INTERHEMISPHERIC VISUAL COMMUNICATION IN HUMAN COMMISSUROTOMY SUBJECTS

Thesis by
Larry E. Johnson

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Abstract

Several problems concerning the transfer of visual information between the cerebral hemispheres in human forebrain commissurotomy patients were examined. These patients, 10-15 years post-surgery, were compared with normal and partially-split (splenium-intact) control subjects both on their ability to verbally categorize or name stimuli tachistoscopically presented unilaterally into either the left or right visual half-field (LVF or RVF), several degrees from the fixation point, and on their ability to compare or name simultaneously presented bilateral visual stimuli. The aim of these experiments was (1) to determine the extent to which stimuli presented to the left visual field could be orally described, (2) to learn whether visual information presented separately to each "disconnected" hemisphere could be compared, and (3) to explain the findings in context with previous neuroanatomical, physiological, and behavioral studies.

Using either a box tachistoscope or a back-projection screen, a wide variety of stimuli (brightness, colors, numbers, letters, patterns, schematic faces, and photographs of human faces) were flashed to one or both visual half-fields, and both the accuracy and the speed of several kinds of manual and verbal responses were measured.

Three of the four split-brain patients were able to orally <u>categorize</u> unilaterally presented stimuli ("yes"-"no", "odd"-"even") in both visual fields. In addition, all four patients responded as rapidly to LVF stimuli as to RVF stimuli in categorization experiments. The control subjects also accurately categorized stimuli and responded equally fast to LVF and RVF stimuli.

When the patients were asked to <u>name</u> the unilateral stimulus, those in the RVF were easily named but the ability to name LVF stimuli was found to vary between patients for different stimuli and sample sizes. However, despite these differences in accuracy, all of the split-brain subjects responded significantly more slowly to LVF than to RVF stimuli, except for facial stimuli. Control subjects, on the other hand, continued to respond equally fast to stimuli in either visual half-field.

Finally, when the patients were required to compare a variety of bilaterally presented visual stimuli as same or different, there was again a wide range of abilities. In general, it was found that those patients who were best at naming stimuli were worst at cross-comparing them, and vice versa. One subject (LB) was able to name two bilaterally flashed stimuli, and yet was unable to compare them as same or different beforehand, while another (NG) could cross-match two stimuli by name identity as well as physical identity, but could not name the LVF stimulus.

These results most easily suggest the following hypotheses: (1) Some commissurotomy patients can make oral categorization responses to unilateral LVF stimuli, perhaps using their left hemisphere by way of midbrain pathways, while (2) naming LVF stimuli most likely requires a different mechanism, probably involving right hemisphere speech. In addition, (3) some patients can cross-compare stimuli between the two visual fields. In these cases, the oral responses likely come from left hemisphere verbal centers since these patients are also poorest at naming LVF stimuli.

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VI. Appendix: Cross-comparison of Bilaterally Presented Brightnesses, Colors, Upper and Lower Case Alphabetic Letters, and Photographs of Faces by Human Commissurotomy Patients

I. GENERAL INTRODUCTION

This thesis examines several problems concerning the transfer of visual information between the cerebral hemispheres in forebrain commissurotomy (split-brain) patients. It proposes that these patients can compare certain kinds of visual stimuli between the two visual half-fields when these stimuli are presented near their fixation point, and that both "disconnected" left and right hemispheres are capable of describing aloud specific characteristics of stimuli presented exclusively within the left visual half-field. The historical foundation for the experiments that support these proposals is presented in Chapter II in an overview of previous research on interhemispheric cross-integration, focusing on the problem of visual transfer in split-brain animals and humans. The specific experimental evidence is then detailed in the remaining chapters. Chapters III and IV discuss the abilities of commissurotomy patients to verbally categorize and to name stimuli presented in only one visual half-field, while Chapters V and VI examine how the patients cross-compare and name bilaterally presented visual stimuli.

II. HISTORICAL OVERVIEW

The effects of callosotomy in humans were intensively studied by Akelaitis and coworkers for about 15 years, from the late 1930's to the early 1950's, using a large series of patients who had undergone various degrees of surgical section of their forebrain commissures for the control of severe epileptic seizures [1-4]. This surgical technique was chosen in part because of the experimental evidence presented by Erikson [5, 6] that showed that the corpus callosum in monkeys played a definite role in the spread of an epileptic discharge from one cerebral hemisphere to the other, and that this spread could be interrupted by cutting the corpus callosum. Over a period of time, the extent of surgery on the human subjects studied by Akelaitis was varied to include finally one patient who had not only his corpus callosum severed (with, presumably, the underlying hippocampal commissure) but also, in a second operation one year later, his anterior commissure as well [7]. In the many studies of all of these surgical subjects, regardless of the extent of their surgery, it was concluded that there was no resultant disturbance of orientation, or discrimination of the size or the recognition of color, objects, or letters in either visual half-field [2]; no dyspraxia of either hand independent of extraneous hemispheric damage [8]; no disturbance of visual, auditory, or tactile gnosis; and no impairment of praxis and language functions [7]. In addition, there were no alterations in binocular depth perception, in the ability to maintain and recover fusion in response to diplopia-producing stimuli [4], nor were there any effects on the learning or bilateral transfer of learning in mirror drawing (and only inconsistent effects on maze learning or its transfer) [9]. These findings found support in some earlier studies of patients with tumors of the corpus callosum that attempted to formulate a "syndrome of the corpus callosum" [10], noting mental disturbances such as apathy or other personality changes, but no difficulty that could be attributed to a defect in information transfer from one side of the brain to the other. A review of similar operations with animals also claimed that overall, there was no convincing or consistent defect in post-surgical cross-integration [11]; any behavioral deficits could be more easily explained by associated brain damage. The evidence against a substantial neurological role for the corpus callosum for a time seemed so overwhelming that it was stated that this massive fiber bundle either had no important function [12] except to aid in the transmission of epileptic seizures from one side of the body to the other [13], or that it served only a simple structural role [14].

At the same time, however, evidence had also been presented that in retrospect can be interpreted to show the possibility that the corpus callosum may indeed have an important neurologic role in the normal brain. Dejerine in 1892 [quoted in 15] studied a patient with a left occipital lobe and splenium damaged by cerebral infarction who showed alexia and right homonymous hemianopia with preserved writing ability. He postulated that the intact visual cortex on the patient's right side was no longer connected with the left hemisphere's speech centers because of the left occipital lesion, not yet recognizing the significance of the damage to the corpus callosum. Liepmann (1900, 1906) [quoted in 16] presented a patient with disconnection symptomatology in whom post-mortem findings confirmed earlier predictions concerning sites of lesions. Liepmann and Maas [17] in 1907 also described a patient with a callosal lesion who showed left motor apraxia to verbal commands. With the benefit of hindsight, numerous similar cases have now been found [15].

Imamura (1903) and Yoshimura (1909) [quoted in 18], as possibly the first experimental demonstration for a higher neurological function for the corpus callosum, showed that cutting the callosum (and specifically the splenium) several weeks after recovery from the visual neglect associated with a unilateral frontal cortex lesion could reinstate the neglect. This suggested that the occipital cortex ipsilateral to the frontal lesion needs an input from the opposite occipital cortex via the callosum in order to sustain its compensating role [18]. And from Pavlov's laboratory, Bykov (1924-25) [quoted in 11, 19] found, following transection of the corpus callosum, that the development of a conditioned response to stimulation of one side of a dog's body no longer was associated with a symmetrical development on the other side. This suggested that the corpus callosum also plays an important role in the generalization of sensory learning between the two sides of the body.

Studying the role of the corpus callosum in man has been complicated by the fact that most naturally occurring lesions of the corpus callosum, because of the invasive nature of tumors and infarctions, are normally not limited to the callosum itself but also involve variable amounts of surrounding tissue, thereby complicating if not masking behavioral changes that would be caused by pure callosal damage alone. While the surgical commissurotomies performed by Van Wagenen and studied by Akelaitis, as described earlier [1-4, 6-8], did not seem to be associated with any specific behavioral abnormalities, other researchers reported significant deficits following what were felt to be rather specific callosal damage. Trescher and Ford [20] presented a patient who had the posterior half of her callosum sectioned during the removal of a colloid cyst of the anterior part of the third ventricle and who exhibited a left visual field (LVF) alexia and a left hand tactile agnosia for letters. A similar LVF alexia was found in two patients, also with cysts, who were studied by Maspes [21]. In addition, Sweet [22] reported that a seeping intracranial aneurysm, which caused a softening confined almost exclusively to the corpus callosum, was associated with apractic agraphia and ideomotor apraxia of the left hand. Still another case, reported by van Vleuten [quoted by 23], presented a patient with agraphia, apraxia, and astereognosis in an otherwise normal left arm.

But these findings were overwhelmed by the vast number of negative findings and the prevailing doctrine continued to maintain that no important functional symptoms could be found following destruction of the corpus callosum and anterior commissure, provided that other brain damage could be excluded [24]. Nevertheless, the discrepancy between the size and position of the corpus callosum on the one hand and the apparent lack of any important functional disturbance following its surgical transection on the other hand continued to remain a dilemma [25].

In the early 1950's, new evidence emerged to radically change the prevailing view of the function of the corpus callosum. While studying interocular transfer in cats, Myers and Sperry [26-29] found that cutting both the optic chiasm (a procedure which allowed visual information from each eye to project only to the ipsilateral cerebral hemisphere) and corpus callosum before training prevented the untrained eye from subserving visual discrimination tasks that the opposite eye had been trained upon. It thus appeared that visual information presented to one hemisphere was <u>not</u> transferred and/or utilized by the opposite hemisphere after the corpus callosum was cut. When only the optic chiasm was cut, it was found that although the visual discrimination was presented directly to only one hemisphere, the opposite hemisphere also learned the task. Further experiments showed that the caudal portion of the corpus callosum, particularly the splenium, was the crucial part of the callosum involved in visual transfer [30], and that the efficiency of interhemispheric transfer may vary for different kinds of discrimination tasks [31]. It was also found that both cats and monkeys with complete optic chiasm and forebrain commissure section could be taught to perform opposing discriminations, trained concurrently thru separate eyes, with no sign of interference [28, 29, 32].

The findings of Sperry, Myers, and others with callosally sectioned animals led Geschwind in the early 1960's to reexamine his series of patients with neurologic tactile identification. She did, however, show defects in crossed visual-tactual matching and in the transfer of training in manual sorting and form-board tasks. Notable is that these post-surgical behavioral defects could be found many years following commissural section.

Why were these disconnection symptoms overlooked earlier? There are probably a number of reasons. Subjects are now tested under very rigorous conditions in order to prevent the inadvertant but common "cross-cluing" of information, whether visual, tactual, verbal, or aural, from one side of the body to the other side. And many experiments are required to exhaustively test and compare a wide variety of intermodal as well as intramodal parameters, strictly lateralizing both input and output in search of any possible deficits. In addition, old, well-practiced or stereotyped responses are avoided since these may have become so automatic as to be performed through lower centers or equally well by either side of the brain.

Furthermore, the roles of the individual commissures are now becoming better defined. As mentioned above, Akelaitis and coworkers studied only one patient who had undergone a complete commissurotomy which included the anterior commissure [7]. While the anterior commissure is not known to have a visual role in the cat [44], it has been found to perform indistinguishably from the splenium with respect to visual transfer between hemispheres in monkeys and chimpanzees [45, 46]. In humans, there may be considerably individual variation as to its function [47]. However, the fact that the anterior commissure and portions of other commissures often remained intact in the Akelaitis series of patients may partly explain the absence of any readily apparent disconnection symptomatology. There still remains the constant problem of evaluating the significance of the variability among patients, their differing medical histories, pre- and post-surgical neurologic lesions, and so forth.

And finally, continuing studies extending over more than a decade on the Bogen-Vogel series of commissurotomy patients seem to show an evolution in the subjects' capabilities over time [48, 49]. This may be due to the emerging role of secondary, residual, redundant, or otherwise previously unapparent pathways which remain intact following forebrain commissurotomy. This idea will be amplified further in the experiments which follow (Chapters III-VI).

In spite of the almost complete functional disconnection of gnostic processes exhibited under rigorous testing procedures soon after complete commissurotomy, the general behavioral normalcy of these patients in everyday life is remarkable, a finding which was also noted by Akelaitis and his coworkers with the earlier patient population. Following surgery, there have been no gross alterations of personality, intellect, mannerisms, temperament, etc. The great majority of disconnection symptoms are readily concealed or compensated for when the special restrictions during testing are neglected [25, 48]. Unifying mechanisms such as conjugate eye movements, uncrossed fiber systems, bilateral emotional and autonomic processes, feedback effects of reinforcement, mechanisms of orientation and attention, auditory and stereognostic cross-cuing all serve to conceal the commissural defect in unrestricted behavior [48, 50].

Although some investigators have been unable to find significant visual transfer following commissurotomy in non-human primates [51] and have postulated various cross-cuing strategies to explain any apparent integration [50-54], others have proposed that the midbrain, the phylogenetically more primitive part of the brain which continues to connect the two sides following forebrain commissurotomy, is responsible for much of the behavioral unity seen in most animals after surgery and may have a greater role in visual cross-integration and transfer than was earlier believed. The many findings of residual vision following various cortical lesions, including visual processing within scotomas (blindsight) [55-64] leads to the inevitable speculation that extra-striate anatomical areas may play an important role in normal vision. Trevarthen [32, 65] found evidence that split-brain, split-optic chiasm monkeys could perceive a relationship of size, orientation, or number when visual stimuli were presented separately to the two eyes. This result could not be explained by the known neuroanatomy of the retino-geniculo-striate pathway [65, 66]. Other evidence from split-brain or cortical lesioned monkeys suggested that these animals could retain a unified field for coordinated visuo-motor functions [67] even if the surgical hemisection was extended to include bisection of the cerebellum [68, 69]. In addition, the finding of extensive afferent and efferent interconnections between many of the visual cortical areas, via thalamic structures like the pulvinar, and the tectum-pretectum region has certainly not diminished the speculation that these "lower" centers may serve a substantial function in visual processing in higher animals.

Many studies now support a midbrain visual role. (For excellent reviews see [70, 71].) Meikle and Sechzer [72] found interocular transfer of brightness and flicker rate discrimination in forebrain commissurotomized cats, and transfer of brightness and color discrimination in split-brain chimpanzees may sometimes occur [73]. Meikle [74] reported that interocular transfer of brightness discriminations could eventually be abolished in cats if the optic chiasm, forebrain commissures, posterior commissure, and commissure of the superior colliculus were sectioned. Furthermore, Sechzer [75] found that cats with section of the optic chiasm and corpus callosum could show significant interhemispheric pattern discrimination transfer when reinforced with shock avoidance but not with food approach.

Other studies suggesting a midbrain visual function [76] have found that split-brain cats could perform a comparative brightness discrimination, while split-brain monkeys have been reported to cross-integrate bilaterally presented simple patterns [77]. Some savings in the transfer of movement and perhaps brightness discrimination between the hemispheres of split-brain cats may also occur [44].

Voneida's results [78] suggested that the interhemispheric transmission of visual signals in cats may depend on the commissure of the superior colliculus. Trevarthen [32] has claimed that while brightness and color interference could occur between the eyes of a forebrain-split monkey, when the surgical split continued into the midbrain color discrimination learning now failed to transfer although he continued to find a pronounced, though transitory transfer effect with brightness.

Schneider [79, 80], from his surgical and behavioral work on vision in hamsters, proposed an hierarchical organization for visual perception and visuomotor processes. He suggested that the striate cortex was necessary for visual discrimination of patterns while the midbrain tectum was important in visual orientation and localization. Spurred by Schneider's findings, Trevarthen [65] subsequently proposed, based on his split-brain monkey results, a two-vision theory involving ambient and focal vision. Ambient vision was defined as motion-dependent vision in three dimensional space by which postural and attention-orienting movements are regulated, while focal vision was concerned with details of form, hue, and pattern necessary for a complete perception of identity.

Trevarthen went on to study the human commissurotomy patients [81-83] and demonstrated that, under certain circumstances, these subjects could integrate left and right visual half-fields and speak about events confined exclusively to the left visual field. This perceptual unity required large long-lasting stimuli, extending deep into the peripheral visual fields, and undergoing changes in position, size, shape, intensity, and color. In addition, performance was highly dependent on a certain mental set, with attention distributed peripherally, which was easily disrupted.

However, more substantial recent evidence now points to the even broader interpretation that "midbrain vision" may include far more complex abilities than the primitive movement and orientation features found by Trevarthen and Schneider and many others. The evidence for this comes from a number of sources. One area of research involves ablations of known or suspected visual areas in the brain. Some researchers have found results which strongly suggest that the striate cortex is not required for pattern vision in cats [84], monkeys [85, 86], or humans [61, 64], and while extra-striate cortical areas and temporal lobe areas may be important regions of the cerebrum for processing complex visual discriminations like pattern vision [87, 88], other data also suggests a significant midbrain-diencephalon role [89-92]. For example, Casagrande, et al. [93] showed that a simple pattern orientation discrimination is performed easily by tree shrews following removal of area 17 but is impossible following bilateral ablation of the superior colliculus. Others have shown that lesions involving not only the superior colliculus [94] but also the pretectum [70, 71], perhaps including the nucleus of the posterior commissure and the medial thalamus in monkeys [96], severely disrupts pattern and perhaps color vision. Certainly in other animals (birds) the importance of lower structures, such as the supraoptic decussation, is important for the interhemispheric transfer of color and pattern discrimination [97, 98].

The pretectal region has been reported to be critical in the "visual memory system" of the white rat [99] and, along with the superior colliculus [70], in the acquisition of pattern discrimination habits in the cat [100]. Tegmental midbrain structures and the posterior thalamus in cats have also been implicated in learned visual responses [101]. Braitman and Wilson, Jr. [102] found visual retention deficits following bilateral pretectal destruction in monkeys. The monkeys were also deficient in learning a new visual discrimination task (but not a non-visual alternation task). Still other researchers have included as midbrain-specific functions a specialization in detection of rate of movement [96].

Finally, and in particular relation to this thesis, are the scattered findings with split-brain human patients suggesting that, occasionally at least, they are capable of cross-comparing bilateral visual stimuli or speaking about left visual field stimuli even when the stimuli are presented in more central vision (in contrast to Trevarthen's studies of peripheral vision) [49, 103, 104].

It has been difficult to form a completely satisfactory unitary hypothesis that can combine what is known about various kinds of visual processing with corresponding neuroanatomical structures. The most common approach has been to propose and look for a dichotomy of function between the striate cortex and midbrain. At least as early as 1932 it was suggested that the cortex is concerned primarily with pattern vision while the midbrain is concerned with brightness and flux [105]. Schneider [79, 80] has proposed that the cortex identifies while the midbrain localizes visual stimuli, and Trevarthen [65, 81-83], as discussed earlier, suggested a focal versus ambient vision dichotomy.

Denny-Brown and Fischer [106] hypothesize a slightly different visual-anatomical dichotomy: one, primarily for object vision, is served by the dLGN and area 17 but also requires an interaction with the superior colliculus to be effective. Thus the colliculi are additional components of the retino-geniculo-calcarine system. The other part, which might correspond to scotopic vision or Trevarthen's ambient vision, is concerned primarily with spatial relationships and movement, and is served by an independent pathway from the mesencephalic tegmentum via the inferior pulvinar to areas 18 and 19.

Berlucchi, Sprague, and their coworkers [70, 71] have proposed a mechanism for a role for the superior colliculi in pattern vision. Since the superior colliculi appear to contribute to the ability to use head and eye movements to localize and follow stimuli, which would therefore aid an animal in changing its fixation point, a superior collicular lesion might impair performance in a pattern discrimination task _if_ the task required frequent changes in the fixation point. This is supported by the finding that lesions of the superior colliculus-pretectum in cats cause deficits in learning but not in retention. These researchers are also probably accurate in trying to down-play the appearance of a dichotomy of function with structure and instead proposing the presence of a complex interaction between the cortex and the midbrain-pretectal region in many visual functions. The present findings may also be a manifestation of the probably large amount of functional redundancy that exists within the central nervous system.

This historical review has highlighted some of the important contributions to the study of visual processing in higher animals. Based on these earlier findings and ideas, a number of experiments were carried out to provide further insight into the mechanisms of visual transfer and integration in forebrain commissurotomy patients; these are described in Chapters III-VI.

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III. LEFT VISUAL FIELD VOCALIZATION BY HUMAN FOREBRAIN COMMISSUROTOMY SUBJECTS

INTRODUCTION

In comparison with earlier studies emphasizing that information presented exclusively to one cerebral hemisphere of a "split-brain" subject is inaccessible to cognitive processing in the other hemisphere [1-4], more recent reports suggest that there may, in fact, be a considerable amount of communication between the two "disconnected" hemispheres [5-7] after a long recovery time (13 or more years). There is growing evidence that some of the patients who have undergone complete forebrain commissurotomy (surgical section of the corpus callosum, hippocampal commissure, anterior commissure, and massa intermedia if present) are now able to give verbal reports of left visual field (LVF) events [6-10], despite the fact that the LVF projects directly to the right hemisphere. Although brainstem integration, cross-cuing, bilateral sensory projections, and minor hemisphere speech have been variously invoked as possible factors in mediating this kind of cross-integration, its exact basis remains to be determined. The present investigation is focused specifically on the problem of how split-brain patients are able under certain conditions to verbally classify or identify visual information that is presented exclusively to their LVF.

Studies in the early years following surgery suggested that split-brain patients could not verbally identify anything but the most coarse visual events (for example, the onset of a light) in the LVF [11]. However, TREVARTHEN and SPERRY [6] later showed that some commissurotomized subjects 4-8 years post-surgery could cross-compare moving stimuli in the far peripheral visual fields (15-20° or more from the fixation point) and could provide simple verbal descriptions of movement and changes in color hue taking place exclusively in the LVF. Based on this and other studies [5, 12], it was hypothesized that visual cross-integration is accomplished through sensory projections that cross in the midbrain and/or diencephalon and which can continue to unify the two sides of the brain following forebrain commissurotomy. This behavioral evidence, combined with considerable anatomical and neurophysiological data, is in conformance with the current general consensus that midbrain visual mechanisms are primarily concerned with specific perceptions of brightness, peripheral movement, and orientation to visual stimuli [13-19]. However, a number of experiments with split-brain cats and sub-human primates have indicated that cross-integration and transfer between the more central parts of the visual field may also be possible [20-27]. This possibility has been further strengthened in more recent studies with forebrain commissurotomy patients. In particular, it has been shown that commissurotomy patients at times can verbally identify visual stimuli (letters and numbers) flashed near "central vision" in the LVF (3-4° from the fixation point) [7], read aloud simple words presented in the LVF [8, 9], or name both halves of a chimeric stimulus, half of which is in the LVF and half in the RVF [28].

These collective observations suggest a number of possibilities: (a) the commissural system below the forebrain is capable of processing and/or transmitting more complex visual information than previously believed, (b) man's right hemisphere has a greater capacity for verbal expression under these conditions than found earlier, or (c) some combination of these - perhaps dependent upon the type or difficulty of the discrimination and the complexity of the verbal response. These alternatives are further investigated in the present study by comparing manual and verbal responses to tachistoscopically presented stimuli in the left and right visual half-fields and carefully measuring and manipulating the important stimulus and response parameters involved.

METHOD

Experimental Design

The following experiments compare the ability of commissurotomy patients to make dichotomous categorizations or to identify (name) unilaterally presented visual information with the same abilities in partially commissurotomized and normal control subjects. These experiments were carried out over many months and were intermixed with other experiments given these subjects in the same testing sessions. The stimuli included single-digit numbers, letters of the alphabet, and simple nonsense symbols or patterns. Responses required included manual toggle-switch movement (out of direct vision) or verbal responses varying from a simple "yes"-"no" or "odd"-"even" to the naming of the stimulus presented. Within a given series of stimulus presentations, manual responses were usually tested before verbal responses to avoid any possible left hemisphere speech mechanisms from interfering with subsequent testing.

Subjects

The subjects in the following experiments were (a) split-brain patients (NG, LB, AA, RY) who had undergone complete cerebral commissurotomy 12-15 years prior to this testing, (b) one patient (NF) who had a partial commissurotomy 9 years before, and (c) normal subjects without a history of epilepsy or neurological damage. The partial and complete commissurotomy subjects are patients of J. E. Bogen and P. J. Vogel of Los Angeles. The normal subjects were of ages approximating those of the patients in (a) and (b) but were otherwise not matched, and were students or technicians associated with Caltech. Further details on the medical and surgical history of the patients have been published in a number of sources [29-33].

NG (b. 1933) was born in the 6th gestational month, spending several weeks in an incubator, but was asymptomatic until she began having seizures in the fourth month of her first pregnancy (1951). Seizures worsened and she had a complete forebrain commissurotomy in 1963 (age 30). Skull X-rays: 1 cm calcification in right central cortex. EEG following seizures: left temporal slowing or focus.

LB (b. 1952) was born by Caesarean delivery (his mother's third), was cyanotic and remained in an Isolette for 8 days. His first convulsion was at age 3-1/2 and became intermittently worse. No neurological abnormalities were found, attacks were without lateralizing signs, and EEG showed only mild, diffuse abnormalities. He underwent a complete forebrain commissurotomy in 1965 (age 13).

AA (b. 1950) was born following induction of labor because of toxemia in his mother's first pregnancy, a forceps delivery. He probably had two convulsions associated with fever at age 4 months but was otherwise asymptomatic until general seizures began at age 5-1/2. EEGs: bilateral abnormalities, more marked over left hemisphere. Complete forebrain commissurotomy in 1964 (age 14) was difficult, with resulting left arm and leg spasticity, most of which has now resolved. (The patient has a sensory deficit in his right hand and preferred to use only his left hand for manually responding in these experiments.) Neurologic signs indicated a seizure focus in the left postcentral cortex.

RY (b. 1923) was normal until age 13 when he was hit by a car, leaving him unconscious for one-half hour. At age 16 he began having spells, with generalized convulsions a year later. A visual aura suggested a possible right posterior cortical origin, but pre-op EEGs were non-localizing. His complete forebrain commissurotomy took place in 1966 (age 43).

NF (b. 1942) began having seizures at age 14. Neurological exam, X-rays, and angiograms were not abnormal. EEGs showed independent temporal foci, more severe on the right. In 1969, at age 26, she had a partial commissurotomy, cutting the anterior commissure plus the anterior 5 cm of the corpus callosum (and presumably any underlying hippocampal commissure), including all of the genu, body and anterior splenium.

Material

The stimuli were presented via a Gerbrands two-field tachistoscope (model T-2B C) and timer (model 130). Reaction times were measured with a time interval meter and a toggle switch (for manual responses) or a voice-activated switch connected to a tape recorder microphone (for verbal responses).

Letters, numbers, and nonsense patterns were black, hand-lettered on a light background. They were about 2° of visual angle in size and were printed on removable labels. The fixation point in the center of the viewing field was a small black dot, again on a light background. Seven numbers (2,3,4,5,6,8,9) were chosen because they were all single digits, pronounced as one-syllable words, and were of irregular shape. The eight letters (F,G,H,K,M,N,R,S) were chosen because of their complexity of shape and their central location in the alphabet. The non-letter, non-number patterns, seven in number, were made up to vaguely resemble letters and numbers. On any series of trials when a smaller sample size was used, the stimuli were chosen from the numbers or letters listed here.

The stimuli were presented at the fixation point or were flashed so that their medial edge was 1-8° (usually 3°) to the left or right of the fixation point. However, in any given series of presentations, each lateral stimulus was always the same distance from the fixation point and this distance was not varied between trials. Except for one instance, the results from fixation point presentations will not be discussed in this paper.

Procedure

Each subject was tested individually in a private room. The tachistoscope was placed on a small table and the subject sat in a chair and placed his or her head before the viewing slot at the side of the tachistoscope. The subject's hands were separated from each other and lay out of sight on the table underneath the tachistoscope. If a manual toggle-switch response was required, the fingers of one hand rested on the toggle switch. The left eye of each subject was covered with an eye patch to ensure monocular viewing with only the right eye. Before each experiment, every subject was instructed as to what kinds of stimuli were to be presented and what the response should be. Sample trials were usually not given and the subject was not informed how far from the fixation point the stimuli would be nor, except in a few cases, the exact numbers or letters to be presented. However, when nonsense patterns were to be included in the experiment, they were shown to the subject in free vision to make certain that the subject recognized them as different from numbers and letters.

The stimuli were presented in a pseudo-random sequence which insured that approximately equal numbers of each stimulus were projected to each visual half-field and the fixation point. The subjects were discouraged from making any verbal remarks during the experiment, except as appropriate responses to the stimuli. Each trial was carried out as follows: The experimenter gave the signal of "ready" to allow the subject time to fixate on the fixation point. Several seconds later, the stimulus was flashed for a duration of 100-150 msec and the subject made a verbal or manual response. Most responses occurred within 1-1/2 sec. Following each trial the responses were recorded and a new stimulus was prepared in the tachistoscope. Preliminary trials never showed any consistent or persistent differences in either reaction speed or accuracy between the left and right hands so only the right hand was used in most of the manual experiments.

Data analyses

Response accuracy for the left and right visual fields and the fixation point was calculated for each subject in each experiment. Where appropriate, the individual experiments were pooled and the statistical significance of the combined results was determined using the binomial distribution sign test or a Chi square test with one degree of freedom. The mean and standard deviation for the reaction times were also calculated. The averaged LVF and RVF reaction times were then compared for each subject by deriving a t value for the differences in means of populations with unequal variances. Many of the reaction times for both visual fields also were compared by pairing observations but this did not change the statistical significance of any of the results.

RESULTS

The following results are divided into three sections: I. Verbal Identification Tasks, II. Manual and Verbal Categorization Tasks, and III. Combined Categorization and/or Identification Tasks.

I. Verbal Identification Tasks

Accuracy and response times for naming unilateral letters and numbers are presented in Table 1. LVF/RVF reaction time (RT) ratios are separately shown in Fig. 1 also. The four split-brain subjects, one partially split subject (NF), and the normal subjects are included. Preliminary results with stimuli at 1-8° from the fixation point showed that there was no significant difference in reaction times or accuracy with stimuli at these distances. Therefore, the subjects were usually tested with the lateral stimuli 3° from the fixation point. In each of the experiments, AA consistently responded more slowly, both manually and verbally, than all of the other subjects.

Response accuracy. LB can name both single-digit numbers and capital letters flashed tachistoscopically into either his LVF or RVF, although he responds somewhat more accurately when the sample size is small than when it is large. 'Surprise' stimuli were occasionally flashed to the subject's LVF, for example, a letter during a number experiment or an unusual letter or number. On these trials, too, LB is able to correctly name the stimulus, though with voiced surprise and disbelief preceding and following the correct response. On one occasion, the subject was observed to draw the 'surprise' LVF stimulus with his right hand, while still looking in the tachistoscope, before he said the correct answer.

NG, in comparison, has difficulty in correctly naming stimuli flashed to her LVF. When capital letters or numbers from a large sample population (7-8) are presented, NG is unable to name any LVF stimulus at a greater than chance level. However, when the sample population of numbers is reduced to two possibilities, NG can now correctly name the LVF number, whether or not she has been preinformed as to the sample size or exact stimuli to be presented. She is still, however, unable to correctly name LVF letters even from a small sample population. In several cases not tabulated in Table 1, when new stimuli were substituted in the course of a series of trials, NG occasionally continued to perseverate her earlier LVF responses while correctly naming the new stimuli in the RVF. She did not seem to be aware that her LVF stimuli had also changed even though she had been told new stimuli would be shown just before the new series began. Whenever 'surprise' stimuli were presented to her LVF, NG would usually guess randomly one of the usual stimuli, or continue to perseverate one of the earlier LVF stimuli. At times, however, she would respond to a 'surprise' stimulus by making an unusual guess, something she never did to normal stimuli. But in all cases, there was never any other indication that she had seen or said something different, and she never remembered anything out of the ordinary when asked about the stimuli at the end of the experiment.

AA, like LB, is able to correctly name LVF numbers. However, he is only able to name LVF letters (Table 1(a)) if he knows either the number of different stimuli in the sample population or if the stimuli are named before the experiment. Otherwise, even with small sample populations of 2-3, he cannot accurately name

LVF letters. When AA is shown a LVF 'surprise' he sometimes merely guesses one of the usual stimuli, just as he incorrectly does on normal LVF trials. At other times he may make an unusual response, for example, when an X or + were substituted for a LVF number, on three of five presentations he said "blank", "zero", or denied that he had seen anything. On one occasion, a pair of stimuli were accidently projected, one to each visual field simultaneously. AA only named the RVF stimulus (correctly) while completely neglecting the one in the LVF, showing no sign of seeing something very unusual.

RY, tested only on the number experiment, performs like NG. He is unable to name the LVF number when it is drawn from a large sample population and at times perseverates his LVF responses. NF, the partial split, easily identifies both LVF and RVF stimuli, as can all the normal control subjects.

Reaction time. In spite of the differences in LVF accuracy among the subjects, a comparison of the reaction times to stimuli in the two half-fields clearly separates them into two categories (Table 1 and Fig. 1). All of the completely split patients show a significantly longer response time when attempting to name (correctly or incorrectly) LVF stimuli than when naming RVF stimuli. (Responses to LVF 'surprises' lengthened even longer LB's and sometimes AA's reaction times but did not affect the LVF reaction times for NG.) On the other hand, those subjects who still have the splenium of the corpus callosum intact (the normals and NF) show no significant difference in their response times to LVF and RVF stimuli.

Stimuli were also projected at random to the fixation point of each subject but the variable reaction times and accuracy of some of the subjects are difficult to interpret, and will not be analyzed here except for one unusual case. When numbers were presented to NG's fixation point, an interesting phenomenon was seen that was not seen with the other subjects. In 64 trials, she named the number accurately 61 per cent of the time (chance = 14 per cent), but more importantly,

Table 1. Accuracy and response times (msec) for the identification (naming) of unilateral capital letters and single digit numbers

			Left Visual Field			Right Visual Field			
Subject	Sample size	% Chance	N	% Correct	RT±S.D.	N	% Correct	RT±S.D.	LVF/RVF RT Ratio
				(a) Identification of Letters					
NG	2	50	16	50	1135±400	15	93**	635±110	1.79**
	3	33	16	31	1100±560	16	100**	660±130	1.67**
	8	13	17	0	1010±550	16	100**	570±70	1.77**
LB	2	50	18	100**	1835±700	12	100**	770±120	2.38**
	8	13	17	88**	1830±490	16	100**	720±170	2.54**
AA	2^{+}	50	22	18	2625±950	25	84**	1260±500	2.08**
	2^{++}	50	23	78*	1960±700	20	100**	1015±300	1.93**
	3^{+}	33	22	18	2200±850	17	82**	1030±260	2.14**
	3^{++}	33	12	67**	2110±710	8	100**	1300±510	1.62**
	8^{+}	13	16	13	2790±1480	14	93**	1090±160	2.56**
RY	2	50	19	40	990±280	17	100**	610±110	1.50**
	8	13	20	5	790±170	20	100**	570±60	1.39**
N1-N3	8	13	51	100**	565±70	48	100**	590±80	0.96
				(b) Identification of Numbers					
NG	2	50	25	88**	1055±300	21	100**	530±50	2.00**
	7	14	63	13	1260±340	64	94**	600±65	2.10**
LB	2	50	14	100**	925±120	14	100**	695±110	1.33**
	7	14	74	92**	1320±500	64	92**	650±100	2.03**
AA	2	50	47	81**	1700±880	50	78**	1090±310	1.56*
	7	14	16	94**	2010±1500	16	81**	1150±160	1.75*
RY	2	50	22	14	910±220	18	100**	540±30	1.69**
	7	14	16	13	1020±210	16	100**	590±50	1.73**
N1-N3	7	14	48	100**	570±80	48	100**	560±90	1.02
NF	7	14	18	83**	1140±110	14	93**	1190±140	0.96

*p ≤ .05

**p ≤ .01

+Told only that letters would be shown, nothing more specific.

++Told either the sample size or the exact letters to be shown.

Fig. 1. A comparison of visual field reaction times for split-brain and normal subjects in categorization tasks and identification (naming) tasks

	Categorization Tasks				Identification Tasks			
Subject	Table	Stimuli+	Manual/Verbal Response	LVF/RVF RT Ratio	Table	Stimuli+	Sample Size	LVF/RVF RT Ratio
LB	2(a)	N	M	1.02	1	L	2	2.38**
	2(a)	N	V	1.04	1	L	8	2.54**
	2(b)	LN	V	1.55	1	N	2	1.33**
	2(b)	P	V	1.19	1	N	7	2.03**
	3(a)	P	V	0.97	3(a)	LN	-	4.85**
NG	2(a)	N	M	1.10	1	L	2	1.79**
	2(a)	N	V	0.94	1	L	3	1.67**
	2(b)	LN	V	1.06	1	L	8	1.77**
	2(b)	P	V	1.27	1	N	2	2.00**
	3(a)	P	V	1.04	1	N	7	2.10**
					3(a)	LN	-	1.96**
AA	2(a)	N	V	1.10	1	L	2	2.08**
	3(a)	P	V	0.96	1	L	2	1.93**
					1	L	3	2.14**
					1	L	3	1.62**
					1	L	8	2.56**
					3(a)	L	8	1.44*
					1	N	2	1.56*
RY	2(a)	N	V	0.96	1	L	2	1.50**
					1	L	8	1.39**
					1	N	2	1.69**
					1	N	7	1.73**
Normals	2(b)	LN	V	1.02	1	L	8	0.96
	2(b)	P	V	1.00	1	N	7	1.02
	3(a)	P	V	0.98	3(a)	LN	-	1.00

+Stimuli: N = numbers, L = letters, LN = letters or numbers, P = patterns.

*$p \leq .05$

**$p \leq .01$

her reaction times were distinctly bimodal corresponding to the accuracy of her response. That is, her correct responses at the fixation point had reaction times equal to her (correct) RVF responses, while her incorrect responses had times equal to her (incorrect) LVF responses. Unfortunately, this unique set of findings was not seen in other experiments with NG.

II. Manual and Verbal Categorization Tasks

Are the high LVF/RVF reaction time ratios found in the experiment above with commissurotomy subjects and naming responses associated with verbalization in general or is there something particularly unique about identification tasks? To answer this question, it is necessary to try to separate some of the interacting factors: different response modes (manual-verbal) and different tasks (categorization-identification). It was decided to first examine manual as compared with verbal responses during a categorization experiment. The task required that the subjects move a toggle switch in one of two directions to distinguish whether a single-digit number was odd or even, or $\geq$ or <'5'. Thus, this was a task which required that each stimulus be placed in one of two categories, but not be specifically named. Table 2(a) clearly shows that both NG and LB not only (1) accurately separate numbers into odd-even or magnitude categories, but also (2) exhibit no difference in manual reaction times between the two visual fields.

When the four split-brain patients were then asked to change from a manual response and verbally classify numbers as odd-even or $\geq$ or <'5' by saying "yes" or "no", three (LB, NG, AA) could (1) make accurate discriminations in both visual fields while all four subjects continued (2) to show no field differences with respect to reaction times. It was decided that perhaps verbal responses of "yes" or "no" were too simple or automatic so NG and LB were asked to respond "odd" or "even" to another series of numbers. Yet even this more complicated verbalization showed (1) high LVF accuracy, and (2) no LVF/RVF reaction time differences.

Table 2. Accuracy and reaction times (msec) for categorization tasks with unilateral letters, numbers, and patterns (chance = 50%)

			Left Visual Field			Right Visual Field			
Subject	Response	Stimuli	N	% Correct	RT±S.D.	N	% Correct	RT±S.D.	LVF/RVF RT Ratio
				(a) Number categorization					
LB	Manual^{+}	Numbers	24	96**	960±200	26	81**	945±180	1.02
NG	Manual^{+}	Numbers	16	94**	1265±320	14	93**	1145±300	1.10
LB	Verbal^{++}	Numbers	36	100**	915±190	33	97**	880±100	1.04
NG	Verbal^{++}	Numbers	29	86**	1165±250	25	96**	1235±320	0.94
AA	Verbal^{++}	Numbers	25	98**	1580±430	25	100**	1430±530	1.10
RY	Verbal^{++}	Numbers	74	42	745±150	67	97**	780±100	0.96
		(b) Combined results of letter vs. pattern and number vs. pattern categorization tasks							
LB	Verbal^{+++}	Letters or Numbers	7	71	1225±500	10	100**	790±220	1.55
		Patterns	8	100**	970±300	7	100**	815±60	1.19
NG	Verbal^{+++}	Letters or Numbers	33	70*	1095±275	40	70*	1035±280	1.06
		Patterns	36	92**	1070±300	30	100**	840±200	1.27
N_1-N_2	Verbal^{+++}	Letters or Numbers	16	100**	625±60	20	100**	610±75	1.02
		Patterns	16	100**	620±85	14	100**	620±80	1.00

$^{+}$Manual toggle responses: Forward = even, backward = odd; forward = ≥ 5, backward = < 5.

$^{++}$Verbal responses: "Yes" = even, "No" = odd; "Yes" = ≥ 5, "No" = < 5; "Even" or "Odd".

$^{+++}$Verbal responses: "Yes" = letter or number, "No" = pattern.

$^{*}p \le .05$

$^{**}p \le .01$

All verbal results (yes-no, odd-even) were subsequently combined for each subject in Table 2(a).

These findings were further supported in another experiment, Table 2(b), where letters had to be differentiated from non-letter figures, or numbers from non-numbers, by saying "yes" to each letter or number and "no" to each pattern. Here too, both LB and NG (1) can differentiate numbers and letters from patterns in both visual fields while continuing (2) to show no difference in reaction times between the two fields.

In summary, the following conclusions are reached from the unilateral categorization experiments: (a) Three of the four split-brain subjects can make accurate verbal categorization responses to LVF stimuli. (b) In addition, and in especial contrast with the earlier naming (identification) experiments (I. above), the LVF/RVF response time differences previously seen between the two visual half-fields are no longer seen in any of the categorization tasks for any of the split-brain patients tested. Responding manually or verbally does not affect either accuracy or reaction time. (c) These results strongly suggest that the earlier findings of a high LVF/RVF RT ratio during naming tasks were not simply due to slow verbal response times to any LVF stimulus. On the basis of their LVF/RVF RT ratios (Fig. 1), the split-brain subjects are not distinguishable from normal or partially split people in the manner with which they verbally respond to dichotomous categorization tasks using either their left or right hemisphere.

III. Combined Categorization and/or Identification Tasks

When comparing the results from the identification (I.) and categorization (II.) tasks presented above, an important question was quickly raised. Perhaps the differences between responses to the two tasks were due to the fact that each of the subjects developed a specific and separate mental set which established or regulated the speed of their LVF responses for each different task, thereby explaining the different reaction times. To try to eliminate this possibility, the letter-number versus pattern experiment was repeated, but this time, the subjects (NG, LB, AA, and the normal subjects) were required to name any number or letter, or say "no" to any pattern. That is, the subjects would not know until each stimulus was flashed whether they were required to respond with a categorization or a naming response. Not only were the stimuli randomized as to the visual field to which they were to be flashed, but also as to the kind of response required.

Response accuracy. LB, as usual, can perform both tasks very accurately in either visual field [Table 3(a)]. NG can accurately respond "no" to the patterns in both visual fields, as seen earlier in the "yes"-"no" experiment, but can only name letters or numbers flashed to her RVF, not to her LVF, as in the earlier verbal identification experiment. NG, however, demonstrated that she can in fact occasionally recognize a distinction between LVF stimuli even though her naming responses are inaccurate - she almost always says "no" to every figure but sometimes responds with an incorrect name and not a simple "no" to numbers or letters. AA was only tested in a letter-figure discrimination. He too could easily respond "no" to figures in both LVF and RVF, but had difficulty in naming letters in both visual fields. However, like NG, he also showed that he was capable of discriminating letters from non-letters in the LVF, since he was completely accurate in his "no" responses to patterns yet responded with a letter name, right or wrong, to 75 per cent of the letters flashed.

Reaction time. Although the stimuli were randomly presented, each of the split-brain patients tested responded more slowly to LVF stimuli that they were required to name (in comparison with their RVF reaction times) than to stimuli they were required to categorize. It is therefore unlikely that the differences in the LVF/RVF RT ratios found for identification versus categorization tasks are due to any simple pre-established mental set of the subject.

Table 3. Accuracy and response times (msec) to unilateral numbers, letters, or patterns when (a) either two-choice categorization or identification (naming) is required on each trial, or (b) both categorization and identification responses are required on every trial

			Left Visual Field				Right Visual Field				
Subject	Stimuli	Response	N	% Correct	% Chance	RT±S.D.	N	% Correct	% Chance	RT±S.D.	LVF/RVF RT Ratio
(a) Categorization or identification of letter vs. pattern and number vs. pattern tasks											
LB	Letters or Numbers	A	7	86**	7	2980±500	7	100**	7	615±30	4.85**
	Patterns	B	10	100**	50	865±270	8	100**	50	895±70	0.97
NG	Letters or Numbers	A	10	0	7	1685±600	10	100**	7	860±410	1.96**
	Patterns	B	16	94**	50	835±180	11	91**	50	800±100	1.04
AA	Letters	A	8^{++}	25	7	2690±880	10^{+++}	40**	7	1870±720	1.44*
	Patterns	B	10	100**	50	1410±280	8	100**	50	1470±450	0.96
N_1-N_3	Letters or Numbers	A	18	100**	7	580±40	18	100**	7	580±70	1.00
	Patterns	B	24	100**	50	635±70	20	100**	50	645±75	0.98
(b) Categorization and identification of single digit numbers											
LB	Numbers	C	16	100**	50	1320±470	10	100**	50	910±130	1.45**
		D	16	94**	14		10	100**	14		
NG	Numbers	C	31	71*	50	1670±580	18	94**	50	1600±720	1.04
		D	32	19	14		18	100**	14		

[+] Response: A. Name the letter or number, or B. say "no" to any pattern.

C. Categorize each number as "odd" or "even" and then D. name the number.

[++] 2/8 = correct letter, 4/8 = incorrect letter, 2/8 = "no".

[+++] 4/10 = correct letter, 1/10 = incorrect letter, 5/10 = "no".

[*] $p \leq .05$.

[**] $p \leq .01$.

What happens if the subjects are required to make both categorization and identification responses to each stimulus? This was tested specifically by tachistoscopically flashing a single-digit number and asking each subject (LB, NG) to first classify the stimulus as "odd" or "even" and then to say immediately the number name (Table 3(b)). The voice actuated timer recorded only the time taken to make the initial (classification) response.

Response accuracy. Both NG and LB are able to accurately categorize LVF numbers, just as they were able to do in previous experiments. LB is also able to make accurate LVF naming responses, while NG is not, often being perseverative--this, too, is like earlier identification tasks.

Reaction time. Reaction times, however, now distinguish the two patients. Categorization tasks normally show a LVF/RVF RT ratio close to unity. In this experiment, combining the two kinds of tasks significantly slows LB's LVF reaction time (when compared with his RVF time) for the initial categorization task (LVF/RVF RT ratio = 1.45, $p < .01$). NG, on the other hand, responded 400-500 ms more slowly to both LVF and RVF stimuli than seen earlier with simple categorization tasks alone and her LVF/RVF RT ratio, unlike LB's, remained close to unity (1.04).

DISCUSSION

The results show that commissurotomy patients can, under certain conditions, make accurate and detailed verbal analyses of stimuli presented exclusively in the left visual field (LVF), near the fixation point. This confirms and amplifies the results of TREVARTHEN and SPERRY [6], TENG and SPERRY [10], and ZAIDEL and SPERRY [7], and is distinct from the earlier view, based on studies of recently post-operative patients, that almost all visual information from the left hemifield is not accessible to verbal identification or description (the disconnection syndrome) [2-4]. However, the split-brain patients appear to use markedly different mechanisms for verbally naming LVF stimuli compared with verbally categorizing these same stimuli.

When the commissurotomy subjects were presented discrimination tasks which required them to categorize different stimuli into one of two groups, for example odd-even or $\geq$ or $<$ '5', three of the four tested were quite accurate in both the left and right visual fields, and all showed no difference in response times between the visual fields. In both these respects, they are almost identical to the partially split patient (with splenium intact) and the normal subjects. In contrast, while LVF naming accuracy varies between subjects, *all* the split-brain patients take a significantly longer time to name (identify) LVF stimuli than RVF stimuli, *unlike* normal or partially split subjects. This response time-visual field dichotomy has also been found when naming unilaterally presented colors (unpublished observations).

What are some possible explanations for these findings? For simple categorization tasks, although right hemisphere speech cannot be ruled out, the experimental findings also support a hypothesis that, under these conditions and for these kinds of tasks at least, commissurotomy patients have pathways from their LVF perceptual centers to verbal centers which are about as functional (in speed and accuracy compared to their RVF control values) as those which exist in normals and partial splits. These pathways can carry information which can be translated apparently equally well into both manual toggle-switch responses and verbal responses like "yes"-"no" and "odd"-"even". It is possible that the right hemisphere could code incoming visual data simply as +/- neural signals, representing each of the two categories. The right hemisphere perceives the LVF stimulus, identifies it as belonging to one of the two groups and transmits to the left hemisphere the appropriate signal. The left hemisphere, in the meantime, in some way learns to translate or associate the +/- signals with the appropriate manual or verbal response. This should be distinguished from indirect, non-neural or non-specific cross-cuing strategies. The variability in response speeds would hide the presumably short transmission time necessary for the signal to be analyzed, labeled, and crossed from the right hemisphere to the left hemisphere speech centers and therefore show no significant difference in reaction times between the two visual fields. Because the categorization tasks used only two classifications, it was necessary to take strict precautions to prevent the subjects from using peripheral cross-cuing clues to choose the correct response.

It is unlikely that the right hemisphere, perhaps by rehearsing and preparing for the two responses prior to stimulus presentation, is making the categorization responses to LVF stimuli. Besides the aforementioned similarity between control subjects and split-brain subjects in categorization tasks and dissimilarity in naming tasks, with respect to both reaction times and accuracy, it was found in naming tasks, when the sample size was reduced to two, the accuracy of NG and AA did not necessarily improve (Table 1) and their reaction times continued to show the typical LVF/RVF RT ratio >1.0. In addition, when stimuli were randomly presented so that either a categorization or a naming response was required [Table 3 (a)], the patients consistently demonstrated the same accuracy and response times as found when the tasks were presented separately. With 8-9 possible responses ("no", plus 7-8 naming responses) it seems unlikely that these results are due to the rehearsal of only one of the many possible answers.

In addition, another mechanism must be hypothesized which is concerned with the actual verbal naming of LVF stimuli. Naming may require a much more complex analysis, using different neurologic pathways, since every stimulus now requires a unique response.

The ability of some of the split-brain patients to name LVF stimuli has several possible explanations. It has been claimed that all of the previous evidence for LVF verbalization to split-brain subjects is explainable by cross-cuing strategies, informing the left hemisphere speech centers [35, 36]. While the possibility of peripheral cross-cuing is difficult to completely discount, it is very improbable that it explains the present results. All of the subjects were very conscientious about following the test instructions and would inform the experimenter whenever they noticed any error in the procedure or accidental misalignment of the apparatus. The stimuli were randomly flashed at speeds of 100-150 msec, too fast for eye movements to play a role. The hands and feet were kept well separated; the subjects did not rely on sounds or overt mouth movements except for the appropriate verbal response if one was required. In the case of number and letter stimuli, there were usually a large number of possible choices (7-8), making unlikely any simple strategy for cross-cuing. When the possible choices were decreased to 3, neither the accuracy nor the response times changed significantly. Only when the sample size was reduced to two did NG's accuracy for naming numbers improve.

The finding that NG can name LVF numbers only when the sample size has been reduced to two, might suggest that she could be informing her left hemisphere speech centers using the simple +/- signal system hypothesized for categorization responses. This seems unlikely, since she is <u>still</u> unable to correctly name LVF letters when they are drawn from a sample population of two, and her response times are consistently independent of her accuracy, showing the classic LVF/RVF dichotomy seen with all naming responses to both numbers and letters and at sample sizes from 8 to 2.

Cross-cuing also does not explain NG's naming responses when numbers were presented at her fixation point. On these trials, her correct responses were very similar to her (correct) RVF responses, while her incorrect responses were like her (incorrect) LVF responses. The best explanation for these results is that, due to both the precise behavioral demarcation between the two visual hemifields at the vertical meridian [37-39], and small eye movements around the fixation point, stimuli were actually either in the LVF or in the RVF, and the processing of visual information seems to be different for naming tasks in the LVF as compared with the RVF. The fact that no dependence of response speed on number order was found, eliminates the type of cross-cuing postulated by GAZZANIGA and HILLYARD [35] where the right hemisphere would count the possible choices in order until one 'stuck out' and could be named by the left hemisphere.

A second possible explanation is right hemisphere speech. There is ample clinical evidence that under certain circumstances the right hemisphere has some limited verbal expression in a left hemisphere dominant person [40-44], for example, following left hemispherectomy, left hemisphere stroke, and in certain cases after sodium amybarbitol injection into the left carotid artery. The disconnected minor hemisphere of some split-brain patients was found by LEVY, NEBES, and SPERRY [34] to have some capacity to express simple cursive language by controlling the left hand (e.g., writing short nouns flashed in the LVF), and the observed inability to vocalize LVF information was described to both an intrinsic limitation of the right hemisphere and a left hemisphere dominance over the motor mechanisms for language expression. After extensive study of the right hemisphere linguistic ability in the split-brain human, ZAIDEL concluded that while the right hemisphere exhibits substantial visual and auditory vocabulary and other lexical abilities, it does seem to be mute [45], and only when the speech area of the left hemisphere is removed by lesion does there occur a right hemisphere competence for speech [46]. However, ZAIDEL's use of a lens system which provides unilateral visual input over an extended time period may significantly affect activation of commissures or brain areas quite differently from that of random tachistoscopic presentation between the half-fields used in the present experiments. Other researchers mentioned earlier [6-10] have presented experimental evidence that certain kinds of LVF stimuli can indeed be vocalized and bilateral stimuli cross-integrated by split-brain patients, and the sudden onset of right hemisphere speech in a callosectomy patient has recently been alleged [47].

The other possibility is the presence of neural connections capable of transferring visual information from one side of the brain to the other in the absence of the forebrain commissures. Neuroanatomical studies in fact have shown that a number of pathways and commissures do continue to pass between the two sides following 'complete' forebrain commissurotomy [48, 49]. Most remaining paths have no known visual role. Some of the interconnections have important visual transfer functions in lower animals (for example, the supraoptic decussation in birds) but probably not in primates. Other pathways have a function in oculomotor reflexes (e.g., the posterior commissure) but not in perception. The most likely region of the brain for visual transfer in split-brain human subjects is the pretectum-midbrain area. It has an evolutionarily important role, has numerous connections both with the visual cortex and retina, as well as thalamic structures with probable visual functions [17-19, 50-52], and lesions of this region affect not only simple vision (brightness, movement) but also pattern vision [53-57]. And finally, this area has very little known about its internal neuroanatomical interconnections.

Conclusion

The present results can be taken to suggest that commissurotomy patients use distinctly different mechanisms to either verbally categorize LVF stimuli or to name them. When required to make two-choice categorizations of LVF stimuli, split-brain patients respond as rapidly (and usually about as accurately) to LVF stimuli as to RVF stimuli, just as normal and partially split subjects do. Since the control subjects are presumed to be responding to both visual fields from their left hemisphere during categorization tasks, it is hypothesized that the commissurotomy patients are doing likewise. Enough information may be transferred from the right hemisphere to the left hemisphere, probably via tectal-pretectal pathways mentioned above, for the normal left hemisphere speech centers to make the correct response.

In contrast, it is proposed that the commissurotomy patients are naming LVF stimuli through centers distinct from normal speech centers, most likely in the right hemisphere. There seems to be a large amount of intersubject variability for functional connections between the right hemisphere perceptual centers and these verbal centers, dependent upon the kind of stimulus, the size of the sample set, and so forth. Evidence in support of right hemisphere naming centers is found in NG's and RY's perseverative responses to LVF stimuli even when separated by accurately named RVF and fixation point responses (also found earlier by TENG and SPERRY [10]). It seems as if the right hemisphere continues to repeat its old responses independent of responses made by the left hemisphere. In addition, data from bilateral field presentations show that LB can name simultaneously presented bilateral stimuli but cannot determine whether they are the same or not [58-61]. This is strong evidence that the left and right hemispheres are each individually naming the stimulus projected to it, but the two stimuli cannot be brought together for direct comparison. (A split-callosum, intact-anterior commissure patient has recently been found to exhibit this same phenomenon [62].) The similar LVF/RVF reaction time ratios found with all split-brain subjects indicate that all are using the same general mechanism for unilateral naming responses which is independent of accuracy.

The interference found when categorization and identification tasks are combined on each trial (Table 3(b)) suggests that the two tasks are not completely autonomous, however. It is not known whether this response deterioration is due to the general increased difficulty of the combined problem or to the fact that the two tasks compete or otherwise interfere with one another on a shared channel at some point. Further study of this interaction may lead to a more refined description of the neurologic mechanisms and pathways used in the transfer of visual information by forebrain commissurotomy patients.

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IV. APPENDIX: IDENTIFICATION OF UNILATERALLY PRESENTED COLORS, SCHEMATIC FACES, AND PHOTOGRAPHS OF FACES BY HUMAN COMMISSUROTOMY PATIENTS

INTRODUCTION

It has been known for some time that emotional auras and experiences may pass between the "disconnected" hemispheres of a forebrain commissurotomy patient [1, 2, but see also 3] and may be an important factor in allowing such patients to unify both their awareness of environmental stimulation and their behavior [4]. A possible explanation, therefore, for the ability of split-brain subjects to identify LVF stimuli is that they are able to affectively label stimuli directed to their right hemisphere and this label can then cross through the brainstem to clue the left hemisphere verbal centers. This hypothesis seems less plausible when large sample populations are involved. However, because of its potential role when using small numbers of stimuli, several experiments were designed to test whether stimuli thought to be easily labeled emotionally are analyzed in a special manner, perhaps faster or more accurately, by the split-brain patients.

METHOD

The stimuli chosen were colored circles, schematic facial drawings, and photographs of human faces. The colors were cut into 5° circles from Color-Aid sheets representing pure red, blue, green, and yellow hues (Geller Artist Materials, Inc.), glued to plastic ovals, and attached to a white background via a Velcro strip. The schematic faces were also 5° in size and attached to disks like the colors above. These faces were drawn to represent three expressions: the well-known 'happy' face, anger, and surprise. The black and white photographs of human faces were taken from Unmasking the Face: A Guide to Recognizing Emotions from Facial Clues by Paul Ekman and Wallace Friesen (Prentice-Hall, New Jersey, 1975). A variety of examples of three facial expressions (happiness, anger, and surprise), about 5° x 7° in size, using both men and women models, were presented.

As in the preceding experiments, the stimuli were tachistoscopically flashed (150 ms), via a Gerbrands two-field tachistoscope, randomly to either the LVF or RVF, and about 2-3° from the centrally located fixation dot. Between stimulus presentations, the white background and fixation point remained visible in the visual field.

RESULTS

I. Colors

Four split-brain subjects, with one partially-split and one normal subject as controls, were tested on their ability to name unilaterally presented colored circles. The results are shown in Table 4.

Accuracy. Both LB and AA are able to name LVF colors quite easily, consistent with their earlier ability to name LVF numbers and letters. Now, however, NG is also able to name these LVF stimuli, although not as accurately as LB or AA. RY was able to name LVF colors on one series of trials (14/20 = 70 per cent, chance = 33 per cent; $X^2 = 3.61$, 1 df, $p = .07$) but was unable to repeat this performance on three subsequent and widely separated series of trials. RVF performance was essentially perfect for all of the patients, and the partially-split and normal subjects were accurate in both the LVF and RVF.

Reaction time. Except for RY, all of the subjects name colors in the same manner as they named earlier LVF stimuli. That is, three of the four commissurotomy patients name LVF colors significantly more slowly than RVF colors, while

Table 4. Verbal identification of unilaterally-presented colors - red, blue, and green (chance = 33%)

Subject	Reaction times (ms) and Accuracy: LVF	Reaction times (ms) and Accuracy: RVF	LVF/RVF RT Ratio	LVF 'surprises' (Yellow)
LB	1275±440 12/13 (92%)**	665±70 15/15 (100%)**	1.92**	Yellow (4.8 sec) Yellow (6.9 sec)
AA	3530±1740 30/39 (77%)**	1150±520 40/40 (100%)**	3.07**	Green (6.5 sec) Red (8.6 sec)
NG	1250±350 32/58 (55%)*	620±60 64/64 (100%)**	2.02**	Red (825 ms) Green (805 ms) Red (1400 ms) Blue (1020 ms)
RY	560±140 14/20 (70%)	580±90 19/20 (95%)**	0.97	Blue (670 ms) Yellow (610 ms) Blue (625 ms) Green (670 ms) Blue (570 ms) Blue (720 ms)
	670±85 6/22 (27%)	600±80 20/20 (100%)**	1.12**	
	710±140 9/24 (38%)	630±60 23/23 (100%)**	1.13*	
	680±110 7/23 (30%)	640±70 24/24 (100%)**	1.06	
NF	900±60 16/16 (100%)**	910±50 16/16 (100%)**	0.99	Yellow (870 ms) Yellow (820 ms)
N1	600±95 16/16 (100%)**	610±40 16/16 (100%)**	0.98	Yellow (850 ms) Yellow (675 ms)

$^{**}p \leq .01$

$^{*}p \leq .05$

the splenium-intact controls name LVF colors as rapidly as those in the RVF. RY, on the other hand, does not show the typically large LVF/RVF reaction time (RT) ratio found previously with him on other naming tasks, and on two of four occasions responds equally rapidly to either visual field, irrespective of the accuracy of his response.

At the beginning of each experiment, each subject was told that he or she would be shown red, blue, or green stimuli which they would be required to quickly name. During the course of some of the experiments, however, on a few occasions and without prior warning or comment, the color 'yellow' was flashed in place of a regular LVF stimulus as a 'surprise'. The results from these 'surprise' trials are also shown in Table 4.

LB is able to correctly name the LVF 'surprise' but with a very delayed reaction time and accompanied by comments of disbelief. AA is unable to name correctly the yellow 'surprises' but his hesitation and abnormally slow reaction times strongly suggest that he, too, recognizes the stimuli as unusual. NG makes no indication that she perceives an unusual LVF color, either through her response or reaction time. On five of six 'surprise' trials interspersed within four completely separate experimental sessions, RY, like NG, showed no obvious recognition of the unusual LVF stimulus. But, on one single occasion he named it correctly, at his normal LVF reaction time and without comment, just as if it had been one of the normal stimuli. The control subjects could identify the yellow 'surprise' indistinguishably from their normal LVF responses.

II. Schematic Faces

Four split-brain patients were tested on their ability to name unilaterally-presented schematic drawings of facial expressions: "angry", "happy", or "surprise". The subjects were shown the faces in free vision before each experiment to ensure that they could recognize each drawing as representing the appropriate expression. The results are shown in Table 5.

Accuracy. Both LB and AA can name LVF schematic faces quite accurately and almost as well as RVF faces. NG has more difficulty in both visual fields but she, too, can name the faces equally well from the two sides. RY can name RVF faces but not LVF faces.

Reaction time. Most interesting now are the response times required to name the schematic faces. As a rule, previous naming tasks by the commissurotomy patients have almost always shown a LVF/RVF RT ratio >1. Now, however, two of the patients (NG and RY) respond significantly faster to LVF than to RVF stimuli (LVF/RVF RT ratio < 1) while AA has a LVF/RVF ratio not significantly different from unity (1.33, $t = 1.69$, $df = 38.3$, $p = .10$). Only LB shows the previously standard ratio, though just barely (1.31, $t = 2.08$, $df = 41.3$, $p < .05$).

III. Human Faces

Four split-brain patients were unilaterally-presented black and white photographs of men's and women's faces to identify, depicting a broad spectrum of ways to express three emotions: "happy", "angry", and "surprise". The subjects were shown stimuli representing examples of each of the three emotions in free vision prior to the experiment but, except for LB, found the task even at this point quite difficult. The results are shown in Table 6.

Accuracy. Three of the four patients (NG, RY, AA) performed poorly in both visual fields. They could not name the emotions in the LVF at a better than chance level, and only one (NG) could name the RVF faces. LB, in contrast, is able to label the photographs quite accurately in both visual fields.

Reaction time. Like the preceding experiment with schematically-drawn faces, the reaction times for naming human facial expressions shows a reversal

Table 5. Verbal identification of unilaterally-presented schematic faces - happy, angry, surprise (chance = 33%)

	Reaction times (ms) and Accuracy		
Subjects	LVF	RVF	LVF/RVF RT Ratio
LB	1790±860 24/25 (98%)**	1370±530 25/25 (100%)**	1.31*
AA	2990±1130 23/26 (88%)**	2240±1880 23/24 (96%)**	1.33
NG	1175±525 44/81 (54%)**	1670±700 37/67 (55%)*	0.70**
RY	900±150 21/55 (38%)	1375±250 34/44 (77%)**	0.65**

*$p \leq .05$

**$p \leq .01$

Table 6. Verbal identification of unilaterally-presented photographs of human faces - happy, angry, surprise (chance = 33%)

	Reaction times (ms) and Accuracy		
Subjects	LVF	RVF	LVF/RVF RT Ratio
NG	1220±660 11/26 (42%)	1420±500 15/24 (63%)*	0.86
RY	790±140 9/25 (36%)	1080±120 12/25 (48%)	0.73*
AA	1970±710 13/25 (52%)	2250±700 15/25 (60%)	0.88
LB	1505±300 22/25 (88%)*	1335±325 23/25 (92%)*	1.13

*$p \leq .01$

of the usual LVF/RVF RT ratio, although this time the reaction time ratios are now ≤ 1.0 for <u>all</u> of the patients tested.

DISCUSSION

These results suggest that stimuli with the potential to be easily labelled affectively <u>may</u> be verbally identified in the LVF of some forebrain commissurotomy patients (which projects to the "disconnected" right hemisphere) more easily than other kinds of stimuli. As mentioned above, this would not explain the ability of some of the patients to identify either stimuli drawn from large sample populations or stimuli that are not easily or naturally labeled emotionally.

Of the four patients tested, only RY does not extend his ability to name LVF stimuli when shown colors or various kinds of faces. NG, who previously had a great deal of trouble naming LVF numbers and letters, can now name both LVF colors and schematic faces. And LB and AA continue to show good LVF naming ability.

Three of the patients (NG, RY, AA) have their greatest difficulty with photographs of faces but this is probably due in great part to the overall difficulty of the task, even in free vision, the large number of different possible stimuli used, and the rapid speed of presentation (150 ms). The further complication with facial identification is the possibility that while the left hemisphere is more vocally fluent, the right hemisphere may be dominant in facial recognition [5-8], even for the schematic drawings of faces, thus causing a complicated interaction and ambivalent responses. This may well explain the better RVF naming accuracy found along side of the (unusual) faster LVF reaction times when faces are presented.

In conclusion, stimuli that may be easily affectively labelled may improve their chances to be identified in the LVF by split-brain patients, but this does not completely explain the ability of these patients to name a wide variety of other LVF stimuli. The unequal reaction times to colors found in the opposing visual fields by three of these patients continues to support the hypothesis, presented in more detail in Chapters III and V, that LVF stimuli can be named from their right hemisphere. And the unusually rapid responses by the right hemisphere to LVF faces support other evidence that the right hemisphere in addition may be specialized for rapid facial recognition.

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V. BILATERAL VISUAL CROSS-INTEGRATION BY HUMAN FOREBRAIN COMMISSUROTOMY SUBJECTS

INTRODUCTION

The perception of a unified visual field despite the projection of the visual half-fields to separate cerebral hemispheres can be the result of many factors, including psychologic perceptual completion, eye and head movement, and neural interconnections within and between the two hemispheres. An important question that arises when studying integration across the midline of the visual field is whether information can still be neurally transferred between the left and right sides of the visual field, in humans who have undergone a "complete" forebrain commissurotomy (section of the corpus callosum, anterior commissure, hippocampal commissure, and massa intermedia if present). The representations of the left and right visual half-fields (LVF and RVF) are normally interconnected along the vertical meridian by two large fiber bundles passing between the cerebral hemispheres (the corpus callosum and anterior commissure) [for general reviews see 1-4] and by less understood neural connections in the mesencephalon and diencephalon [5-7]. While many other pathways cross from one side of the brain to the other (the supraoptic, habenular, hippocampal, and posterior commissures, among others), some of which have known visual functions in other animals, these have no proven role in visual transfer in mammals [8, 9].

The studies of human commissurotomy patients begun in the 1960's indicated that this surgical procedure severely disrupts both the transfer of visual information from one visual hemi-field to the other and the integration of information between the two fields, resulting in a "disconnection syndrome" [10-12], with visual information directed to one hemisphere apparently inaccessible to the opposite hemisphere.

More recently, however, it has been shown that "split-brain" humans could transfer and integrate simple visual stimuli, involving changes in motion or brightness, between the peripheral visual fields, 45° of visual angle or more from the fixation point [13-15]. These findings, along with those from lower animals [16], supported a hypothesis that there are at least two relatively independent, yet complementary visual systems, one represented by a retino-mesencephalic pathway, responsible for orienting and for locating targets in peripheral space ("ambient vision") [13], the other, a retino-telencephalic pathway, for pattern recognition in focal vision. However, further studies on the commissurotomy patients have suggested that they not only may be able to cross-compare or distinguish rather complex visual stimuli, such as letters, numbers, or chimeric patterns, but they can do so when stimuli are projected in central vision, close to the fixation point [17-19]. On the other hand, it has been claimed that all but the most primitive types of cross-integration in any split-brain animal can ultimately be explained by cross-cuing strategies which have not been controlled [20-22].

From this controversial background, the following series of experiments was designed to further assess visual cross-integration in split-brain human subjects, to determine what they can and cannot integrate between their left and right visual fields, and to try to explain the possible neurologic mechanisms involved.

METHOD

Experimental Design

The purpose of these experiments is to determine the ability of commissurotomy patients to cross-compare or identify two visual stimuli when they are presented simultaneously in the left and right visual half-fields (LVF and RVF) near the fixation point, either by indicating whether the two stimuli are the same or different or by naming the two stimuli.

The bilateral visual stimuli included patterns (crossed lines and circles, XO and +O), single digit numbers, capital alphabetic letters, colored disks, and schematic drawings of facial expressions. The subjects were required to respond to these stimuli either manually or verbally. Manual responses entailed moving a small toggle switch with one hand in a direction indicating same or different, while verbal responses required either that the stimuli be categorized as "same" or "different" or be individually named. During any given experimental session, manual responses were tested prior to verbal responses to decrease any possible interference from the activation of speech centers in the left hemisphere.

Subjects

The subjects in these experiments were patients who, 9-15 years earlier, had undergone either complete forebrain commissurotomy (NG, LB, RY, AA), or partial commissurotomy (NF) that left the posterior splenium of the corpus callosum intact, for intractable epilepsy. The subjects have been patients of Drs. J.E. Bogen and P.J. Vogel of Los Angeles. Details of the medical and surgical histories of these patients have been published [23-28]. In short, these patients present a broad spectrum of medical histories, age at onset of symptoms and age at surgery, current intellectual ability, and include both sexes.

Material

The stimuli were presented with a Gerbrands two-channel tachistoscope (model T-2B C) and timer (model 130). Reaction times were measured with a time interval meter and a toggle switch (for manual responses) or a voice-activated switch connected to a tape recorder microphone (for verbal responses). The stimuli were presented in pairs, one member of each pair on each side of the fixation point. Each stimulus was placed so that its most medial edge (the side closest to the fixation point) was from 1-4° of visual angle from the fixation point. Within any given series of trials, this distance was not varied. The stimuli varied in size from 2-5°. In most cases the non-color stimuli were black and flashed on a permanently lit white background, although in early experiments white stimuli on a black background were also used to control for effects of contrast and afterimages. The crossed lines and circle stimuli (XO and +O) and schematic faces were 5° in size, glued to plastic ovals and affixed to the light or dark contrasting background using a Velcro strip. The schematic faces were drawn as black lines on a white background, depicting three stereotyped emotional expressions: the well-known "happy" face, anger, and surprise. The colored stimuli, cut from sheets of Color-Aid pure hues (Geller Artist Materials, Inc.) were not equated for brightness. The stimuli were red, blue, and green circles, 4° in diameter, glued to a white background so that their medial edge was 2° from the fixation point. The small (2°) stimuli included the single digit numbers, alphabetic letters, and additional +O patterns, each hand-lettered on white removable labels. There were seven possible numbers (2,3,4,5,6,8,9), selected because they were irregular in shape and pronounced as one-syllable words. The letters were divided into two sample sizes: eight (F,G,H,K,M,N,R,S) and three (G,R,S), chosen because of their varied shape and central position in the alphabet. Occasionally an unusual or 'surprise' stimulus was shown in the LVF paired with a normal stimulus in the RVF. Stimuli presented as 'surprises' were selected from the above stimuli and were, for example, an unexpected number during a bilateral letter experiment or a letter during a number experiment. The fixation point was a small black or white dot permanently in view in the center of the visual field.

Procedure

The subjects were tested individually in a dimly lit, private room. The tachistoscope was placed on a table and the subject sat in a chair before the viewing slot. The subject's hands were separated from each other and placed out of sight on the table under the tachistoscope. If a manual response was required, the fingers of one hand were placed in contact with a small toggle switch on the table. The left eye of each patient was covered with an eye patch to ensure monocular viewing with the right eye. At the beginning of each experiment, the subject was told what type of stimuli he or she would have to cross-compare and the response required. The patients were familiarized with the schematic faces to make sure they could name the emotional expression on each face. When numbers or letters were to be shown, the subjects were not preinformed as to exactly which ones would be used. The stimuli were presented in a pseudorandom order so that each stimulus would be shown an approximately equal number of times and, in the categorization experiments, so there would be an equal number of same and different responses. The right hand was usually used for manual responses (the left hand by AA), but occasionally the opposite hand was used to see if there were any difference in response accuracy or reaction time between the two hands; no statistically significant difference was ever found. The subjects were asked not to converse when responding manually, or to make only the appropriate verbal response.

Two types of manual response were used in the following experiments. In one (go-no go) the subject was required to move the toggle switch forward <u>only</u> if the two stimuli were believed to be the same and to make no response if they were different. The other type of manual response required the subject to move the toggle switch on every trial, in one direction if the stimuli were identical and in the opposite direction if they were different. Three different verbal responses were used: (1) a go-no go response in which the subject had to say "same" if the two stimuli were the same or make no response if they were different, (2) a "same"-"different" response, where the subject had to respond verbally on every trial, and (3) a verbal identification response, in which the two stimuli had to be named in any order. The subjects were told before each experiment that there would always be two stimuli presented at every trial. They were also to guess if they were not sure of the correct answer.

The basic procedure on each trial was as follows: The experimenter gave a signal of "ready" to warn the subject to focus his eye at the fixation point. Several seconds later the paired stimuli were flashed for a duration of 100-150 msec and the subject immediately made a manual or verbal response. New stimuli were then prepared for presentation. Each testing session included about 40-60 trials, lasting 20-30 minutes. Several minutes were taken in the middle of each session for a brief break, and a longer rest period at the end of each series of trials. Three or four consecutive testing sessions were given in one day.

RESULTS

The following experiments are divided into three sections based on the discrimination task involved: I. Categorization, II. Identification, III. Categorization and Identification.

I. Categorization of Bilateral Stimuli

Four split-brain patients (NG, LB, RY, AA) and one partially-split patient (NF) were tachistoscopically presented a variety of bilateral stimuli 1-4° to each side of a fixation point and were required to distinguish either manually, with a toggle switch, or verbally whether the two stimuli were the same or different. Table 7 summarizes the results for stimuli at 2° and 3° from the fixation point, but does not include the smaller number of trials at 1° and 4°.

NG can correctly cross-compare line and circle patterns (XO and +O), numbers (sample size = 7), letters (sample size = 3), schematic faces, and colors. She can do so when the stimuli are 1-4° from the fixation point and when responding manually or verbally. There is a decrease in accuracy as number and letter stimuli

Table 7. Accuracy and reaction times (msec) for the manual and verbal same-different categorization of various bilateral visual stimuli. The table summarizes results for stimuli presented 2° and 3° from the fixation point and for different kinds of manual and verbal responses (chance = 50%).

Subject	Stimuli	Sample size	Response[+]	N	% Correct	RT±S.D.
NG	XO, +O	2	Manual	479	80*	850±300
	Numbers	7		245	79*	850±325
	Letters	3		25	72*	1070±380
	Letters	8		25	52	1310±570
	Colors	3		25	92*	1240±400
	XO, +O	2	Verbal	188	69*	1065±315
	Numbers	7		25	76*	955±250
	Letters	3		12	92*	1120±330
	Letters	8		25	52	1290±390
	Line faces	3		50	66**	1140±380
	Colors	3		49	84*	810±190
RY	XO	2	Manual	20	55	740±180
	Numbers	7		25	52	1000±250
	Line faces	3	Verbal	100	65*	945±250
	Colors	3		50	74*	800±150
LB	XO, +O	2	Manual	452	60*	950±350
	Numbers	7		147	58	880±300
	Letters	3		12	50	990±400
	Letters	8		12	42	1020±290
	Colors	3		25	32	1120±530
	XO, +O	2	Verbal	117	52	975±315
	Numbers	7		75	47	1025±325
	Letters	3		13	62	1000±230
	Letters	8		13	38	1040±230
	Line faces	3		25	36	1580±390
	Colors	3		98	51	1000±270
AA	XO	2	Manual	25	56	2650±1470
	Numbers	7		25	48	3870±1650
	Line faces	3	Verbal	50	52	1380±490
	Colors	3		49	57	1400±420
NF	XO	2	Manual	25	100*	1370±280
	Numbers	7		25	100*	890±180
	Colors	3	Verbal	50	90*	1040±150

[+] Manual responses (toggle switch): Go-no go (forward if same, no response if different); forward if same, backward if different.

Verbal responses: Go-no go ("same" only, no response if different); "same" or "different".

[*] $p \leq .01$

[**] $p \leq .05$

are moved farther apart (1° = 89 per cent, 2° = 83 per cent, 3° = 77 per cent, 4° = 67 per cent), but at each distance NG can still respond with an accuracy greater than chance ($p < .05$). Only when the letters are chosen from a large sample population (8), however, is NG unable to correctly determine, either manually or verbally, whether the stimuli are the same or not. RY was able to cross-compare both colors and schematic faces as same or different ($p < .01$), but not numbers or XO patterns.

In contrast, LB is almost always *unable* to correctly distinguish same from different stimuli. His manual responses reached significance only with pattern circle patterns (XO, +O) after a very large number of trials. When pattern or number stimuli were placed either closer (1° = 57 per cent) or farther (4° = 58 per cent) from the fixation point (not tabulated in Table 7), LB's responses were still not significantly different from chance. For manual responses to letters and colors and for all verbal responses, LB was also unable to correctly categorize two stimuli as same or different. AA, too, could not cross-compare XO, number, face, or color stimuli, while the splenium-intact subject (NF) could integrate XO, number, and color stimuli very accurately.

A 'surprise' stimulus was occasionally substituted for a regular LVF stimulus when testing NG and LB. NG was always able to give a 'different' response, either manually or verbally, but made no other indication about the strangeness of the stimulus. LB, on the other hand, was *not* able to correctly recognize the LVF 'surprise' as different. He, too, never made any comment that he noticed anything odd about these stimuli.

In conclusion, two of the four commissurotomy patients tested were able to cross-integrate some bilateral visual stimuli. NG was able to cross-compare all the stimuli presented, except when the sample population was too large. RY was able to cross-compare colors and schematic faces, but not numbers or XO stimuli. The two other completely split patients (LB, AA) were unable to consistently perform this bilateral visual integration. Only once did LB reach a significantly accurate score and then only after an extraordinarily large number of trials.

II. Identification of Bilateral Stimuli

In contrast to the categorization experiment above, the split-brain subjects show quite different results when they are required to name the two bilateral stimuli presented (Table 8). The order of report was not suggested to the subject at any time. NG's responses were almost always 'RVF dependent' when identifying either numbers or letters, that is, she would merely repeat the RVF stimulus twice. However, when a 'surprise' stimulus replaced a normal LVF stimulus, NG often indicated that she could in fact recognize an unordinary difference between two stimuli both because of her significantly longer reaction times on these trials and also because she often responded by saying two different names, unlike her 'RVF dependent' responses on normal trials. But in no other manner did she indicate, either during the trial or at the end of the complete experiment, that she had ever seen an unusual LVF stimulus.

LB, on the other hand, and in marked contrast to his inability to correctly compare bilateral stimuli as same or different (I. above), can name bilateral letters, numbers, schematic faces, and colors. He almost always names the LVF stimulus before the RVF stimulus. In addition, 'surprises' cause considerable distress and disbelief both before and after his naming responses, and elicit a long delay before any response. In spite of this, LB could often correctly identify the 'surprise' although occasionally he would name the RVF stimulus before the LVF 'surprise'. It is notable that LVF 'surprises' elicited no verbal comment or change in response time from LB in the earlier categorization experiments (I. above). RY and AA were only tested with bilateral numbers but, like NG, they were unable to name

Table 8. Accuracy and reaction times (msec) for the verbal identification (naming) of bilateral stimuli, with occasional LVF 'surprises'. These 'surprises' are either a LVF number paired with a RVF letter and randomly projected during a bilateral letters experiment, or a LVF letter with a RVF number during a bilateral numbers experiment.

Subject	Stimuli	Sample size	Accuracy	% Correct	RT±S.D.
NG	Letters	3	a	-	1010±520
	Numbers	7	a	-	1050±450
	LVF 'surprises'		0/12	0	1580±650
LB	Letters	3	16/24	67*	1490±530
	Letters	8	16/25	64*	2030±720
	Numbers	7	67/86	78*	1250±510
	LVF 'surprises'		7/12	58*	2930±1020
	Line faces	3	20/25	80*	2350±970
	Colors	3	33/47	70*	2330±800
RY	Numbers	7	b	-	1520±300
AA	Numbers	7	c	-	4310±3490
NF	Numbers	7	14/14	100*	1170±290

[a] Response is RVF dependent, i.e., subject repeats RVF stimulus twice.

[b] RVF stimuli correctly identified; however, LVF stimuli elicit guesses or are completely neglected.

[c] RVF stimuli usually correctly identified; LVF stimuli usually guessed at but some 'same' pairs were identified correctly.

[*] $p \leq .01$.

them both successfully. RY could correctly name the RVF stimulus but would guess at the LVF stimulus or completely neglect it. AA could usually name the RVF stimulus correctly and usually guessed at the LVF stimulus, but on occasion would name 'same' number pairs (e.g., 6-6) correctly. This response did not become significant, however, because of the small number of trials used. NF, the partially-split patient, was always completely accurate in naming the bilateral stimuli.

In conclusion, only one of the commissurotomy subjects, LB, could accurately name bilateral stimuli. NG, however, did give some verbal indication that she could notice unusual stimuli in her LVF, and AA was sometimes able to name 'same' stimuli pairs.

III. Categorization and Identification of Bilateral Stimuli

The above results suggest that the ability to cross-compare and categorize bilateral stimuli as same or different may be quite distinct from the ability to name the two stimuli. To study this further, a final experiment was designed to combine the two kinds of discriminations and responses used individually in the previous experiments. Two subjects (NG, LB) were presented bilateral numbers and required to say "same" or "different", and immediately thereafter name the two numbers. The results are presented in Table 9. In the earlier experiments, LB had shown that he was generally unable to compare two stimuli as same or different when they were presented in opposite visual fields, although he could often correctly name them. Here we now see a distinct interference between these two processes. As earlier, LB is unable to verbally indicate whether the two numbers are the same or different (accuracy = 40 per cent, chance = 50 per cent), but now his subsequent ability to name the numbers is also markedly decreased (33 per cent correct versus 78 per cent correct when naming alone is required). Although not reflected in reaction times, LB is able to classify 'same' stimuli

Table 9. Accuracy and reaction times (msec) when bilaterally presented numbers must be categorized (say "same" or "different") and then identified (name the two stimuli) on each trial. A LVF 'surprise' is an occasional LVF letter paired with a RVF number.

		Categorization		Identification			
Subject	Stimuli	Correct	RT±S.D.	Both Stimuli Correct	Only RVF Correct	Only LVF Correct	Both Stimuli Wrong
LB	Same	11/22 50%	1320±300	11	7	4	0
	Different	7/23 30%	1350±450	4	14	4	1
	Overall	18/45 40%		15/45 33%			
NG	Same	16/22 73%	1020±370	14	6	0	2
	Different	6/15 40%	1410±770	1	14	0	0
	LVF 'surprise'	5/11 45%	1290±430	0	11	0	0
	Overall	27/48 56%		15/48 31%			

pairs more easily than 'different' pairs (50 per cent versus 30 per cent) and is able to correctly name 'same' pairs almost three times as often. NG, too, shows a decrease in accuracy in her normally good categorization ("same"-"different") ability, even though categorization precedes identification. NG can recognize 'same' pairs more accurately and more rapidly than 'different' pairs, but her accuracy overall is not greater than chance (56 per cent correct versus 76 per cent when categorization alone is required, Table 7). As usual, her naming responses are almost entirely RVF dependent, repeating twice the RVF stimulus. These results suggest that the combination of tasks is causing interference either because of a sharing of channels at some point in the process or because of a general increase in task difficulty when the two discriminations are combined.

DISCUSSION

The manner in which forebrain commissurotomy patients respond to both bilateral and unilateral [28] visual stimuli (their accuracy and response times) strongly suggests that there may be at least three distinct ways that split-brain humans verbalize LVF stimuli.

When split-brain patients make naming responses to either unilateral or bilateral visual stimuli, it seems most likely that RVF stimuli are identified by the left hemisphere verbal centers while LVF stimuli are separately identified by the right hemisphere. The evidence for this is several-fold. From experiments using unilaterally presented stimuli [28], it was found that naming responses to LVF stimuli are significantly slower than naming responses to the same stimuli presented in the RVF. Thus, unlike normal and partial-splits, split-brain patients are hypothesized to use different mechanisms for naming LVF and RVF stimuli. The proposal that the right hemisphere is, in fact, naming LVF stimuli is based on the finding that NG and RY frequently continue to perseverate responses to randomly presented LVF stimuli while accurately naming RVF and fixation point stimuli [28]. In addition, the results from bilateral presentations clearly show that while LB cannot cross-compare two stimuli as same or different (Table 7), he can accurately name each of them (Table 8), presumably by the individual hemispheres. Abstracts of these results have been published earlier [29-32]. This same phenomenon has also recently been found in a split-callosum intact-anterior commissure patient [33]. The inter-patient differences in naming accuracy are presumed to reflect the presence or absence of functional pathways between the right hemisphere perceptual centers and verbal centers. The patency of these pathways was found to depend on the tasks involved, the size of the stimulus set, and so forth. The use of stimuli which are more easily affectively labeled (emotional facial expressions and colors) still did not allow accurate cross-comparisons between the visual fields in two of the subjects.

The only finding which is not easily reconciled with what is interpreted to be simple right hemisphere naming responses occurs on trials where an unusual LVF stimulus, either unilateral [28] or combined with a normal RVF stimulus in bilateral presentations (Table 8), is projected to LB. In most of these trials, LB exhibits overt verbal disbelief at what he has seen, both before and after his usually correct naming response, to an extent far greater than what has been presumed to be the disconnected right hemisphere's speaking ability.

In contrast, when required to make two-choice categorization responses to unilaterally presented visual stimuli, the strong similarity between complete splits, a partial split (splenium intact), and normal subjects with respect to both their speed and accuracy of responses to LVF and RVF stimuli, can be most easily interpreted that the verbal responses all arise from the left hemisphere [28]. Thus, the pathways remaining following forebrain commissurotomy, presumably through the midbrain, must be able to transfer enough information from the right hemisphere perceptual centers to the left hemisphere for a correct (same-different) verbal response. However, the potential simplicity of the message which is sufficient to code the transferred information in turn may require only a very simple neural interconnection between the two sides of the brain.

A third mechanism for LVF vocalization is probably required to explain the ability of NG and RY to correctly cross-compare bilateral stimuli as same or different (Table 7). While same-different verbal categorizations of LVF stimuli could be due to a simple (+/-) signal relayed from perceptual centers in the right hemisphere to the left hemisphere [28], such a simple system would not be easily capable of transferring sufficient information to distinguish each LVF stimulus when large stimulus sets of 7-8 members are used. It is necessary that the essence of each unique LVF stimulus be combined with the RVF stimulus for a comparison of identity to take place. This presumably requires the transfer of a substantial amount of information for each stimulus. It is not known where this comparison takes place neuroanatomically but it seems likely that the conclusions are ultimately vocalized from the left hemisphere since both NG's and RY's right hemisphere is far less fluent than their left in verbal ability.

While one can never be certain that the subjects are not cross-cuing, the numerous precautions taken (fixation control, rapid tachistoscopic presentations, etc.), the large stimulus set sizes, the lack of any obvious peripheral cross-cuing, the absence of any correlation between stimulus and response speed, and so forth argue against cross-cuing as a significant factor in these experiments.

Thus, the visual-oral dissociation syndrome which seemed so prominent in recently post-surgical patients [10-12] seems to have changed, or resolved, dramatically in the decade or so following commissurotomy. Five to seven years after surgery, studies of peripheral visual ability in these patients suggested that moving objects and light could be cross-integrated between the bilateral visual fields, and sometimes simple comments concerning LVF events could be elicited [13]. The kinds of stimuli involved and their location far from central vision lent support to a proposed visual system using the midbrain and concerned primarily with orientation to movement and brightness stimuli [13-16]. Later work indicated that split-brain patients could also occasionally speak about events near the more focal part of their LVF, which was presumed to project primarily and directly to the minor, "nonverbal" right hemisphere [17-19]. The question still remained, however, whether this vocalization was an artifact due to non-neural cross-cuing strategies [20-22], left hemisphere speech elicited using pathways still remaining after forebrain commissurotomy, or right hemisphere speech.

The experimental evidence presented here and elsewhere [28] suggests that, via neuronal pathways, LVF stimuli can be verbalized in either the left or right hemisphere, dependent primarily upon the discrimination involved. Further study is now needed both to determine precisely what kinds and how much information can still pass between the disconnected cerebral hemispheres of commissurotomy patients, and where this transfer is occurring. This may lead, in addition, to a better understanding of the potential capabilities of these lower visual pathways in normal and brain-damaged human beings.

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VI. APPENDIX: CROSS-COMPARISON OF BILATERALLY PRESENTED BRIGHTNESSES, COLORS, UPPER AND LOWER CASE ALPHABETIC LETTERS, AND PHOTOGRAPHS OF FACES BY HUMAN COMMISSUROTOMY PATIENTS

INTRODUCTION

The preceding studies of visual cross-integration in human commissurotomy subjects originated from the intriguing reports that these patients not only could cross-compare stimuli involving movement and brightness in the peripheral visual fields [1, 2], but were also able to verbally identify, on occasion, more complex stimuli located close to the fixation point, exclusively within the left visual field (LVF) [3, 4]. Since the LVF projects to the right hemisphere, which is thought to be generally mute when disconnected from the left hemisphere by forebrain commissurotomy [5], it has been proposed that these patients may be using various cross-cuing strategies to allow the verbal left hemisphere to make accurate responses [6-8]. It was therefore suggested by Dr. R. W. Sperry that visual transfer and integration in split-brain subjects be investigated more thoroughly to evaluate its extent and to propose and test possible explanations.

The original preliminary experiments involved a study of cross-integration of both (A.) brightness and (B.) color. Later, in the course of studying more complicated visual stimuli, the ability to compare bilateral (C.) upper and lower case alphabetic letters was also examined. The experimental studies concluded by testing whether commissurotomy patients could integrate two photographs showing (D.) human facial expressions and correctly decide whether the emotions depicted were the same or not. The results from each of these studies are discussed below.

A. Brightness

Methods. Unlike later experiments (Chapters III-V) which utilized front-lighted stimuli projected in a box tachistoscope, the first experiments with brightness, and later with color, used a back-projection screen on which were presented the stimulus pairs. Light was projected through various Kodak Wratten neutral density gelatin filters (No. 96) onto the rear of the screen using a slide projector with a 300 watt lamp. A light-opaque cardboard mask was fastened to the front of the screen to eliminate light diffusion and reflections across the field. Two open circles were cut in the mask for the stimuli, 5.2° in diameter and 2.8° to either side of the central fixation point. The screen was placed 37 cm from the subject's eyes. Ten different stimulus pairs were projected in pseudo-random sequence, each for a duration of 150 ms, using a Gerbrands shutter attached to the projector lens and a digital millisecond timer.

The light intensity of the individual circles of light, measured by a Gossen Luna Pro meter placed several centimeters from the screen, varied from 0.7-2.8 log foot lamberts. The difference in brightness within any 'different' pair of stimuli varied from 0.4-1.7 log foot lamberts.

The experiments were carried out in a dimly lit, private room. Before beginning the actual testing session, several stimulus pairs were presented at long exposures to familiarize the subjects with the various kinds of stimuli and the responses required. The subjects, viewing the screen monocularly with the right eye, were asked to judge whether the two circles of light were the same brightness or not by saying "same" or "different" on each trial.

Results. The results are shown in Table 10. Both NG and LB are able to successfully cross-compare two circles of light and verbally indicate whether they are of equal or unequal brightness, as long as the unequal pairs differ by more than 0.4 log foot lambert. Stimuli that differed in brightness by only 0.4 log

Table 10. Cross-comparison of bilaterally presented brightnesses by human commissurotomy patients. Back projection screen method.

Subject	Response Mode	Stimulus Duration (ms)	Accuracy (Chance = 50%)	
NG	Verbal[+]	150	49/69 (71%)	$X^2 = 10.6, p < .01$
LB	Verbal[+]	150	61/69 (88%)	$X^2 = 37.5, p < .001$

[+] Verbal responses — "same" or "different".

foot lambert could not be correctly differentiated as unequal under these conditions. Normal subjects also have a great deal of difficulty at this level of discrimination (unpublished data).

B. Color

Methods. These colored stimuli were presented to the patients using the back-projection screen apparatus employed in the brightness experiment above. The stimuli were made from Kodak Wratten gelatin filters (red = No. 25, blue = No. 47, green = No. 58) inserted in 35mm slide mounts and projected onto the screen via a slide projector with a 300 watt lamp. The colors were deliberately equalized or unequalized for brightness with Kodak Wratten neutral density filters (No. 96). An opaque mask attached to the front of the screen again made the stimuli 5.2° in diameter and located them 2.8° to each side of the fixation point. The brightness of each stimulus was measured with a Gossen Luna Pro meter placed several centimeters from the screen.

The subjects were tested individually in a dimly lit, private room. The subject's hands were separated from each other and, if a manual response was required, placed out of sight under the apparatus, with the fingers of one hand resting on a pressure-sensitive button. Each subject's left eye was covered to ensure monocular viewing with only the right eye. The stimuli were presented in pseudo-random order so that approximately equal numbers of 'same' and 'different' stimuli pairs and equal numbers of each color would be shown.

On trials requiring manual responses, the subjects pressed a button-like disk if the two stimuli were thought to be the same, and made no response if they were different (go-no go). Verbal responses required the subjects either to respond "same" or "different" on each trial, or to name the two stimuli.

Results. In the brightness experiment (A.), the two subjects (NG and LB) demonstrated that they could accurately distinguish the brightness of two lights projected simultaneously to the two hemi-fields. The following color experiments were therefore divided into two sections and were designed to artificially manipulate the brightness of the colors to see if subsequent choices of 'same' and 'different' could be influenced by differences in intensity.

In the first series of experiments, the brightness of the colors was equalized with neutral density filters, so that the brightness between any two colors in a stimulus pair would not differ by more than 0.2 log foot lamberts, and averaged 0.1 or less. The absolute brightness varied from 0.5-1.0 log foot lamberts. Nine stimulus pairs were used. The results are shown in Table 11(a).

Both NG and LB are able to cross-integrate 'brightness-equalized' back-projected colors, using either manual or verbal (same-different) responses. NG is slightly more accurate than LB in both kinds of responses.

In contrast, when the subjects were asked to name the two colors flashed, LB could do very well (43/48 = 90%), but NG's responses were RVF dependent, that is, she would neglect the LVF stimulus and repeat twice the right field stimulus.

In the second of these color experiments using the back-projection screen, the brightness of one of the colors in each of the 12 stimulus pairs was deliberately changed with neutral density filters, so that both stimuli were of unequal brightness even when they were the same color. The absolute brightness of the colors ranged from 0.3-1.8 log foot lamberts and the difference between any two stimuli in a pair was 0.45-0.95 log foot lamberts. The results are seen in Table 11(b).

Both NG and LB are still able to distinguish identical from different colors under these conditions using either manual or verbal responses. They thus can make their decisions independent of any brightness differences between the stimuli. LB performs somewhat more accurately than NG using both manual and verbal responses.

Table 11. Cross-comparison of bilaterally presented colors (red, blue, green) by human commissurotomy patients. Back projection screen method.

Subject	Response Mode	Stimulus Duration (ms)	Accuracy (Chance = 50%)		
		(a) Brightness equalized			
NG	Manual[+]	100	41/48	(85%)	$X^2 = 22.2$, $p < .001$
LB	Manual[+]	100	92/120	(77%)	$X^2 = 32.8$, $p < .001$
NG	Verbal[++]	100	40/48	(83%)	$X^2 = 18.9$, $p < .001$
LB	Verbal[++]	100	106/132	(80%)	$X^2 = 46.9$, $p < .001$
NG	Verbal[+++]	100	28/48	(58%)	
LB	Verbal[+++]	100	43/48	(90%)	
		(b) Brightness unequalized			
NG	Manual[+]	100	38/48	(79%)	$X^2 = 15.0$, $p < .001$
LB	Manual[+]	100	44/48	(92%)	$X^2 = 30.9$, $p < .001$
NG	Verbal[++]	90	56/70	(80%)	$X^2 = 24.6$, $p < .001$
LB	Verbal[++]	90	70/75	(93%)	$X^2 = 53.5$, $p < .001$

[+] Manual go–no go responses — press button if 'same', no response if 'different'.

[++] Verbal responses — "same" or "different".

[+++] Verbal responses — name the color of each stimulus.

Brightness and Color Discussion

Unlike later experiments using more complex stimuli, such as letters, numbers, or patterns (Chapter V), both NG and LB can easily cross-integrate bilateral visual stimuli involving back-projected brightnesses and colors. While NG can accurately compare colors presented either via the box tachistoscope (these results are presented in Chapter V) or the back-projection screen, LB, in contrast, can do so only in the present experiment using the overall more intense colors on the projection screen.

C. Upper and lower case alphabetic letters

As the complexity of the stimuli was increased over many experiments, it became obvious that some of the split-brain patients could continue to accurately cross-match stimuli between their visual fields while others were not able to do so. In studying one subject (NG) who was particularly successful at accurately cross-comparing bilateral stimuli, one question which naturally arose was whether the matching was done simply by template comparison, i.e., by physically matching one stimuli with another, or could more complicated comparisons also be carried out, for example, involving different physical characteristics but still the same identity [9, 10]. An experiment was therefore designed to determine whether two of the commissurotomy patients (NG and LB) could match various letters of the alphabet as same or different irrespective of whether the letters were presented in the lower or upper case.

Methods. Three letters of the alphabet were chosen (D-d, H-h, and E-e). They were cut from white paper and glued to a gray-black background on a series of cards representing all possible permutations of letter and case, 2° to each side of the fixation point. Both upper and lower case stimuli were made equal in size, approximately 4° in diameter.

The stimuli were presented using a Gerbrands two-field tachistoscope for 100 ms duration and were viewed monocularly with the right eye. The field remained dark between trials except for a tiny red LED in the center which served as the fixation point. Responses included either manual go-no go button-press responses with the right hand, or verbal "same"-"different" responses.

Results. The results are shown in Table 12. NG is easily able to compare, both manually and verbally, alphabetic letters by their name identity as well as their physical identity. LB, tested only with manual responses, cannot compare these bilateral stimuli better than chance.

Discussion. The finding that NG can match bilaterally projected letters by their name as well as their physical identity strongly suggests that she is able to cross-compare visual stimuli across the midline using more than just a simple template matching system. A further inference is that the interhemispheric connections remaining following forebrain commissurotomy are capable of transferring enough information to allow this more complicated comparison to take place. In addition, even though LB's right cerebral hemisphere has significant verbal capabilities, he is not (successfully) cross-cuing his left hemisphere by any naming from his right hemisphere.

D. Human Facial Expressions

Methods. The appendix following the experiments with unilaterally projected stimuli (Chapter IV) has discussed the possibility that commissurotomy patients are able to transfer information between their "disconnected" hemispheres using strongly affective stimuli such as unilateral colors and faces. This idea was also later examined by presenting bilateral colors and schematic faces for cross-comparison (Chapter V). Here it is studied a final time using bilateral photographs of human facial expressions.

Table 12. Cross-comparison of bilaterally presented upper and lower case alphabetic letters by human commissurotomy subjects.

			Accuracy (Chance = 50%)	
Subject	Response Mode	Stimulus Duration (ms)	Physical or Name Matching	Name Matching Only
NG	Manual⁺	100	18/24* (75%)	49/72** (67%)
	Verbal⁺⁺	100	8/12 (67%)	27/36** (75%)
LB	Manual⁺	100	4/12 (33%)	20/36 (56%)

⁺Manual go-no go responses -- press button if 'same', no response if 'different'.

⁺⁺Verbal responses -- "same" or "different".

$* = p \leq .05$

$** = p \leq .01$

The black and white photographs of human faces were taken from *Unmasking the Face: A Guide to Recognizing Emotions from Facial Clues* by Paul Ekman and Wallace V. Friesen (Prentice-Hall, New Jersey, 1975). Again a variety of examples of three facial expressions (happiness, anger, surprise), about 5° x 7° in size, from both male and female models were used. The photographs were glued to a white background, 2-3° to each side of the fixation point. The stimuli were flashed (150 ms) using a Gerbrands two-field box tachistoscope. Between stimulus presentations, the plain white background and centrally located fixation point remained visible.

Results. This task proved exceptionally hard for all of the subjects, including several of the controls. When required to compare two tachistoscopically presented photos as same or different with respect to their facial expression, none of the split-brain patients could perform better than chance, either manually or verbally (Table 13). The difficulty of the discrimination is also obvious on the within-hemisphere control trials where two faces were simultaneously projected, one above the other, into the same visual half-field. In all but one case, the patients were unable to compare the two photographs correctly within one hemisphere. All patients, however, were more accurate in identifying the control stimuli projected to their right than to their left hemisphere, and their LVF/RVF reaction time ratios were equal to or less than 1.0, indicating that the right hemisphere was responding as fast or faster than the left hemisphere. Only LB was tested on his ability to *name* the two facial expressions ("happy", "angry", "surprise") which he was able to do (17/25 = 65%).

The partial-split (NF) and one of the normal subjects performed more poorly on the bilateral facial comparison task than on previous inter-hemispheric comparison tasks (Chapter V), but still did significantly better than chance.

Discussion. The difficulty of this comparison of bilateral human facial emotions (happiness, anger, surprise) is due in part to the large number of complex

Table 13. Cross-comparison of bilateral photographs of human facial expressions

(happiness, anger, surprise)

		Response Accuracy			
		Verbal^{++} (Chance = 50%)			
Subject	Manual^{+} (Chance = 50%)	Interhemispheric	Intrahemispheric Controls	LVF/RVF RT Ratio	Verbal^{+++}
NG	25/50 (50%)	57/106 (54%)	LVF = 60% RVF = 50%	1.02	
RY	26/50 (52%)	27/50 (54%)	LVF = 48% RVF = 36%	0.64	
AA		30/50 (60%)	LVF = 68% RVF = 52%	0.86	
LB		8/25 (32%)	LVF = 80%* RVF = 44%	1.00	17/25* (68%)
NF		36/50* (72%)			
N1		39/50* (78%)			
N2		50/50* (100%)			

$^{+}$Manual toggle switch responses — forward = 'same', backward = 'different'.

$^{++}$Verbal responses — "same" or "different".

$^{+++}$Verbal responses — name the emotion of each face.

*p <.01

stimuli and to the rapid flash duration necessary to prevent eye movement away from the fixation point. All of the split-brain patients showed an inability to compare two stimuli under these conditions, and even several of the control subjects performed less accurately than usual. In fact, this was the first task found in which NG was not able to correctly cross-compare two stimuli as same or different. The difficulty of the discrimination was shown more conclusively when it was found that the patients were unable to compare the two facial stimuli even within a single hemisphere. Therefore, it is not possible to decide from this experiment whether human facial expressions can be cross-compared between visual half-fields in forebrain commissurotomy subjects.

In spite of this, these results do (1) reconfirm LB's ability to name LVF and RVF stimuli but not cross-compare them, further evidence for right hemispheric speech, and (2) provide more evidence that the right hemisphere is specialized in some way for facial recognition, since the right hemisphere of all the split-brain subjects is not only consistently more accurate than the left but also responds as fast as if not faster than the left hemisphere. This is in contrast to earlier findings of a consistent left hemisphere superiority in both speed and accuracy for identifying non-facial stimuli (Chapters III and IV).

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