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THE EMERGENCE OF THE CAPACITY TO NAME LEFT VISUAL FIELD STIMULI IN A CALLOSOTOMY PATIENT: IMPLICATIONS FOR FUNCTIONAL PLASTICITY

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Abstract—Callosotomized patient J.W. has a well-documented history of right hemisphere language abilities, including an auditory and visual lexical–semantic system with limited phonology and syntax. However, J.W. has not previously exhibited the ability to name stimuli presented to the left visual field (LVF). We report the emergence of this ability. Experiments were conducted in which pictures and text were presented to the subject's LVF using retinal stabilization techniques to ensure lateralization. J.W. was able to correctly name approximately one-quarter of these stimuli under a variety of presentation conditions. The newly developed ability to respond verbally to complex LVF stimuli can be the result of (1) enhanced inter-hemispheric transfer of information via sub-cortical pathways, (2) sophisticated cross cueing strategies, or (3) control of motor speech in the right hemisphere. Although it appears that the first two mechanisms make a contribution to J.W.'s LVF naming performance, accuracy for unpredictable stimulus sets and the error patterns require acknowledgement that control of motor speech is now available to the right hemisphere.

Key Words: right hemisphere language; hemispheric differences; laterality.

INTRODUCTION

The study of callosotomy and commissurotomy† patients has yielded striking documentation of the existence of independent, self-determined cognitive systems operating within a single being [13]. Of special interest is investigation of the differing language abilities in the disconnected left and right hemispheres. In general, the left hemisphere is language dominant and evidence of right hemisphere language capacity is absent in most patients. The studies that explore right hemisphere language in this population have concentrated on seven patients that have demonstrated this ability [4, 14, 31].

The insight that the disconnected right hemisphere was characteristically mute and required a non-verbal means of expression to respond was what first permitted observation of right hemisphere cognition in these patients [23]. However, subsequent

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†Commissurotomy and callosotomy procedures are surgical interventions which have been employed to limit interhemispheric spread of seizure activity in patients who suffer from intractable epilepsy. A commissurotomy includes resection of the anterior commissure as well as the corpus callosum; a callosotomy entails severing the corpus callosum only.

work has demonstrated that vocal responses can sometimes be elicited to LVF displays [1, 14]. Interpretation of this phenomenon has not been uniform. Zaidel [42] has cautioned that inadequate lateralization, cueing, and subcortical transfer must be thoroughly ruled out to conclude that right hemisphere speech has developed. The majority of the experiments reported here were carried out using retinal stabilization techniques to insure lateralization and the use of a bite bar limited subvocalization. Transfer issues were addressed experimentally. The role of cueing and left hemisphere strategies continue to present a challenge in the interpretation of data from callosotomy patients and will be discussed where appropriate.

The issue of right hemisphere control of motor speech is of interest in establishing the limits of functional plasticity in the adult brain. It has been stated that the non-dominant right hemisphere can develop language skills in the absence of the left hemisphere only when left hemisphere damage occurs in childhood [9, 29]. However, St James-Roberts [37] has suggested that the limited life span of adult patients post-hemispherectomy may have restricted observations of right hemisphere language development. The development of the ability to produce speech concerning stimuli only presented to the LVF would indicate that reconsideration of the basis and limits of functional plasticity is warranted.

SPEECH IN THE WEST COAST SERIES

Among the early commissurotomy patients to be examined in detail, L.B. and N.G. were found to have some receptive language including auditory comprehension and reading and limited written expressive language in the right hemisphere [15, 23, 30]. The right hemisphere seemed to lack the left hemisphere's skill at phonological analysis in both comprehension tasks [41] and rhyme judgements with either word or picture stimuli [43].

One early report suggested that some verbal responses to LVF stimuli were possible in commissurotomy patients [6]. When these researchers used long exposures with an electronic switching system designed to darken the screen if the subject lost fixation, L.B. named six of eight left visual field stimuli. The verbal reports occurred about 20 sec after exposures of at least 5 sec. It remained uncertain if the items were successfully lateralized or, if so, what the mechanism was for this vocal response [see Ref. 12 for additional problems in interpretation].

The second report of vocal responses to LVF stimuli in the West Coast series utilized tachistoscopic presentation of letters and numbers to four commissurotomized patients (L.B., A.A., N.G. and R.Y.) who were at least 12 years post-commissurotomy [25]. Set size varied from two to eight items and exposure duration was 150 msec. L.B. could name both numbers and letters. N.G. could name numbers, but only in sets of two items. A.A. could name numbers, but needed to be informed about the content of the set in order to name letters. Generally, responses to LVF stimuli took 1.5–2 times as long as responses to right visual field (RVF) stimuli. LVF verbal categorization responses were faster relative to RVF responses. These researchers concluded that the naming responses were mediated directly by the right hemisphere.

However, restricted sets of items with repeated trials provide conditions that favor the development of cross-cueing strategies, as Zaidel [42] pointed out. He suggested a variety of ways that split brain patients might, in the absence of right hemisphere speech, name objects lateralized to the LVF or palpated with the left hand including improper lateralization, ipsilateral sensory fibers, subcortical transfer of information, and cross-cueing. He concluded that no evidence to date ruled out all of these factors.

SPEECH IN THE EAST COAST SERIES

Two patients in the East Coast series have demonstrated the ability to respond verbally to LVF stimuli. The first patient in which this ability was observed was a 15-year-old boy P.S. [21]. P.S. was observed to have a well-developed right hemisphere language system shortly after surgery. He comprehended a variety of linguistic relations lateralized to the LVF and could spell out words with blocks with his left hand [17, 19]. Two years post-callosotomy, P.S. was able to name words and pictures presented in his LVF with about 80–90% accuracy. He could read aloud both words and pseudo-words presented in either visual field. However, if he had seen 'COTE' in his LVF he would pronounce it correctly, but verbally spell it 'C-O-A-T'. The conclusion was that P.S. had developed the ability to control speech mechanisms from his right hemisphere. Further work demonstrated that he was able to transfer phonological information paracallosally from his right hemisphere to his left, but was unable to transfer semantic information [21].

The patient V.P. appeared to have a steadily increasing ability to name LVF stimuli beginning about 1 year post-surgery. Thirty months after her callosotomy V.P. was able to read aloud 38 of 40 nouns and verbs presented to her LVF. Under conditions of bilateral stimulation, she was able to read aloud 33 of 36 RVF stimuli and 32 of 36 LVF stimuli. When two syllable words were presented across the visual midline, she read them as two words, for example, 'FATHER' as 'FAT' and 'HER' and 'NOTICE' as 'NOT' and 'ICE'. Thus, it appeared that a second patient had developed the ability to make verbal responses to LVF stimuli [22]. Electrophysiological studies demonstrated that patients P.S. and V.P. also generated a right hemisphere N400, a brain wave associated with semantic incongruity, whereas L.B., N.G. and J.W. did not [27].

After J.W.'s callosotomy surgery in 1979, he demonstrated an extensive lexicon in the right hemisphere, but no speech. Despite greater psychometric intelligence [1], he has performed more poorly than V.P. on a variety of linguistic tasks lateralized to the LVF [3, 22, 35]. When stimuli or response choices were presented in the LVF, J.W. was unable to demonstrate the ability to use syntactic rules to guide comprehension or to complete tasks that were dependent upon phonological analysis. Although J.W. was able to make verbal responses to LVF stimuli in limited sets, careful testing suggested these responses were the result of transmission of a response set into the dominant left hemisphere rather than vocalization by the right hemisphere [16]. However, in the fall of 1990, while evaluating visual field stabilization equipment, J.W. was observed to name pictures presented for extended periods in his LVF. Subsequently, he was observed to name objects palpated out of view with his left hand in a tactile naming experiment [2]. The experiments reported in this paper were designed to confirm and quantify this emerging ability.

GENERAL METHODS

Subject

J.W. is a 41-year-old right-handed male who underwent two stage section of the corpus callosum in 1979. (For a more complete medical history, see Refs [20, 40].) He is a high school graduate who was working full-time at the initiation of these experiments. He was paid for participation.

Apparatus

All stimuli were viewed monocularly with the right eye via a mirror image stabilization system controlled by a Purkinje image eyetracker [11]. If a subject's gaze shifts, the mirrors of the stabilizer shift the visual scene, holding the retinal position of stimuli constant. Procedures for calibrating stabilization have been previously described [10]. Consequently, the stimuli remain consistently lateralized, regardless of the subject's eye motions. This permits stimulus presentations with prolonged exposure durations. In the current experiments, all stimuli were presented on a Macintosh computer monitor with the medial edge of the stimuli 1.5° to the right or left of fixation.

Procedures

Prior to each trial, J.W. was told to fixate a non-stabilized illuminated point superimposed with a beam splitter at the center of the screen. J.W. was instructed to respond as quickly as possible with a verbal description of the stimulus. Occasionally, he was prompted to elaborate on his response. His responses were manually typed into a computer file by an experimenter for later analysis.

PICTURE IDENTIFICATION

Experiment 1a

Materials and procedure. Stimuli for the first experiment consisted of 28 color pictures of familiar people and real world objects found in our laboratory. The stimuli subtended approximately 2° of visual angle square and were centered 2.5° from fixation. Hence, maximum eccentricity was 3.5° from midline. These pictures were presented for 5 sec, in two blocks of 14. Both blocks were presented to the LVF, one final block was presented to the RVF.

Results. J.W. correctly identified 21% of the pictures presented to LVF (see Table 1). In addition, he made several superordinate naming errors. For example, he replied "wild animal" when a deer was shown and replied "person" rather than naming the image of a familiar person (C.M.W.). Superordinate responses were made to both left and right visual field stimuli at approximately equal rates (32% vs 29%, $z=0.2$, n.s.). When asked what he could see in the LVF he described the display as "shadowy". Despite the 5-sec display, he complained that the presentations in the left visual field were too rapid to see, sometimes while the stimuli were still being displayed. His naming accuracy for the 14 pictures presented to the RVF was more than twice that for LVF stimuli (see Table 1).

Experiments 1b and c

Materials and procedure. Pictures of monochrome line drawings were used in this experiment. The pictures were taken from a series standardized for consistent naming responses [36]. The subset used was chosen with consideration to size such that all were approximately 2° of visual angle on a side, allowing consistent stimulus eccentricity (centered 2.5° from fixation). One hundred pictures were divided into four sets of 25. Two different stimulus display times were used, 5 sec and 150 msec. In the left visual field, all four sets were presented with the 5-sec display time and three of the four sets with the 150-msec display time. One set of 25 was presented with the 5-sec display time in the right visual field.

Table 1. Picture identification performance

Experiment	Field of presentation LVF	RVF
Full color pictures		
1a. 5 sec display	21%^{a}	79%^{b}
Line drawing pictures		
1b. 5 sec display	26%^{c}	96%^{d}
1c. 150 msec display	25%^{e}	—^{f}

Notes: LVF = left visual field; RVF = right visual field. $^{a}n=28$; $^{b}n=14$; $^{c}n=100$; $^{d}n=25$; $^{e}n=75$; ^{f}not tested. Values given are expressed as percent correct performance.

Results. J.W. was able to name correctly about one-quarter of the left visual field pictures, regardless of display time (see Table 1). Nonetheless, his most frequent response was "I don't know" or "I didn't see anything". As in Experiment 1a, when J.W. was unable to name the stimulus correctly, he sometimes identified the superordinate category (see Table 3). J.W.'s naming of right visual field presentations improved to nearly perfect performance in this experiment. These results clearly indicate that J.W. has the capacity to name pictures of objects displayed in the LVF, but do not reveal the mechanism by which this is accomplished. Before investigating the mechanism of vocalization, experiments were conducted to determine if this naming ability extended to textual material.

TEXT IDENTIFICATION

Experiments 2a, b, c and d

Materials and procedure. Two word lists, each consisting of 10 three and 10 four letter nouns, were used in these experiments. Text size, display time and visual field of presentation were manipulated. In Experiment 2a and 2b, words subtending approximately 1/2° by 1° of visual angle were used (small text). In Experiment 2a both lists were displayed in each visual field using a 5-sec presentation duration; in Experiment 2b, one list was presented to each hemisphere with a shorter (150 msec) exposure duration. Experiments 2c and 2d were identical to 2a and 2b (respectively), except words subtending approximately 2° by 4° of visual angle were used (large text).

Results. J.W.'s ability to name LVF stimuli extended to textual material (see Table 2). Percent correct for each condition was submitted to a two-factor ANOVA (font size × display duration). As in the picture naming experiments there was no effect of display duration [$F=1.01$, n.s.]. However, performance is enhanced significantly when large font is used [$F=7.43$, $P<0.01$]. There was no interaction between font size and display duration [$F=0.185$, n.s.].

J.W. did not verbally note that the stimuli consisted of words rather than pictures. During the first LVF block, he correctly identified the *word* "dog". When asked to elaborate, he said the presentation "looked like a hound dog". Such a response suggests left hemisphere confabulation about an auditory response to a stimulus that it did not see. Had the left hemisphere initiated the vocal response based on transfer of *visual* information, some recognition of the format might be expected. Another similar error occurred when J.W. identified the word "cup" as a drawing that he was unable to recognize. When asked to draw what he had seen with his left hand, he wrote "cup". However, transfer of some unspecified higher order information cannot be ruled out as the basis of this type of response.

Table 2. Text identification performance

Experiment	Field of presentation: LVF	RVF
Small text		
2a. 5 sec display[a]	20%	83%
2b. 150 msec display[b]	15%	95%
Large text		
2c. 5 sec display[a]	48%	93%
2d. 150 msec display[b]	35%	100%

Notes: LVF = left visual field; RVF = right visual field. [a]$n=40$; [b]$n=20$. Values given are expressed as percent correct performance.

Table 3. Summary of error data for picture and text identification experiments

Error type	Field of presentation LVF	RVF
	Picture naming	
Random	46 (56%)	2 (29%)
Superordinates	28 (34%)	4 (57%)
Associates	8 (10%)	1 (14%)
Visually similar	0 (0%)	0 (0%)
Total	82	7
	Text identification	
Random	30 (79%)	3 (33%)
Superordinates	1 (3%)	0 (0%)
Associates	4 (11%)	1 (11%)
Visually similar	3 (8%)	5 (56%)
Total	38	9

Notes: Values given are sorted by type as a function of visual field of presentation and experiment. Each is expressed as actual error count and percentage of total errors (in parentheses).

When text rather than pictures were used as stimuli, errors of the superordinate type became infrequent to either LVF or RVF stimuli whereas errors of visual similarity increased. That is, while the *picture* of a deer might elicit the superordinate response "animal", the *word* "cat" elicited the response "hat". Although this outcome does appear to be consistent with a crude visual transfer hypothesis, this shift in error type occurred in *both* visual fields. It therefore appears that both hemispheres make associative errors at about the same rate to either picture or text stimuli, but that superordinate errors are more frequent to pictorial material and visual errors are more frequent to text (see Table 3 for a summary of the error data). Were these errors caused by crude transfer of visual information from the right hemisphere to the speaking left hemisphere, the superordinate and visual error rates would be expected to increase after LVF displays of pictures and text. Although there are more errors overall after LVF displays, the rate of superordinate errors to picture displays and the rate of visually similar errors to text displays is higher following RVF displays.

Although the small number of errors made to RVF stimuli limit strong conclusions about the hemispheric characteristic of the errors produced, either hemisphere is apparently capable of producing any of the error types. This observation raises questions about positions that attribute semantic paralexic and paraphasic errors to qualitative differences resulting from right hemisphere participation in language processes after neurologic damage, rather than from changes in the quality of processing within the damaged left hemisphere.

CONTROL OR TRANSFER?

Experiments 3a, b, c and d

J.W. was able to name pictures and words presented to his LVF but it remained unclear if the responses were generated by the right hemisphere or were generated by the left after paracallosal transfer of information. We therefore undertook a series of experiments designed to explore the possibility of transfer. In order to better understand what sort of

Table 4. Stimulus pairs consisting of matching and non-matching visual pairs used for Experiments a and b

Matching	Non-matching
GOAT–GOAT	GOAT–GOTE
CAKE–CAKE	CAKE–KAIK
GOTE–GOTE	GOTE–GOAT
KAIK–KAIK	KAIK–CAKE

Table 5. Stimulus pairs consisting of matching and non-matching auditory pairs used for Experiments 4c and d

Matching	Non-matching
GOAT–GOAT	GOAT–CAKE
GOAT–GOTE	GOAT–KAIK
CAKE–CAKE	GOTE–CAKE
CAKE–KAIK	GOTE–KAIK
GOTE–GOTE	CAKE–GOAT
GOTE–GOAT	CAKE–GOTE
KAIK–KAIK	KAIK–GOAT
KAIK–CAKE	KAIK–GOTE

information might be transferred, experiments were designed to investigate whether explicit transfer of visual (orthographic) or sound (phonemic) information could be documented.

Materials and procedure. Stimulus pairs were constructed to test J.W.'s ability to perform orthographic (3a and b) and phonemic (3c and d) matching tasks, using words and pseudo-words which were homophones of real words. The stimulus pairs are shown in Tables 4 and 5. These words were chosen so that same/different judgements could be made based on the auditory identity or on the visual identity of the paired letter strings. Within visual field presentations were used to assess the ability of each hemisphere to perform the tasks and between visual field presentations were used to assess the transfer of information, either orthographic or phonemic in nature, between hemispheres. On each trial a pair of letter strings was presented for 150 msec. Stimuli were presented, both in the same visual field, at a 3° eccentricity 0.5° above and below the horizontal meridian, for the within field portions (3a and 3b). On the between field portions (3b and 3d) one stimulus was presented in each visual field at a 3° eccentricity. J.W.'s task was to indicate with a key press whether or not the words looked alike (3a and b) or sounded alike (3c and d). Half of the trials required a "yes" response and half required a "no" response in each condition.

Results. Results are presented in Table 6. The within field portions of this series indicate that J.W. was able to perform the orthographic matching task (3a) within each visual field [within LVF; $z=4.13$, $P<0.001$: within RVF; $z=2.88$, $P<0.01$] but could only perform the phonemic matching task (3c) within the RVF [within LVF; $z=1.03$, n.s.: within RVF; $z=3.48$, $P<0.001$]. On both of the between field tasks (3b and d), J.W. was unable to perform above chance [orthographic; $z=0.97$, n.s.: phonemic; $z=0.125$, n.s.]. Thus it is

Table 6. Orthographic and phonemic matching performance

	Presentation type		
Experiment	Within LVF	Within RVF	Between VF
Orthographic	77%[a]	69%[a]	55%[b]
Phonemic	44%[c]	68%[c]	48%[a]

Notes: LVF = left visual field; RVF = right visual field; VF = visual field; within presentations used for Experiments 4a and c; between presentations were used for Experiments 4b and d. [a]$n=64$; [b]$n=128$; [c]$n=95$.

unlikely that his ability to name left visual field stimuli is due to transfer of strictly orthographic or phonemic information. Moreover, the orthographic matching task could be accomplished as a purely visual match, so the failure to perform above chance on between hemisphere trials of this task also argues against visual transfer.

CUEING STRATEGIES

Experiment 4

As explicit transfer of orthographic or phonemic information does not offer an explanation for J.W.'s improved LVF naming, another approach is to examine the contribution that the use of cross-cueing strategies to communicate limited sets of information to the left hemisphere might make to the change in performance. Prior experimental work with J.W. demonstrated that in a very restricted set, he was able to accurately supply verbal labels for LVF stimuli [16]. When the digits 1 and 2 were presented to him tachistoscopically, he could name them accurately in either field. If, however, the digit 9 was substituted for the digit 2 in LVF trials, he would continue to identify stimuli as 1 and 2. At that time, if the series was extended to four digits, J.W.'s performance declined. This result was interpreted as demonstrating that some cue was available to the left hemisphere, which made the verbal responses based on its understanding of what the response choices were. There was no evidence of conscious awareness of the experience. We attempted to replicate and extend this experiment to a longer series of digits, continuing to use the digit 9 as a substitute for 2 in a subset of LVF trials. If the digit 9 was not vocally identified, it would appear likely that the speaking hemisphere was not directly identifying the stimulus items and hence improved performance must be attributed to either extra-callosal transfer or cross-cueing.

Materials and procedures. Stimulus sets of digits from one to eight were constructed so that each set consisted of repetitions of an ascending number of digits, i.e. set one was repetitions of 1 and 2, set two of 1, 2 and 3, set three of 1, 2, 3 and 4, up to set seven which consisted of the digits 1–8. A second group of stimuli was constructed that was identical except that a 9 was substituted for the 2 in each set. Length of each set varied from 20 (10 repetitions of two digits) to 32 (four repetitions of eight digits).

The experiment was run in five sessions. Each set was presented from one to three times, always moving from smaller to larger sets of digits. J.W. was asked to name out loud the number that appeared on the screen. He was given no further information about the make-up of the set. After working on the original sets for about an hour, a break was given and the same sequence was repeated, except that sets with the 9 substitution were displayed to the LVF.

At the last session, a set of 20 8s and 9s was presented for naming as the final trials.

Results. J.W. was able to name digits with above chance accuracy in either field (see Table 7). His accuracy was superior, almost flawless, in the RVF as would be expected, but remained clearly above chance levels in the LVF even in sets of eight digits. This marks an extension of the ability demonstrated in 1987 when J.W.'s LVF responses fell to about 50% in sets of four [16].

However, when an unannounced digit was introduced to the LVF but not the right, accuracy levels remained unchanged overall, but 9s were never correctly named. Responses were always digits from within the set being displayed. The final run of 20 8s and 9s yielded 100% accuracy in the RVF and 85% accuracy in the LVF. The first two 9s displayed on the LVF were called '4'; one subsequent 8 was called '9'. This result demonstrated that an inability to recognize or name the digit 9 could not be responsible for failing to name an unannounced 9 in the prior experiments.

Table 7. Number naming with and without unannounced LVF substitution

Without LVF substitution Number of digits		Field of presentation LVF	 RVF
		96% (50)	100% (49)
3		88% (50)	100% (50)
4		82% (60)	98% (60)
5		60% (60)	98% (60)
6		56% (72)	100% (72)
7		45% (56)	100% (62)
8		58% (64)	100% (64)
With LVF substitution of '9' Number of digits	 Number of 9's named	Field of presentation LVF	 RVF
	0% (11)	95% (19)	100% (30)
3	0% (9)	89% (28)	100% (40)
4	0% (12)	71% (28)	100% (40)
5	0% (12)	67% (48)	100% (60)
6	0% (8)	63% (40)	100% (48)
7	0% (8)	59% (34)	100% (56)
8	0% (8)	50% (56)	100% (88)

Notes: LVF = left visual field; RVF = right visual field; values given are expressed as percent correct performance; parenthesized values are the N at each level.

Discussion. Although as the set size increased, accuracy to the LVF displays but not the RVF displays decreased, naming was remarkably accurate in both fields. Responses were rapid and effortless and, to superficial observation, strongly suggested right hemisphere speech. However, when an unannounced digit substitution occurred, it was apparent that the hemisphere that was initiating the speech response was not aware of the actual digit displayed. There was some indication that J.W. was aware that some additional manipulation was occurring, however. He indicated on several occasions his suspicion that some LVF trials were 'different'. He twice suggested that we were displaying two digits rather than one on some trials. Therefore, in this paradigm, the conclusion must be reached that the vocal responses are being initiated by the left hemisphere based on some as yet unidentified information provided by the right hemisphere which viewed the stimulus item. Moreover, there was some indication that the right hemisphere was able to convey some discomfort upon hearing the incorrect responses, although it could not provide sufficient information to change them. The problem presented by such a pattern of response is whether the information about the RVF stimuli is available due to sub-cortical transfer or if it can be accounted for by some sort of cross-cueing mechanism.

In order to address this question, we returned to the data to examine the accuracy for each digit displayed to the LVF to determine if there was a pattern of response that could be accounted for by a signaling or cueing strategy or whether errors were randomly distributed. Tables 8 and 9 present the responses digit by digit for trials with and without the nine substitution. The pattern that emerges does not appear to represent a random distribution of response errors. J.W. is extremely accurate in identifying the digit 1 when it is displayed to the LVF. He maintains this accuracy regardless of the size of the stimulus set. He maintains a fairly high accuracy (61–87%) for the digits 2–4 in sets of up to four digits, but accuracy falls off somewhat when a fifth digit is introduced. He is at or below

Table 8. Verbal identification of numbers displayed in the LVF

		SAID									
	SEEN	1	2	3	4	5	6	7	8	9	% correct
	1	30	0								100
	2	0	18	1							90
Total		30	18	1							96
	1	15	0	0	0						100
	2	1	13	0	1						87
	3	2	3	15	0						79
Total		18	16	15	1						86
	1	12	0	0	0						100
	2	6	11	1	0						61
	3	1	2	14	1						78
	4	3	1	0	8						75
Total		22	14	15	9						75
	1	11	0	0	0	1					92
	2	1	5	1	4	1					42
	3	2	1	6	1	2					50
	4	3	2	0	7	0					58
	5	2	0	2	2	6					50
Total		19	8	9	14	10					58
	1	10	0	0	2	0	0				83
	2	1	5	3	3	0	0				42
	3	1	0	8	2	1	0				75
	4	2	1	0	7	2	0				58
	5	0	0	2	2	7	1				58
	6	0	1	3	5	0	3				25
Total		14	7	16	21	10	4				56
	1	8	0	0	0	0	0	0			100
	2	2	2	0	3	0	0	1			25
	3	1	0	3	0	1	1	2			38
	4	1	0	0	7	0	0	0			88
	5	1	0	1	2	4	0	0			50
	6	0	0	4	2	1	0	1			0
	7	1	0	1	4	1	0	1			13
Total		14	2	9	18	7	1	5			45
	1	6	0	0	0	0	0	0	0		100
	2	1	2	0	3	0	0	0	0		33
	3	0	0	4	0	2	0	0	0		67
	4	0	0	0	6	0	0	0	0		100
	5	0	0	0	0	5	0	1	0		83
	6	0	1	1	1	1	1	1	0		17
	7	1	0	1	2	1	0	0	1		0
	8	0	0	2	0	2	0	0	2		33
Total		8	3	8	12	11	1	2	3		54

chance in naming the digits 6, 7 and 8 when they are displayed in the LVF. In many runs there is a peak of response accuracy for 4 and 5, with more inconsistent performance for the digits 2 and 3. Despite the fact that his hands had been monitored for possible cueing, the distribution of the errors raised the question of whether he might be using some manual system to transmit information to the left hemisphere.

Table 9. Verbal identification of numbers displayed in the LVF with substitutions

		SAID									
	SEEN	1	2	3	4	5	6	7	8	9	% correct
	1	17	0	0	1	0					94
	9	0	3	2	5	2					0
Total		18	5	5	10	7					94
	1	12	0	0	0	0					100
	9	5	1	1	2	3					0
	3	1	0	13	1	1					81
Total		18	1	14	3	4					89
	1	7	0	0	1	0					88
	9	2	1	3	4	1					0
	3	2	2	5	3	0					42
	4	1	1	0	6	0					75
Total		12	4	8	14	1					64
	1	11	1	0	0	0					92
	9	2	1	4	2	3					0
	3	3	0	9	0	0					75
	4	2	0	1	7	2					58
	5	4	0	2	2	4					33
Total		22	2	16	11	9					65
	1	7	0	0	1	0	0				88
	9	0	0	1	1	6	0				0
	3	1	0	5	1	1	0				63
	4	0	0	0	8	0	0				100
	5	1	0	0	2	5	0				63
	6	1	0	2	3	1	1				25
Total		10	0	8	16	13	1				65
	1	8	0	0	0	0	0	0	0		100
	9	1	0	0	0	4	2	1	0		0
	3	0	0	3	4	1	0	0	0		38
	4	0	0	0	8	0	0	0	0		100
	5	0	0	1	2	4	0	1	0		50
	6	1	0	3	3	0	0	1	0		0
	7	2	1	0	0	4	0	2	1		25
Total		12	1	7	17	13	2	5	1		52
	1	8	0	0	0	0	0	0	0		100
	9	1	0	1	1	4	1	0	0		0
	3	1	0	5	0	1	0	1	0		63
	4	2	0	0	6	0	0	0	0		75
	5	0	0	0	2	6	0	0	0		75
	6	0	0	2	0	1	1	1	2		25
	7	2	0	1	3	1	0	1	0		0
	8	1	1	1	3	2	0	0	0		0
Total		17	1	10	15	15	2	3	2		46

If he were able to make a minute ipsilateral motor movement of a single digit, the left hemisphere might be able to translate that motor signal into a verbal label with relative ease. It is well known that there is both ipsilateral and contralateral control of arm movements, but there is less agreement regarding the precision of the ipsilateral pathways for hand and digit control. Control of hand and digit movement via ipsilateral pathways is limited for rhesus monkeys [5]. However, Volpe *et al.* [39] demonstrated above chance performance by callosotomy patients on a task which required unilateral imitation of hand positions. More to the point, Trope et al. [38] were able to demonstrate ipsilateral motor control of individual digits. Although there was considerable variation between the two callosotomy patients tested, some ipsilateral control was present in all conditions. Notably, ipsilateral control of the thumb was good in all conditions tested in the LVF/ right-hand conditions, the thumb, index and middle fingers remained above chance. Of interest, one subject demonstrated superior ipsilateral control of the thumb and little finger with a decline in performance for the middle fingers. This pattern was, however, for the RVF/left-hand trials for which it is more problematic to explain left hemisphere interpretation. Nonetheless, this ability suggests that ipsilateral motor control might provide a method of signaling that fits the pattern of the data.

Another possible explanation involves paracallosal transfer of visual information. Such an explanation would predict confusion of numbers of similar appearance like 1s and 7s or 3s and 8s. Visual 1s and 3s never elicited the higher number that might be visually associated with them. Of 32 7s displayed to the LVF, six 7s were identified as 1, one as 2, three as 3, nine as 4, seven as 5, zero as 6, four as 7, and two as 8. Of the 14 8s displayed to the LVF, one 8 was identified as 1, one as 2, three as 3, three as 4, four as 5, zero as 6, zero as 7 and two as 8. Although the numbers are low, this pattern may lend some credence to the notion of visual transfer of information, mostly evidenced by the greater likelihood of calling 7s but not 8s 1. However, the tendency to make many guesses of 4 and 5, as might result from a manual attempt to signal 'high' with the 4th and 5th digits, is equally apparent in even this limited data set and further supports the notion of manual signals as the cross-cueing mechanism in this paradigm. Further investigation will be required to determine if the possible contribution of visual transfer is real. Were some higher order information regarding the value of the number being transferred, more errors involving the numerically closest digits would be expected. This pattern was not found.

This data represents an increase in sophistication of the strategy used by J.W. to respond in this paradigm from the data obtained with this patient in 1987 [16]. The use of complex strategies has been previously documented in other patients as well. As early as 1971, L.B. was observed to make verbal responses to LVF numbers, but examination of the reaction time data demonstrated that he was using a subvocal counting strategy that yielded longer reaction times for higher numbers [15]. Voice-onset time following right and left visual field displays was not collected in this experiment, but use of a counting strategy seems unlikely in this patient given the distribution of errors.

In sum, what superficially appears to be accurate naming, can be explained as the result of manual signaling and naming strategies in this experiment. However, the use of these strategies in a paradigm with predictable sets does not rule out the participation of right hemisphere speech mechanisms in other circumstances. Therefore, we made one more attempt to provide the right hemisphere with a chance to speak its mind.

VOCALIZATION OF 'SECRET' STIMULI

Experiment 5

There have been differing reports concerning the ability of split-brain patients to transfer information paracallosally between the hemispheres for use in integrated decision making. A number of studies have argued strongly that the two hemispheres can integrate lateralized information for unified action [7, 8, 28, 32, 33]. Some of these results have proven difficult to replicate and further analyses have been offered that explain apparent integration as the result of strategic responses [34] or post-response integration by the dominant hemisphere [26]. Clearly, the observation and documentation of inter-hemispheric integration of cognitive information for problem solving or speech is problematic.

In general, the presence of speech in response to LVF stimuli has been taken to indicate left hemisphere participation and at times a failure of lateralization techniques. In the experiments reported above, we have reported naming of new and unpredictable pictures and text under conditions where we do not believe failure of lateralization is possible. We have been unable to demonstrate any cross-hemisphere transfer of phonemic or orthographic information that would allow the left hemisphere sufficient information to explain the naming performance. In a paradigm with restricted predictable sets, strategic left hemisphere use of manual signals appears to account best for the response pattern. Although we have credited the right hemisphere for initiating speech under circumstances where a failure of lateralization is inconceivable and random or even informed guesses do not offer sufficient explanation, there is no "marker" of right hemisphere speech. There is no reliable information regarding differences in onset (a delay could mean time for transfer or slower initiation within the right hemisphere), articulation, or voice quality that would allow the direct inference that the right hemisphere was speaking. A positive example of right hemisphere speech where the left hemisphere was in error and the right hemisphere was correct was needed to help rule out the influence of transfer of information. In the following experiment, if information regarding the identity of the 'secret' stimulus was being transferred, the left hemisphere should either name it incorrectly or 'break the code'. Therefore, we attempted to elicit speech in a paradigm where the left hemisphere was intentionally deceived regarding the appropriate response. The paradigm chosen was similar to that used with P.S. ([21].

Materials and procedure. Ten pairs of concrete three and four letter nouns were created so that one member of each pair was animate and one was inanimate (RUG–BUG, FOG–DOG, PEN–HEN, MAT–RAT, PAN–MAN, HAT–CAT, GUN–NUN, BOWL–OWL, DISH–FISH, BOAT–GOAT). Eight files were created randomly choosing one item to be the 'secret' item for that file. The secret item always occurred on the first trial in one visual field (see Table 10). Pilot testing indicated that a single learning trial followed by a short run best suited to preventing the left hemisphere from "guessing" the game. The secret item appeared pseudo-randomly throughout the set for five presentations in that visual field and for one presentation in the other visual field. Five additional items were chosen from the set to make 10 trials in the experimental field and nine additional items to make 10 trials for the contralateral field. One file with two presentations of each item one to each visual field was created for post-testing.

For the experimental trials, J.W. was told "Every time you see the next word we display, call it 'X' ". X was a one syllable noun chosen so that it had no straight-forward association to the secret items. X was changed with each set, so that J.W. had 21 trials in each set for which he had to remember to "misname" a different item.

For post-testing, J.W. was placed in the eye-tracker and viewed the words at normal tachistoscopic speeds (150 msec) despite the precise eye-movement control. The task was to press a key marking alive or dead.

Table 10. Manual and verbal response accuracy for 'dead/alive' decisions for 3 and 4 letter concrete nouns

Response mode	LVF	RVF
Left hand key press	100%	95%
Verbal response	90%	100%

Notes: N is equal to 20 in each cell. LVF = left visual field; RVF = right visual field; values given are expressed as percent correct performance.

Table 11. Example of first six hypothetical trials of a 'secret' word paradigm when the right hemisphere is the 'informed' hemisphere

Instruction: "Whenever you see the next word, say 'book'."			
	LVF	RVF	Verbal response
Trial 1	DOG		"Book"
Trial 2		MAT	"Mat"
Trial 3	CAT		"Cat"
Trial 4		DOG	"Dog"
Trial 5	DOG		"Book"

Notes: LVF = left visual field; RVF = right visual field. Visual field receiving the first trial is considered to be the 'informed' field.

Results. In post-testing on 'dead/alive' decisions, J.W. was accurate for both manual and verbal responses demonstrating that both hemispheres were able to read accurately and understand the tachistoscopic displays despite the fact that pairs of items differed only on one letter (see Table 11). Therefore, we can examine the results of the primary manipulation with confidence that both hemispheres were able to comprehend the visual display accurately.

Percent correct of hits (saying the X word aloud when the secret word was displayed) were calculated for each hemisphere. False alarms (percent of the time the X word was used as a response for a non-target item) were also calculated for each visual field. These numbers were used to calculate an A′ statistic for each visual field (see Table 12). A′ is a non-parametric signal-detection statistic that yields an estimate of true two-choice accuracy [24]. Using this measure, LVF displays of the secret word yielded about the same rate of accuracy whether the right or left hemisphere was informed of the stimulus item that should elicit the X word. This result suggested that the left hemisphere was controlling the verbal responses to LVF displays regardless of the informational state of the right hemisphere.

However, the accuracy of RVF responses was strongly influenced by being informed of the appropriate target item. If the left hemisphere were controlling verbal responses, the effect of the informedness manipulation should be seen for responses to both visual fields. When the secret word was revealed to the RVF/left hemisphere, the 'secret' word was always responded to with the X word for RVF displays. There were no false alarms for other items in the set that were displayed in the RVF. In contrast, LVF displays were

Table 12. Signal detection analysis of secret word substitution

	'Informed' hemisphere			
	Left		Right FF	
	LVF	RVF	LVF	RVF
Hits[a]	0.66 (3)	1.00 (15)	0.55 (20)	0.00 (4)
False alarms[b]	0.33 (27)	0.00 (15)	0.20 (20)	0.03 (36)
A′[c]	0.75	1.00	0.77	0.50

[a]P (X word/'secret' word)
[b]P (X word/other word)
[c]A′ = non-parametric index of sensitivity analogous to d′. Computational formula used for this data was taken from Grier [24].

responded to with the X word more than one third of the time, regardless of whether the appropriate item had been displayed. There was a larger proportion of X reponses to the appropriate targets than to the other items in the set, but the numbers of secret word trials in the LVF were too small to say any more than that. This pattern of response could indicate that when the left hemisphere knows the relation between the X word and the secret word, verbal responses to LVF trials simply represent a relatively steady rate of guessing by the left hemisphere.*

When the secret word was revealed to the LVF/right hemisphere, RVF trials were strikingly different from those described above. There were no 'hits' and only a very few false alarms (see Table 12). In other words, when the left hemisphere does not know what the appropriate target for the X response is, it does not use the X word. Responses to the displayed words are accurate and the X word is not used frequently as a guess. LVF trials do not yield such a clear pattern. Hits occur about half of the time and false alarms about one quarter of the time, a significantly different response rate (55% vs 20%, $z=1.74$, binomial $P<0.05$, one-tailed), indicating that the right hemisphere understands the experiment and is influencing the response. We cannot be sure that it is initiating the vocal response. However, given the high accuracy in the number naming experiment, and the need to signal only for a single item in this paradigm (the appearance of the secret word), if a similar signaling strategy were being used here, a higher hit rate would be expected.

We suggest that the left hemisphere remains dominant and will control responses whenever it can and will guess in the face of uncertainty. When the right hemisphere alone 'knows' the correct response, it can make limited verbal responses.

DISCUSSION

These experiments indicate that J.W. now has the capacity, albeit limited, to correctly name stimuli presented in the LVF. This naming capacity is less reliable than that of the dominant left hemisphere. Moreover, right hemisphere naming may not occur if the dominant left hemisphere can find a way to control responses. It is likely that this naming capacity sometimes reflects cross-cueing strategies of the right hemisphere to the left hemisphere, rather than the generation of speech by the right hemisphere. If any visual transfer does occur, it does not appear to be complete or consistent enough to allow visual matching of orthographic information between hemispheres. None of the experiments provided evidence for transfer of higher order information between hemispheres.

The strongest evidence comes from naming of unknown text and pictures. Some of these experiments used items that were familiar but we do not believe they were predictable. The original picture experiment (1a) used newly generated stimulus items that had never been used as part of one of our experiments. Although they may have represented familiar items or acquaintances of J.W., they were not predictable in the experimental situation. This is less true of the line drawings and text items used in Experiments 1b and 1c. These were drawn from the set of 260 Snodgrass pictures which have been used in various

*There are, as noted above, very few trials in some conditions of this experiment. One crucial condition with few trials is that of LVF 'hits' when the left hemisphere is the informed hemisphere. Although this hit rate appears high, it may be due to guessing as it represents only two out of three trials. Had only one of those responses not occurred, the hit rate and false alarm rate would have been identical indicating left hemisphere guessing at a steady rate on trials when it did not see the target.

experimental paradigms with J.W. over the last 10 years. Accuracy for these items increased over the accuracy for naming color pictures for RVF but not LVF presentations, so that enhanced guessing for familiar materials does not easily account for his performance. J.W.'s pattern of responses in the secret word paradigm confirms that the right hemisphere can control speech under circumstances where the left hemisphere is misinformed.

However, there is clear evidence in the number naming experiment, that given a limited easily codeable set of responses, J.W. can use cross-cueing techniques to make verbal responses to LVF stimuli with an accuracy that far exceeds chance values. He remains despite his callosotomy an integrated organism that follows a behavioral plan based on whatever information is at his disposal. J.W. is an experienced subject who has long since learned that he is expected to respond to information that he does not believe that he has seen. It is not surprising that he will use any means at his disposal to do so. When we provide him with an experimental paradigm where there is a limited set of easily codeable items, he is quick to use those characteristics of the stimuli to improve his performance.

There is also limited evidence for some crude transfer of visual information. Within the number naming experiment, there was some evidence that J.W. was selecting numbers based on visual similarity as well as using ipsilateral digit control to signal the identity of digits up to 5. This evidence remains unconvincing, but will continue to be considered in continuing investigations.

Were the problem solving strategies of the human organism less adaptable, integrated, and motivated, sorting out the hemispheric contributions to human behavior and to control of speech would be a simpler task. The results presented here require minimal contributions from right hemisphere speech and manual signaling for left hemisphere interpretation to provide a satisfactory explanation. It is clear that the particular experimental paradigm used will influence the behavioral strategy used to complete the task. Further work will be required to determine the task requirements that will allow us to manipulate which one of these behavioral strategies will be the most successful and perhaps at that point we will be able to specify more precisely the contribution of right hemisphere control of motor speech, the use of various cross-cueing strategies, and paracallosal transfer of information to verbal responses to LVF stimuli.

The most important point to be made here is that despite the existence of a variety of routes to verbal responses from LVF stimuli, some contribution of right hemisphere control of motor speech is required to explain J.W.'s change in behavior. This change is particularly remarkable in this patient as it has occurred so far beyond the surgical intervention. J.W.'s callosotomy was performed in 1979. The first evidence of access to speech was observed in 1990 despite the fact that this patient was being seen on an almost weekly basis from mid 1988. This development so far beyond the period of neurological recovery or the critical period for language acquisition is quite remarkable. Four other callosotomy patients have demonstrated that they have some ability to generate speech from the right hemisphere. L.B.'s surgery was in 1965 and some suggestion of right hemisphere speech was reported in 1968 [6]. P.S. had "excellent right hemisphere linguistic comprehension" [21, p. 62] shortly after surgery. He was able to generate short phrases by 18 months post-surgery. V.P. also demonstrated superior comprehension shortly after surgery and single word reading was documented about 30 months post-surgery [22]. K.O., a left-handed young woman who is right hemisphere dominant for language, was not investigated until she was 6 years post-surgery [31].

Table 13. Summary information for callosotomy patients with some bilateral motor speech

Subject	Sex	Handedness	Age onset	Age surgery	Type surgery	Anterior commissure sectioned?
L.B.	M	R	3.5 years	13	One stage	Yes
P.S.	M	R	20 months	15	One stage	No
V.P.	F	R	9 years	22	Two stage, anterior 1st 7 week interval	No
K.O.	F	L	6 months	9	Two stage, anterior 1st 8 month interval	No
J.W.	M	R	19 years	20	Two stage, posterior first 10 week interval	No

In all cases except K.O. whose early post-surgical course was not observed, the ability to make some right hemisphere controlled verbalizations appeared to develop gradually after the surgery. These individuals are all unusual in that they displayed relatively good right hemisphere language comprehension shortly after surgery. However, they differ in time of onset, age at surgery, sex, handedness, and staging and extent of the surgical procedure itself. We are far from being able to specify what the requirements are for the development of even limited right hemisphere speech, but the development in a patient so far post-surgery is exceptional. Such long-term functional plasticity has been suggested in adults but seldom documented. This issue is of theoretical importance in understanding the limits of functional plasticity and of practical importance in establishing treatment guidelines for patients with language dysfunction following stroke.

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