Human callosal function:
MRI-verified neuropsychological functions

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Article abstract—A commissurotomy patient, with MRI-revealed sparing of some rostral and splenial fibers of the corpus callosum, judged whether pairs of words rhymed. We presented one word in each pair to her left visual field and the other to her right visual field. The 2 words in each pair either sounded and looked alike (R+L+), sounded alike but looked different (R+L−), sounded different but looked alike (R−L+), or both sounded and looked different (R−L−). Although in previous studies the patient has demonstrated little or no ability to transfer information between her brain hemispheres, she was able to perform the rhyming judgment significantly better than chance when the words both looked and sounded alike. However, her accuracy did not differ from chance in the other 3 conditions, or when she was asked to indicate if 2 letters presented to her opposing visual fields were the same or different. A second commissurotomy patient, with an MRI-verified full callosal section, performed at chance in all conditions, and normal control subjects were significantly better than chance in all conditions but R+L−. We discuss the results in terms of the specificity of the information carried by groups of callosal fibers.

NEUROLOGY 1989;39:942-946

Although the corpus callosum interconnects all major neocortical regions associated with cognitive activity, we know little about how it subserves its function. For example, what is the nature of the information transmitted across the corpus callosum? Is it sensory, abstract, or both? Does the nature of the code vary depending on the areas of cortex connected? Are all callosal transmissions bidirectional or are some communications unidirectional? These questions and others remain unanswered. Much of what we do know has come from investigations of the behavior of animals with partial or complete sections of the corpus callosum. By removing only a small part of the corpus callosum at a time, it has been possible to identify those functions that the animals can no longer perform, and thus infer the modality of the information that must travel along those pathways when they are intact. Based on such animal studies, functional regions of the callosum in animals have been delineated as follows: (1) the posterior region of the corpus callosum (ie, the splenium) together with the anterior commissure are involved in the transfer of visual pattern, color, and brightness information[1-3]; (2) a region anterior to the splenium is involved in the transfer of tactile information; and (3) the most anterior regions of the corpus callosum transfer information between the frontal lobes.[4]

Similar claims have been made on the basis of data from humans with partial or complete sections of the corpus callosum.[5-7] However, by necessity, these data have been interpreted with caution because no existing technique could unequivocally verify the extent of callosal damage in these individuals prior to autopsy. Recently, MRI has proved capable of defining the extent of brain lesions with greater precision than was previously possible.[8] This advance has allowed a more precise specification of the areas of the callosum that are cut in the split-brain patient. In fact, MRI revealed that at least 1 patient (V.P.), originally assumed to be fully split, had 2 small regions of callosal fibers remaining. By investigating the kind of information that can be cross-integrated in such a patient, we hope to begin to specify the functional zones of the human callosum as well as to provide insight into how the cortex distributes its functions.

Patient V.P. differs from the majority of split-brain patients in her ability to speak about materials presented to either hemisphere.[9,10] Although the available data have suggested that this ability reflects independent control of the speech apparatus by either hemisphere, the presence of even a few callosal fibers could make this conclusion questionable. Accordingly, it was particularly important to determine the extent to which V.P.'s remaining fibers are capable of transmitting linguistic information. In the current study we sought to evaluate her ability to transfer phonemic information. To this end, we devised a test to assess her ability to cross-communicate words that varied in their phonemic similarity. Specifically, we required her to judge whether 2 words, 1 presented in each visual hemifield, did or did not rhyme. Since numerous experiments have

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Aided by NIH 5PO1-NS17778 and 3R01-NS22626 and the Alfred P. Sloan Foundation. Dr. Kutas was supported by a Research Career Development Award from NIH (MH00322) and NICHD (HD 22614). C. Van Petten was supported by an NSF Graduate Fellowship.

Received June 3, 1988. Accepted for publication in final form January 31, 1989.

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demonstrated that orthography has a strong influence on the efficiency with which rhyming judgments are made,[11,12] we varied the words in each pair systematically in a way that allowed for an analysis of orthographic and phonemic contributions to the rhyme judgment. Thus, there were 4 conditions: (1) words that both looked alike and rhymed, (2) words that looked alike but did not rhyme, (3) words that rhymed but did not look alike, and (4) words that neither looked alike nor rhymed. We compared V.P.'s performance in this rhyming task with that of another patient, in whom a complete callosal section was verified by MRI, and with the performance of normal control subjects.

Subjects. V.P. had staged callosal section at age 26 to control otherwise intractable epileptic seizures. The front half of the callosum was sectioned first, followed (in 2 months) by the posterior half. She remains in good health at the present time, approximately 10 years after her last surgery. In 1984 she had 2 MRI sessions, approximately 6 months apart. These revealed small regions of spared fibers at the splenial and rostral tips of the corpus callosum. An MRI showing V.P.'s spared callosal fibers has been previously published.[8]

V.P. showed no evidence of interhemispheric interactions on routine and frequent tests of visual perception. There was no suggestion of transfer or cross integration of information on tests examining her capacity to compare simple visual stimuli.[13,14] Similarly, she performed at chance when required to decide whether 2 words presented to the different hemispheres were semantically related.[9,15] In short, even though V.P. evidently had some visual fibers remaining, she performed at chance in many tests of visual interaction.

Patient J.W. also had staged callosal section at age 26 in an effort to control his epilepsy. MRIs showed that his callosum was severed completely.[8] Earlier evaluations of J.W. showed that he had no capacity to cross-compare perceptual information between his 2 disconnected hemispheres.[13]

It is important to note that J.W. and V.P. are 2 of a small group of split-brain patients who have the capacity to comprehend language in the right hemisphere. V.P. has, in addition, demonstrated the capacity to generate speech out of both hemispheres.[9] J.W., by contrast, can control speech only with his left hemisphere.[9] (See reference 16 for detailed case histories of V.P. and J.W.)

The normal control subjects consisted of 18 undergraduate and graduate students (8 men). All subjects were right-handed; 3 had an immediate family member who was either ambidextrous or left-handed. One control subject was replaced because this subject's performance, collapsed across all the conditions, was more than 2 standard deviations (SD) below the mean of the group.

Methods. The pairs of words employed as experimental stimuli included most of those used by Polich et al[17] and Kramer and Donchin.[18] There were 60 pairs in each of 4 experimental conditions. These conditions were based on the phonemic (ie, rhyming [R+] versus nonrhyming [R−]) and orthographic (ie, look-alike [L+] versus non-look-alike [L−]) similarity of the words in each pair. The conditions were as follows.

(1) R+L+: words in a pair rhymed and looked alike (eg, look-book, tire-fire). (2) R+L−: words in a pair rhymed but did not look alike (eg, bake-ache, rule-tool). (3) R−L+: words in a pair did not rhyme but looked alike (eg, gasp-wasp, cough-dough). (4) R−L−: words in a pair neither rhymed nor looked alike (eg, shell-paths, keys-fort).

Table 1. Judgments on rhyming task (percent correct)

	R+L+	R+L−	R−L+	R−L−
V.P.	77*	54	57	56
J.W.	54	48	53	48
Controls	78* (10) (95-55)	56 (16) (77-25)	76* (10) (90-53)	85* (09) (100-70)

Accuracy data as percent correct in the 4 conditions of the rhyming task, for subjects V.P., J.W., and 18 normal controls. Means are given for the control group; parenthesized numbers are the standard deviations and ranges associated with these means. Values marked with an asterisk are significantly better than chance.

All stimuli were presented on a 15-inch black and white monitor under the control of a microprocessor. They were displayed 1.5 degrees to the left and right of fixation. The stimuli pairs were flashed for 180 msec. Following the stimuli, both patients were required to judge whether the words presented rhymed or not by a delayed verbal report in one session and by pushing either a "yes" or a "no" button with their right hand in others. The full set of 240 stimuli was run twice on subject V.P., yielding a total of 120 trials per condition, and 5 times on subject J.W., yielding a total of 300 trials per condition. Each control subject was run once with the full stimulus set, yielding a total of 60 trials per condition. Fourteen of the control subjects responded by verbal report, while 4 pressed either a "yes" button or a "no" button. Subjects were instructed to respond on each trial even if they did not feel that they had perceived both words clearly. Each testing session took approximately 1 hour to run.

In a follow-up session, V.P. was tested on her ability to perform a same-different judgment with 2 single letters. The letter combinations were composed of either 2 vowels (eg, *AA*), 2 consonants (eg, *BB*), or a vowel and a consonant (eg, *AB*). Each of these letter combinations was presented in the within- and between-visual field conditions. There was a total of 96 trials per condition.

Results. The results from the 2 commissurotomized patients are shown in table 1. Two-tailed binomial tests were performed to determine whether the commissurotomy subjects were exceeding a chance accuracy of 50% in each condition. J.W. did not exceed chance at the 0.05 level in any condition. V.P.'s accuracy, on the other hand, was significantly better than chance in the sound-alike/look-alike condition (R+L+), where she was 77% correct ($z = 5.8$, $p < 0.0001$). She failed, however, to perform better than chance at the 0.05 level in the other 3 conditions. Thus, V.P. demonstrated an ability to integrate information from the 2 visual fields only when the words both looked and sounded alike. Moreover, when asked to say whether 2 letters were the same or different in the follow-up experiment, she performed at chance levels when the letters went to different hemispheres, although her within-hemisphere performance was near perfect. The results of this experiment are given as table 2.

The results (mean, SD, and range of % correct reports) from the normal control subjects are also included in table 1. These data were subjected to a 2-way repeated measures analysis of variance (ANOVA) with

Table 2. Same-different letter classification (percent correct)

	Left visual field		Right visual field	
	AA/BB	*AB/BA*	*AA/BB*	*AB/BA*
Within field				
Left hand	87	100	100	95
Right hand	83	95	91	95
Combined	85	97	95	95
Between field		*AA/BB*	*AB/BA*	
Left hand		31	37	
Right hand		44	50	
Combined		37	43	

Accuracy data for subject V.P. when she was asked to report if 2 letters were the same or different. Within-field performance is excellent; between-field performance never exceeds chance.

phonemic (rhyming versus nonrhyming) and visual similarity as factors. This ANOVA revealed a main effect for both these factors, and a significant interaction between them. The main effect of visual similarity [$F(1,17) = 23.6, p < 0.001$] indicates that subjects were more likely to be correct in their rhyme judgment if the words in the pair looked alike than if they did not. The main effect of phonology [$F(1,17) = 18.7, p < 0.001$] indicates that the rhyme judgment was more accurate for nonrhyming than rhyming pairs. The significant interaction between visual similarity and phonology [$F(1,17) = 36.4, p < 0.001$] reflects the decreased accuracy of the rhyming judgment for the word pairs in which the phonemic and orthographic information were in conflict.

Table 1 shows that the control subjects performed very poorly in the R+L− condition: their accuracy in this condition was only 55%. Individual *t* tests were carried out comparing the means of the 4 experimental conditions to 50%. These confirmed that the controls did not differ significantly from chance in the R+L− condition ($t = 1.59$, $df = 17$, $p > 0.1$), although they exceeded chance performance levels in the other 3 conditions beyond the 0.001 level.

We thought that a response bias might be contributing to the pattern of results obtained with the controls. Although they were informed that rhyming and nonrhyming pairs were equiprobable, the control subjects tended to judge the pairs as nonrhyming unless they were quite certain that they rhymed. Furthermore, we felt that the visual similarity between the 2 words in a pair might have influenced subjects' certainty. To test these suppositions, we decided to model our subjects' data via the theory of signal detection. In so doing, we were able to get independent estimates of the effect of visual similarity on the ability of our subjects to discriminate rhyming from nonrhyming pairs and their criterion for acknowledging rhymes.

We computed the d′ and beta values for the R+L− and R−L− conditions, taking the "yes" responses to R+L− as "hits" and the "yes" responses to R−L− as "false alarms." The mean d′ for these conditions is 1.31 with an SD of 0.62, and the mean value of beta is 2.44 with an SD of 1.99. A z-score showed that the obtained d′ was significantly larger than a d′ of 0, which would have been expected if the subjects had not been able to discriminate R+L− from R−L− ($z = 2.11, p < 0.05$). The high value for beta indicates that the subjects adopted a strict response criterion; when word pairs did not look alike, they were biased toward saying "no."

The mean d′ for the rhyming judgment in the 2 look-alike stimulus pairs, R+L+ and R−L+, was 1.59 with an SD of 0.48. This value of d′ is significantly higher than 0 ($z = 3.31, p < 0.001$), and significantly higher than the d′ obtained in the L− conditions [$F(1,17) = 5.82, p < 0.03$]. This indicates that visual similarity increased the controls' ability to detect rhymes. As we suspected, the manipulation of visual similarity also affected the response criterion of the controls. The beta for the L+ conditions was 1.03 with a SD of 0.43, approximating the 1.00 of an unbiased observer. This value of beta was substantially lower than the value obtained for the L− conditions, suggesting that when words looked alike, subjects were more willing to say "yes" than when they did not.

A similar analysis for V.P. suggests that visual similarity increased her sensitivity but did not have a large effect on her criterion. Calculated across the various sessions, V.P.'s d′ was 0.92 with a beta of 0.77 for the L+ stimuli, and 0.25 with a beta of 1 for the L− stimuli. With both the L+ and L− stimuli, J.W.'s d′ was close to 0.

Discussion. Control subjects committed significantly more errors in response to word pairs in which there was a conflict between the words' orthography and phonology than when there was no such conflict. Similar findings in a variety of paradigms have been taken as evidence that both visual and speech-based codes are accessed automatically, even in cases where only 1 code is relevant to the task at hand.[12,17-25] The present results differ from those in the literature in that the worst performance occurred for the R+L− rather than the R−L+ stimuli. We suspect this discrepancy is due to the fact that our difficult presentation conditions caused subjects to adopt a stricter criterion in response to orthographic dissimilarity than subjects in other experiments have adopted. In any case, it appears the mismatch between phonology and orthography both reduced our subjects' sensitivity to rhymes and elevated their criterion for acknowledging rhymes.

As expected, the split-brain patient with a complete section of the corpus callosum (J.W.) gave no indication that the way the words were spelled influenced his decision as to whether or not they rhymed. J.W. was incapable of performing this cross-hemispheric task regardless of the phonemic or orthographic characteristics of the experimental stimuli. These results can then be added to a long list of tasks that J.W. cannot perform, presumably because they are contingent on successful cross-hemispheric communication.

Unlike J.W., subject V.P., who has small callosal remnants, exceeded chance performance in the experimental condition in which the words both rhymed and looked alike. However, her accuracy did not differ significantly from chance in the other 3 conditions. She was distinguished from the controls by her poor performance in the R−L+ and R−L− conditions. In the R−L+ condition, her accuracy was 1.9 SD below the control group mean, and lower than the score of 17 of the 18 control subjects. In the R−L− condition, her accuracy was more than 3 SD below the control group mean, and below the range of the control group scores. Her chance performance in this last condition indicates that the conjunction of orthographic and phonemic dissimilarity did not help V.P. identify nonrhymes.

These data indicate that if she is presented with the appropriate stimuli, V.P. is capable of comparing both phonologic and orthographic information across her hemispheres. We would like to conclude that this ability reflected the functioning of her callosal remnant fibers. It is important to note, however, that in numerous other testing sessions, V.P. was unable to cross-compare the simplest of visual stimuli. For example, the data in table 2 demonstrate her inability to make cross-field same-different judgments for single letters. She was able to report that "lake" shown to the left hemisphere rhymes with "bake" shown to the right hemisphere but not to report if an *A* in one visual field is the same or different from an *A* in the opposite visual field. As earlier noted, V.P. was previously unable to cross-integrate semantic information,[9-15] and could not match simple shapes presented to her opposing visual fields.[13-15]

The results of the present experiment therefore underscore the remarkable specificity of the information that is communicated between the hemispheres. Cognitive specificity of this sort has been documented in other commissurotomized patients and for other tasks.[15,26] Such results suggest that it is necessary to demonstrate empirically even the simplest of inferences from one function to another that might on the surface appear to be linked.

Why was it that V.P. failed to perform better than chance in all the conditions save R+L+? Control subjects were less able to detect rhymes when there was a mismatch between phonology and orthography. This mismatch may also be responsible for V.P's poor performance in both the R+L− and R−L+ conditions. Assume that the strength of the evoked sense of similarity in V.P.'s responding hemisphere had to reach some threshold level in order to be useful. Since V.P.'s callosal remnants are limited, it might well have been that when the phonologic and orthographic signals failed to correspond, there was a low probability that this threshold would be reached. However, a combination of the 2 signals might have had a higher probability of exceeding the threshold. This would account for the fact that only the combined presence of phonemic and orthographic similarity allowed V.P.'s hemispheres to interact effectively. The idea that V.P. was able to cross-communicate weak or degraded phonologic and orthographic signals is commensurate with the fact that, while she did not exceed chance performance in any single condition but R+L+, when the 3 nonsignificant conditions are combined, her overall accuracy of 56% differs from chance at the 0.05 level ($z = 2.05$).

V.P.'s poor performance in the R−L− condition requires special comment. In this condition, the phonologic and orthographic signals agreed: words were both visually and phonologically dissimilar. Why did the combination of phonologic and orthographic dissimilarity fail to improve V.P.'s accuracy? To account for this, we speculate that when the information transmitted by V.P.'s callosal remnants did not generate any sense of similarity in her responding hemisphere, she tended to treat this absence of a sense of similarity not as a sign of dissimilarity but simply as "no information." Since V.P. lacked the "nay-saying" response bias found in the control subjects, her response to "no information" would be to respond randomly.

Since the splenium of the corpus callosum interconnects visual association cortex, V.P.'s ability to transfer limited orthographic information is commensurate with the splenial locus of one of her callosal remnants.[6] It is possible that VP's surviving rostral fibers contributed to the transfer of phonologic information, but little is known about the function of these fibers. However, there is evidence that semantic information at least can transfer in the anterior portion of the corpus callosum.[27] It is also possible that some of V.P.'s surviving splenial fibers were tied to a left hemisphere visual word analyzing system. Peterson et al[28] recently reported PET data that provide evidence for the existence of such a system. Peterson et al suggest the presence of this system argues against "obligatory visual-to-auditory recoding." Nevertheless, such a system might play a role in the extraction of phonemic codes from visual word forms, if only by relaying critical information to other regions. If this is the case, information processed through this system could be providing the phonologic signal V.P. used.

Whatever the precise nature of the signals conveyed by V.P.'s callosal remnants, the finding that she could cross-integrate only very circumscribed linguistic information is consistent with the view that her ability to name objects presented in her left visual field[9] reflects a true right hemisphere control of the speech apparatus. The existence of V.P.'s right hemisphere linguistic abilities underscores the fact that her brain organization is not typical. Therefore, we cannot conclude that the orthographic and phonemic information she was able to cross-integrate is conveyed by the same fibers in the typical, intact corpus callosum. The present results do, however, give a hint of the nature and specificity of the information that the corpus callosum can transmit between the 2 cerebral hemispheres.

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Reprinted from NEUROLOGY, Vol. 39, No. 7, pp. 942-946, July 1989