of Cognitive Neuroscience*, 15, 260–271.

- Mummary, C. J., Shallice, T., & Price, C. J. (1999). Dual-process model in semantic priming: A functional imaging perspective. *Neuroimage*, *9*, 516–525.
- Paap, K. R., McDonald, J. E., Schvaneveldt, R. W., & Noel, R. W. (1987). Frequency and pronounceability in visually presented naming and lexical-decision tasks. In M. Coltheart (Ed.), *Attention and performance XII* (pp. 221–244). Hillsdale, NJ: Erlbaum.
- Paulesu, E., McCrory, E., Fazio, F., Menoncello, L., Brunswick, N., Cappa, S. F., et al. (2000). A cultural effect on brain function. *Nature Neuroscience*, *3*, 91–96.
- Perea, M., & Carreiras, M. (1998). Effects of syllable frequency and syllable neighborhood frequency in visual word recognition. *Journal of Experimental Psychology: Human Perception and Performance*, *24*, 134–144.
- Perea, M., Rosa, E., & Gómez, C. (2005). The frequency effect for pseudowords in the lexical decision task. *Perception & Psychophysics*, *67*, 301–314.
- 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.
- Price, C. J., Gorno-Tempini, M. L., Graham, K. S., Bigio, N., Mechelli, A., Patterson, K., et al. (2003). Normal and pathological reading: Converging data from lesion and imaging studies. *Neuroimage*, *20*, s30–s41.
- Price, C. J., & Mechelli, A. (2005). Reading and reading disturbance. *Current Opinion in Neurobiology*, *15*, 231–238.
- Price, C. J., Wise, R. J., Watson, J. D., Patterson, K., Howard, D., & Frackowiak, R. S. (1994). Brain activity during reading. The effects of exposure duration and task. *Brain*, *117*, 1255–1269.
- Price, C. J., Wise, R. J. S., & Frackowiak, R. S. J. (1996). Demonstrating the implicit processing of visually presented words and pseudowords. *Cerebral Cortex*, *6*, 62–70.
- Pugh, K. R., Rexer, K., & Katz, L. (1994). Evidence of flexible coding in visual word recognition. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 807–825.
- Ratcliff, R., Gomez, P., & McKoon, G. (2004). A diffusion model account of the lexical decision task. *Psychological Review*, *111*, 159–182.
- Ridderinkhof, K. R., Ullsperger, M., Crone, E. A., & Nieuwenhuis, S. (2004). The role of the medial frontal cortex in cognitive control. *Science*, *306*, 443–447.
- Sebastián-Gallés, N., Martí, M. A., Carreiras, M., & Cuetos, F. (2000). *Lexesp: Una base de datos informatizada del español*. Universitat De Barcelona, Spain.
- Seidenberg, M. S., & McClelland, J. L. (1989). A distributed developmental model of word recognition and naming. *Psychological Review*, *96*, 523–568.
- Stone, G. O., & Van Orden, G. C. (1993). Strategic control of processing in visual word recognition. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 744–774.
- Tahossi, P., & Laghi, L. (1992). Semantic priming in the pronunciation of words in two writing systems: Italian and English. *Memory & Cognition*, *20*, 303–313.
- Turkeltaub, P. E., Eden, G. F., Jones, K. M., & Zeffiro, T. A. (2002). Meta-analysis of the functional neuroanatomy of single word reading: Method and validation. *Neuroimage*, *16*, 765–780.
- Van Orden, G. C. (1987). A ROWS is a ROSE: Spelling, sound and reading. *Memory & Cognition*, *15*, 181–198.
- Xu, B., Grafman, J., Gaillard, W. D., Ishii, K., Vega-Bermudez, F., Pietrini, P., et al. (2001). Conjoint and extended neural networks for the computation of speech codes: The neural basis of selective impairment in reading words and pseudowords. *Cerebral Cortex*, *11*, 267–277.
- Ziegler, J. C., Jacobs, A. M., & Klüppel, D. (2001). Pseudohomophone effects in lexical decision: Still a challenge for current models of word recognition. *Journal of Experimental Psychology: Human Perception and Performance*, *27*, 547–559.