

Reading with the Right Hemisphere: Evidence from Transcranial Magnetic Stimulation

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Although many patients with dominant hemisphere damage retain some reading ability, the anatomic substrate of the preserved reading remains controversial. We tested the hypothesis that the right hemisphere mediates the reading of some patients with acquired dyslexia by using Transcranial Magnetic Stimulation (TMS) to assess the effect of transient cortical stimulation on reading. A patient with (partially recovered) pure alexia was asked to read aloud briefly presented words, half of which were shown in association with TMS of the right or left hemisphere. Consistent with the right hemisphere reading hypothesis, stimulation of the right but not the left hemisphere disrupted oral reading. © 1994 Academic Press, Inc.

Since the seminal contributions of Dejerine (1891, 1892), acquired dyslexia has been associated with damage to the left (dominant) hemisphere. This finding, in conjunction with the observation that damage to the right hemisphere is rarely associated with dyslexia, has led a number of investigators to argue that the right hemisphere is "word blind" (Dejerine, 1892; Geschwind, 1965); indeed, many investigators continue to support this claim (Shallice & Warrington, 1980; Shallice, 1988; Baynes, 1990). In recent years, however, several lines of evidence have suggested that the right hemisphere may possess the capacity to read. Patterson et al. (1988), for example, described a patient who, after undergoing a left hemispherectomy at age 15, was able to read approximately 30% of single words. The performance of some split-brain patients is also consistent with this claim; these patients may, for example, be able to match printed words presented to the right hemisphere with an appropriate object (Zaidel, 1978; see also Zaidel & Peters, 1981). Investigations of the reading performance of patients with acquired dyslexias such as "deep dys-

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lexia" have also been interpreted by some investigators as support for the right hemisphere reading hypothesis (Saffran et al., 1980; Coltheart, 1980).

Another line of evidence supporting the claim that the right hemisphere is literate comes from evaluation of the reading of patients with pure alexia and optic aphasia (see Coslett & Saffran, 1993). Coslett and Saffran (1989), for example, reported data from four patients with pure alexia who performed well above chance on a number of lexical decision and semantic categorization tasks with briefly presented words which they could not explicitly identify. Three of the patients who regained the ability to explicitly identify rapidly presented words exhibited a pattern of performance which was consistent with the right hemisphere reading hypothesis. These patients read nouns better than functors and words of high (e.g., "chair") better than words of low (e.g., "destiny") imageability. Both patients for whom data are available demonstrated a deficit in the reading of suffixed (e.g., "flower") as compared to pseudosuffixed (e.g., "flowed") words. Similar data have been reported for other pure alexics by Shallice and Saffran (1986) and Coslett et al. (1993). These data are consistent with a version of the right hemisphere reading hypothesis which postulates that the right hemisphere lexical-semantic system primarily represents high-imageability nouns. On this account, functors, affixed words, and low-imageability words are not adequately represented in the right hemisphere.

We report data from an investigation with a patient with pure alexia in which transcranial magnetic stimulation (TMS) was employed to directly test the hypothesis that the right hemisphere mediates the reading of at least some patients with acquired dyslexia. We reasoned that if the right hemisphere provides the neural substrate for reading, the transient, localized disruption of cortical processing caused by TMS of the right hemisphere would interfere with reading. An extensively investigated patient with pure alexia, with the reading pattern described above, was asked to read aloud briefly presented words, half of which were presented in association with TMS. Consistent with the right hemisphere reading hypothesis, stimulation of the right hemisphere disrupted this patient's oral reading.

PATIENT DESCRIPTION

The patient, JG, is a 57-year-old man who exhibited pure alexia after suffering small, exclusively subcortical infarctions of the splenium of the corpus callosum and in the region of the left lateral geniculate body. (See Coslett & Saffran, 1989, Case 1, for details.) Initially, he could write and name spelled words but was unable to read aloud except by means of serial letter naming. Under rapid presentation conditions (e.g., 150 msec)

which prevented effective use of the slow letter-by-letter strategy, JG demonstrated "implicit" reading; he performed significantly better than chance in discriminating words from nonwords and sorting words according to semantic class (e.g., "Was the word an animal name?") although he was unable to identify the word and, in some instances, claimed not even to have seen the word.

Over a 3-month period, as JG gradually regained the ability to explicitly identify many rapidly presented stimuli, he exhibited the pattern of performance assumed to characterize right hemisphere reading (Saffran et al., 1980; Coltheart, 1980); he read nouns ("horse") better than functors ("which"), and high-imageability ("cradle") better than low-imageability ("destiny") words. Finally, he read pseudosuffixed words ("flower") significantly more reliably than suffixed words ("flowed").

During the subsequent years, JG's reading continued to improve. Currently, he peruses newspapers on a daily basis and occasionally reads short magazine articles; although he states that he reads relatively rapidly, reading is effortful and, therefore, limited.

Neurologic examination at the time of the testing reported here revealed a normal mental status. Language was normal except for a mild dyslexia (see below). Writing was grammatically correct and fluent; there was no effect of part of speech or imageability. Cranial nerve examination revealed normal ocular movements. Visual acuity was 20/25 OU with correction. Visual fields to confrontation were abnormal by virtue of a right homonymous hemianopia manifested as color desaturation and an inability to detect finger movements in the right visual field. He counted fingers quickly and accurately in the left visual field but frequently erred on this task in the right visual field. He stated that objects (and written words) in the right visual field appeared to be "washed out" and indistinct. He was unable to name words written in large block letters in the right visual field. Motor, sensory, and cerebellar examinations were normal as were the deep tendon reflexes. There was no evidence of neglect or extinction in any sensory modality. He performed normally on letter cancellation and line bisection subtests of the Behavioral Inattention Test (Wilson, Cockburn, & Halligan, 1987).

MRI scan obtained at the time of the testing reported here demonstrated an infarction of a portion of the splenium of the corpus callosum (Fig. 1) as well as a lesion involving small portions of the left parahippocampal gyrus and, perhaps, the left lateral geniculate (Fig. 2). Figure 2 also reveals dilatation of the left occipital horn, an abnormality not demonstrated in the MRI obtained shortly after JG's infarction (see Coslett & Saffran, 1989); this dilatation may be attributable to degeneration secondary to damage to the lateral geniculate. No abnormalities are noted in the occipital cortex. Finally, an old infarction of the cortex of the left frontal lobe was identified (Fig. 3).

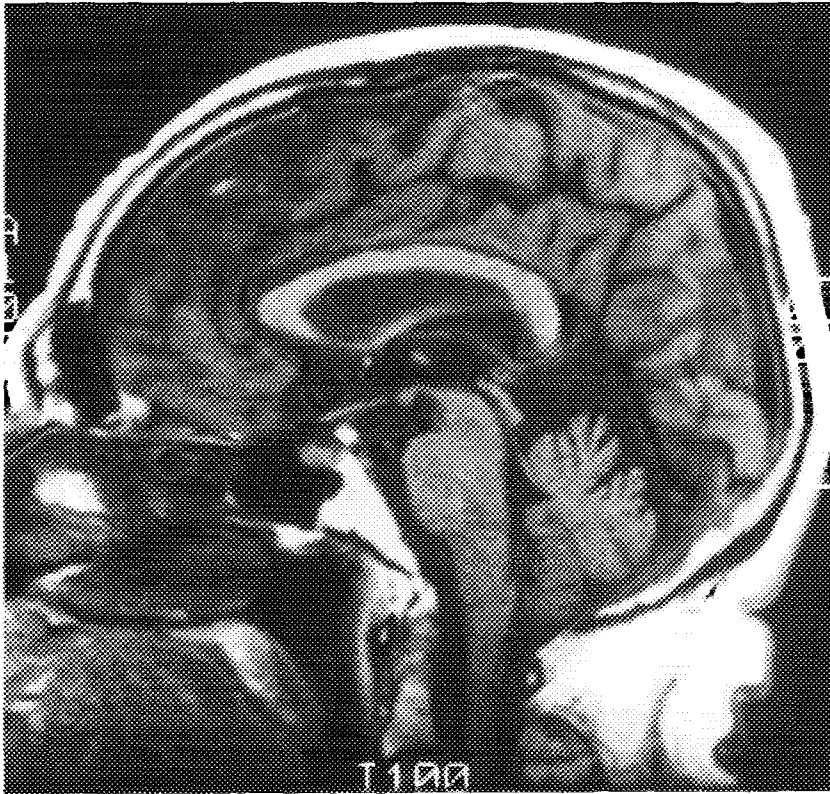


FIG. 1. A midsagittal MRI demonstrating a lesion of a portion of the splenium of the corpus callosum.

EXPERIMENT 1: BASELINE READING WITH BRIEF PRESENTATION

Experiment 1 was performed to assess JG's current reading abilities.

Methods

For all of the reading tasks described below, single words were presented using an Apple Macintosh computer and software which controlled stimulus exposure to the nearest millisecond. Each trial was initiated by the experimenter after the subject indicated his readiness; a fixation point was present in the center of the screen for 1000 msec before being replaced by a letter string which was, in turn, visible for 149 msec. There was no poststimulus mask. JG (and controls) was instructed to name the word.

JG sat at a distance of 50 cm from the screen; at this viewing distance, the visual angle subtended by the words ranged from 1.5° for three-letter words to 3.9° for seven-letter words.

Stimuli included three lists of letter strings drawn from the Psycholinguistic Assessment of Language Processing in Aphasia (Kay, Lesser, & Coltheart, 1992). List one included 40 words of high (>550 MRC Psycholinguistic Database; Kay et al., 1992) and 40 words of

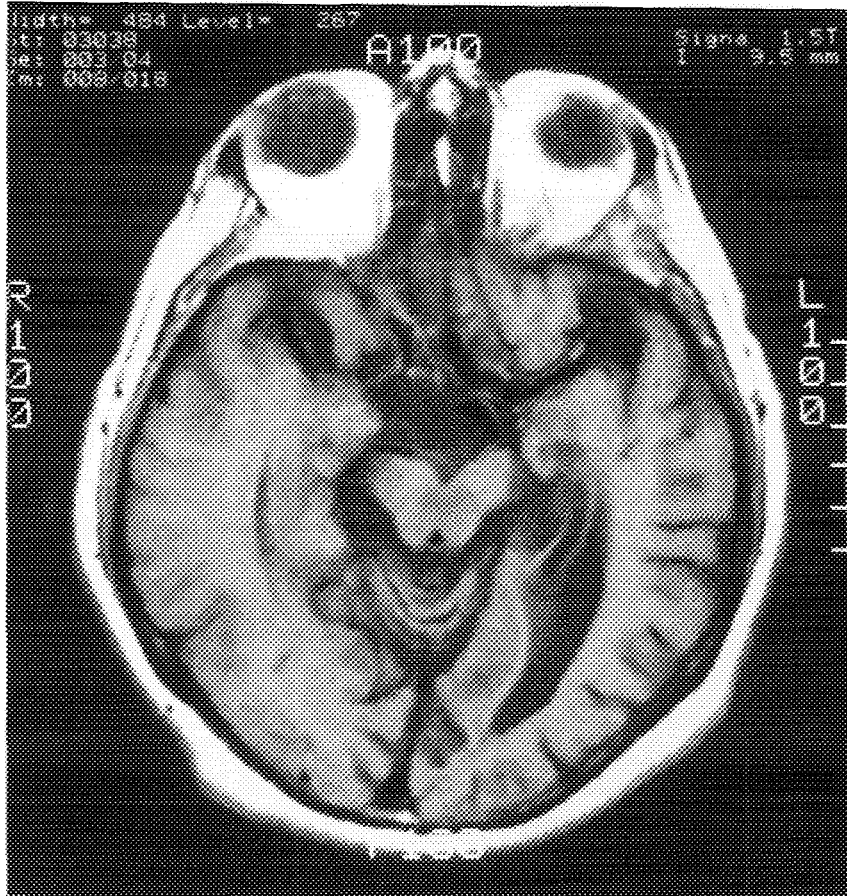


FIG. 2. An axial MRI demonstrating a lesion involving portions of the left parahippocampal gyrus and probably the left lateral geniculate; enlargement of the left occipital horn in the absence of damage to the occipital cortex is also noted.

low (<399) imageability. Half of the high- and half of the low-imageability words were of high frequency (>70 counts per million; Kucera & Francis, 1967) and the remaining words were of low (<25) frequency; high- and low-imageability words were matched for letter length. List two included 30 nouns and 30 functors matched for imageability, length, and frequency. List three included 24 pronounceable nonwords (e.g., "churst") including an equal number of three-, four-, five-, and six-letter strings.

Results

High/low imageability. JG correctly read aloud 18/20 words of high frequency/high imageability and 15/20 words of low frequency/high imageability for a total of 33/40 words of high imageability. He read 14/20

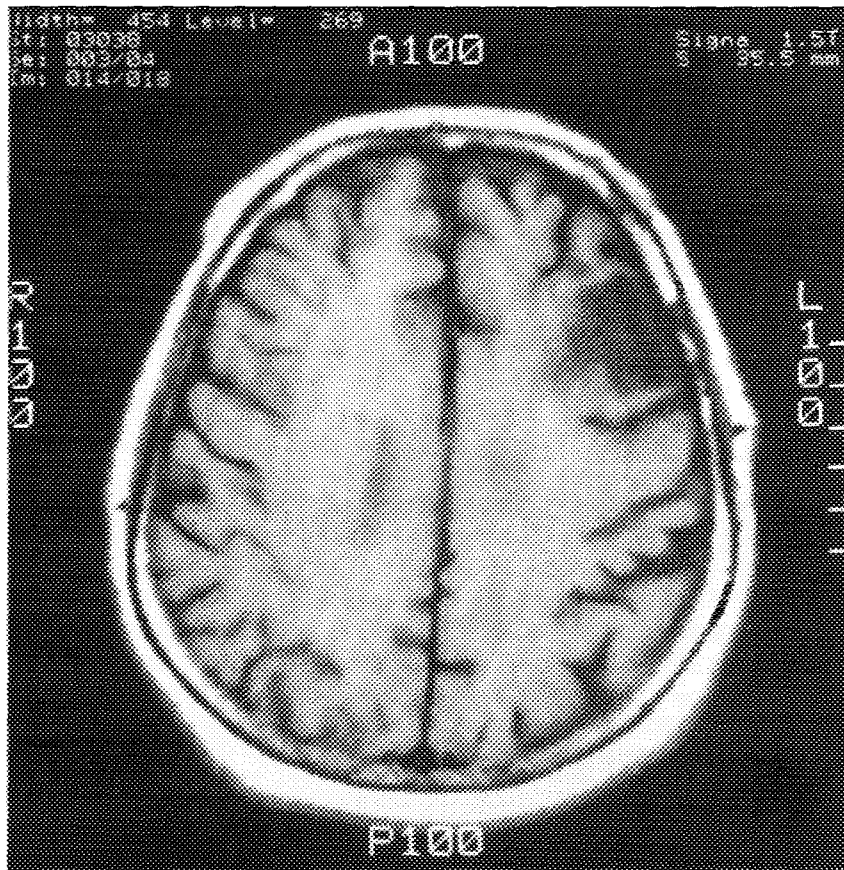


FIG. 3. An axial MRI demonstrating a lesion of the cortex of the left frontal lobe.

words of high frequency/low imageability and 7/20 words of low imageability/low frequency for a total of 21/40 low-imageability words. Overall, JG correctly named 54/80 (68%) words. JG read high-imageability words significantly more reliably than low-imageability words ($\chi^2 = 8.21, p < .01$). He also exhibited a significant effect of word frequency, reading 32/40 high- as compared to 22/40 low-frequency words ($\chi^2 = 5.70, p < .05$).

Errors included 21 trials on which a visually similar word was produced (e.g., "angry" in response to *analogy*, "follow" in response to *folly*). There was a tendency for the visually similar words to be shorter than the target; thus, for 13 of the 21 visual errors, the incorrect response contained fewer letters than the target, whereas the letter length was the same for 3 errors and the target word was shorter than the response on 5 trials. On 5 trials JG named one or more of the constituent letters, usually from the beginning of the word.

Func-tors. JG correctly read 23/30 (77%) nouns and 16/30 (53%) func-tors for an overall score of 39/60 (65%). There was a trend for JG to read nouns better than func-tors ($\chi^2 = 3.59, p = .06$). The type and distribution of errors was similar to that described above.

Nonwords. JG correctly pronounced 1/6 three-letter, 2/6 four-letter, 2/6 five-letter, and 0/6 six-letter nonwords for a total of 5/24 (21%). On 10 trials he named two or more of the constituent letters and offered an incorrect (but phonologically plausible) nonword response based on the partial or incorrect letter information. Although JG had been told that the letter strings were not real words, he produced real words on 9 trials (e.g., "form" to the target *fon*), often while indicating that his response couldn't be correct.

Discussion

Eight years after his cerebral infarctions, JG continues to be mildly dyslexic, correctly reading only approximately two-thirds of briefly presented words. Interestingly, the *pattern* of performance is similar to that previously reported (Coslett and Saffran, 1989): JG reads words of high imageability more reliably than words of low imageability and nouns better than func-tors. Additionally, his reading of nonwords is quite poor. As previously noted (Coslett & Saffran, 1989), this pattern of performance is consistent with the claim that JG's reading is mediated by the right hemisphere (see also Coslett & Saffran, 1993).

EXPERIMENT 2: READING WITH TRANSCRANIAL MAGNETIC STIMULATION

Experiment 2 was performed to test the hypothesis that JG's reading was mediated by the right hemisphere. In this experiment we employed TMS, a technique by which the discharge of storage capacitors into a stimulation coil produces a magnetic field which, in turn, induces an electric current in underlying tissue (see Barker et al., 1989, and Roth et al., 1991, for recent reviews). The induced current is assumed to produce a localized depolarization block of neuronal activity which may last at least 150 msec (Day et al., 1989). TMS has been demonstrated to be a useful technique for investigating motor (Wassermann et al., 1991), sensory (Amassian, 1989), and language (Pascual-Leone et al., 1991) function. We reasoned that if JG's reading is mediated by the right hemisphere, transient disruption of right hemisphere function would be expected to impair reading; in contrast, if reading is mediated by the left hemisphere, right hemisphere stimulation would be expected to have no significant effect.

Methods

A Cadwell MES-10 stimulator with circular, air-core coil with an internal radius of 9.5 cm was employed. The unit was set at 60% capacity, producing a magnetic field of approximately 1.26 Tesla. The coil was placed flat against the scalp in a position such that the center of the coil was located approximately 6.5 cm superior and 4 cm posterior to the external auditory canal. The electric fields induced by circular coils with this design are maximal under the coil itself and minimal at the center of the coil (Cohen et al., 1990). As the strength of the magnetic field decreases quickly as a function of distance from the coil, we assume that the stimulation primarily effected cortical neurons. Because of individual variability in the relationship between external (i.e., scalp and skull) markings as well as some (presumably) minor variability in coil placement from trial to trial, we are unable to precisely identify the structures stimulated; however, given the location and design of the stimulating coil, it is likely that a depolarizing electric field was induced in a (hollow) cylindrical region of cortex overlying portions of the posterior temporal lobe and the angular and supramarginal gyri.

The experiment was performed in two parts, one involving stimulation of the left hemisphere (Experiment 2A) and the other, the right (Experiment 2B) hemisphere. Fifty-six words were presented in the former and 48 words in the latter experiment. For both experiments, TMS randomly accompanied half of the words and was delivered 145 msec after the word appeared on the screen. An interval of 145 msec between stimulus onset and TMS was selected as we estimated that processing in the stimulated cortical regions would be likely to commence at approximately that interval after the stimulus onset. The patient was asked to read each word aloud.

Both parts of the experiment were performed in two sessions. All subjects gave written informed consent; the investigation was approved by the Temple University Institutional Review Board.

Stimuli were drawn from the list of 80 words of high and low frequency and imageability described above; stimuli for Experiment 2A included 14 words in each of the four combinations of high and low frequency and imageability. Half of the words in each of the four categories were presented in association with TMS. (Due to an error in constructing stimulus files, JG was presented 16 words of high imageability and 12 words of low imageability under the No Stimulation condition.) Stimuli for Experiment 2B included 12 words in each of the 4 categories, half of which were presented in association with TMS. Stimuli were presented for 149 msec using the apparatus described in Experiment 1.

Results

The results of the two parts, expressed as the number of words read correctly, are presented in Table 1. In Experiment 2A involving left hemisphere stimulation, JG correctly read 17/28 (61%) of words with stimulation and 19/28 (68%) of words without stimulation; thus, stimulation of the left hemisphere did not influence reading accuracy ($\chi^2 = 0.31$, $df = 1$). There were no significant effects of frequency or imageability in this small sample.

In contrast, a robust effect of stimulation of the right hemisphere was observed in Experiment 2B ($\chi^2 = 12.1$, $df = 1$, $p < .01$); JG correctly read 17/24 (71%) of words presented without TMS but only 5/24 (21%) words presented with stimulation. A significant interaction of frequency and stimulation was observed; JG read 5/12 high-frequency words as

TABLE 1
Effect of TMS on Oral Reading

	Left hemisphere		Right hemisphere	
	Stimulation	No stimulation	Stimulation	No stimulation
High imaging				
High frequency	5/7	7/7	3/6	4/6
Low frequency	5/7	5/9	0/6	4/6
	10/14	12/16	3/12	8/12
Low imaging				
High frequency	4/7	5/5	2/6	5/6
Low frequency	3/7	2/7	0/6	4/6
	7/14	7/12	2/12	9/12
Total	17/28 (61%)	19/28 (68%)	5/24 (21%)	17/24 (71%)

compared to 0/12 low-frequency words presented in conjunction with TMS ($\chi^2(c) = 4.02$, $df = 1$, $p < .05$).

Two types of reading errors were observed in Experiment 2A. Visual errors, operationally defined as responses which shared at least 50% of the letters of the target word, were most frequent under both the stimulated and the unstimulated conditions, comprising 75% of all errors. Most visual errors involved the end of the word (e.g., *THING* read as "thigh"). The second type of error was the correct reporting of one or more letters but a failure to name the word (e.g., "h, a" to *hand*, "t, t" to *letter*).

The same two types of reading errors were observed in Experiment 2B. Once again, visual errors were most frequent, occurring on 17 trials and comprising 65% of errors; most errors involved the end of the word. The correct reporting of one or more initial letters but a failure to name the word was observed on 9 trials (35%).

Table 2 reports analysis of errors for Experiments 2A and 2B.

TABLE 2
Analysis of Errors

Error type	Left hemisphere		Right hemisphere	
	Stimulation	No stimulation	Stimulation	No stimulation
Letters				
Correct	2 (18)	3 (33)	1 (5)	5 (71)
Incorrect	0	0	4 (21)	0
Visually similar words	9 (82)	6 (67)	14 (74)	2 (29)

Note. No. of errors; parentheses indicate percentages.

Three normal controls (ages 41, 28, and 21) were also tested using the same stimuli and experimental paradigm. Two performed perfectly with both right and left hemisphere stimulation while the second made a total of four errors, three of which were associated with TMS; one error was observed with left and two with right hemisphere stimulation.

Discussion

As predicted by the hypothesis that JG's reading is mediated by the right hemisphere, TMS over the right parietal lobe disrupted oral reading whereas stimulation of homologous regions of the left hemisphere did not. These data support the claim, initially derived from a series of neuropsychological investigations, that JG's reading is supported by the right hemisphere. More generally, these data demonstrate that the right hemisphere may be involved in the reading of at least some patients with acquired alexia.

Prior to a more general discussion, there are several potential objections to these data which should be considered. As the stimuli presented in the two experiments were drawn from the same pool of words but were not identical, one possible criticism is that the words presented in conjunction with stimulation of the right hemisphere were more difficult for JG; thus, although the stimuli employed in the two experiments contained an equal proportion of words of high and low imageability and frequency, one list might have contained a disproportionate number of words which JG was simply unable to read.

To assess this possibility we compared his performance on the 28 words presented in conjunction with TMS in Experiment 1 to his performance on the baseline administrations of the entire 80-item corpus; a similar calculation was performed for the stimuli presented in conjunction with TMS in Experiment 2. In the baseline administrations, JG correctly read 82% of the 28 words presented in conjunction with TMS in Experiment 1 and 76% of the 24 words presented with TMS in Experiment 2. Thus, as JG performed equally well in the baseline condition with the critical experimental stimuli used in Experiments 1 and 2, differences in stimulus difficulty do not account for the difference in performance with right and left hemisphere TMS.

Another possible objection to the interpretation offered above is that the reading impairment associated with right hemisphere stimulation is attributable to disruption of early visual processing leading to a failure to adequately register visual feature information. Several lines of evidence argue against this possibility. First, it should be noted that omissions or failures to respond to stimuli were never encountered; as this type of error is observed with TMS-induced visual deficits (Amassian et al., 1989), the absence of these errors in this experiment suggests that the

reading deficit observed with right hemisphere stimulation was not attributable to a disruption of visual feature registration or integration. Second, the similarity between the error profiles observed in Experiments 1, 2A, and 2B suggests that the reading disruption was not attributable to a visual deficit; in light of the lateral placement of the stimulating coil, one might expect that the lateral or temporal portions of the visual field would be most likely to be adversely affected by the TMS. If this were so, one might expect stimulation of the right hemisphere to be associated with impaired registration and identification of the initial letters of the stimulus; as previously noted, however, under all conditions, including right hemisphere stimulation, visual errors tended to involve the end of the word. Last, although introspective reports may be misleading, it is noteworthy that JG as well as controls explicitly denied that TMS induced visual loss.

Another issue concerns the nature of the processing impairment which underlies JG's reading deficit. Although the data do not permit one to fully characterize the processing deficit, they do provide certain constraints. As argued above, several lines of evidence suggest that the impairment was not attributable to early visual processing deficits. Additionally, the fact that JG produced responses, even if incorrect, suggests that the deficit did not affect speech output procedures (Pascual-Leone, 1991). Rather, the predominance of visual errors argues for a disruption in a lexical-semantic system.

One possible objection to the contention that TMS causes a disruption in JG's putative right hemisphere lexical-semantic system is that JG does not produce errors in which the stimulus and response are related in meaning but not sound or visual form (e.g., the response "king" to *queen*); a number of investigators have, in fact, argued that "semantic" errors are characteristic of right hemisphere reading (Coltheart, 1980; Saffran et al., 1980). One possible explanation for the absence of semantic errors in the case of JG is that responses which were semantically related but visually dissimilar to the stimulus were rejected because of an inconsistency between the semantically based response and partial letter information (see Marshall & Newcombe, 1973). This speculation is supported by JG's response to the stimulus "dogma" which was presented in conjunction with stimulation of the right hemisphere; although JG's initial response was "fact," he added, after a pause, "no, I saw a 'd'; was it dog?"

Although no effect of left hemisphere stimulation was observed in JG's performance, one cannot exclude the possibility that the left hemisphere may have contributed to his reading. Disruption of language function with left hemisphere TMS was not observed in our controls and, to our knowledge, has only been achieved with rapid, repeated TMS which has been demonstrated to induce speech arrest (Pascual-Leone et al., 1991).

As the left hemisphere clearly plays an important role in normal reading, what accounts for the failure to disrupt reading with single left hemisphere stimulation? One possibility is that the failure is attributable to experimental variables such as insufficient magnet strength, improper selection of the time interval between word onset and TMS, or an inappropriate site of stimulation. As these variables were held constant, these factors are unlikely to explain why JG's reading was disrupted by stimulation of the right but not the left hemisphere.

An alternative account of the observation that left hemisphere stimulation fails to disrupt reading in normal subjects is that the left hemisphere may support multiple reading procedures (Patterson & Shewell, 1987; Coslett, 1991), perhaps with different anatomic substrates (Coslett, Gonzalez-Rothi, & Heilman, 1984). If, in fact, the left hemisphere is able to derive the pronunciation of words by means of different procedures supported (at least in part) by distinct anatomic regions, a localized, transient cortical disruption may disturb one (or more) but not all of the putative reading mechanisms and therefore not abolish reading. The right hemisphere, in contrast, is thought not to support a nonlexical reading mechanism but to support only a single, semantically mediated reading procedure (Zaidel & Peters, 1981; Coltheart, 1983). Additionally, it would seem reasonable to assume that the putative right hemisphere reading system is less well elaborated than that of the left hemisphere system which presumably mediates normal reading in most individuals. Thus, for both of these reasons, right hemisphere reading might be expected to be less resistant to disruption with TMS.

Heretofore, TMS has been found to have its greatest utility in evaluation of the motor and sensory function. "Higher" cognitive functions, perhaps because of the availability of different strategies and procedures to accomplish the same objective, have often been regarded as resistant to this manipulation. These data demonstrate that TMS may indeed contribute to the understanding of the anatomic localization and psychological fractionation of complex behaviors.

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