■ **Special Lecture**

Contributions of Split Brain Studies to Aphasia, Apraxia and Agnosia

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Introduction

When considering the more classical and integrative problems of aphasia, apraxia, and agnosia, it is now clear the neuropsychologist is free to puzzle the rich set of dissociations that always occur within and between patients that in the past have tended to be dismissed, in favor of the larger fact that the left hemisphere of most human beings is dominant for language and thought and that the right is capable of carrying out perceptual and perceptual motor tasks. The richness of the possible cognitive models now being proposed to explain mental activities urges a microscopic view of what is and is not impaired following brain damage. This same sub-process or modular view has been adopted in studies on patients with hemisphere disconnection (Gazzaniga,1985). In these studies, instead of looking for variations in capacity as a function of lesion site or size, specific callosal fiber systems are assessed as to their function. Additionally, the disconnected hemisphere can be assessed and its capacities analyzed in light of preoperative performance. In the following, this approach will be used to examine the problem of language, motor control and perception.

STUDIES ON LANGUAGE

The patients we study have undergone callosal surgery which isolates their left half brain from their right. What is of interest to consider is the language and cognitive capacities of the isolated right hemisphere. What we have concluded is that the right hemispheres becomes a productive laboratory for studying the relationships between language and thought and to that end we are forever amazed to learn how dissociable the two mental activities seem to be.

We have recently been examining the syntactical capacity of two patients who have undergone hemisphere disconnection (Baynes and Gazzaniga, 1987). In previous studies we have shown that each patient has a rich lexicon in each hemisphere (Sidtis et al., 1981; Gazzaniga et al.,1984). The presence of this lexicon and the ability to recognize semantic relations does not correlate with extensive general problem solving ability in either a cognitive or perceptual domain (Gazzaniga and Smylie, 1984). Still, earlier studies did suggest that at least one of the patients possessed some more advanced language capacities, even in the presence of this rather impoverished general cognitive capacity. The present studies, in part, address the

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role of syntactic competence in the presence of a limited cognitive system.

It has been found that aphasics who were unable to interpret correct active and passive sentences were able to judge accurately whether sentences were grammatical (Linebarger et al., 1983). The results suggest that even though a patient may not be able to use a grammatical constraint in a comprehension task, he or she may still know something about grammar and be able to use this knowledge in other tasks, such as a grammaticality judgment task. Alternatively, the results are consistent with the view that brain systems exist that are able to judge whether or not an utterance is grammatical without having that system assist in making use of the grammatical infomation for meaning. The implied two stage model here is not unlike the recognized fact that the human brain which can retain knowledge for thousands upon thousands of words, can instantly tell you whether a word string is in fact a word or not. There would appear to be some kind of primary capacity to judge admissability to higher language processes before considering meaning. We have begun to examine this constellation of questions in the isolated right hemispheres of Cases J.W. and V.P..

J.W.'s left hemisphere performs well on the grammatical tests. Although less accurate his right hemisphere has the greatest difficulty with the same conditions as the agrammatic aphasics. Howerer, there is much less difference in the performance between the two hemispheres of V.P. Both J.W. and V.P.'s left hemispheres respond with the same level of accuracy, but J.W.'s right hemisphere is much more impaired than V.P.'s.

The most striking finding in these two commissurotomized patients with right hemisphere language is the dissociation between the ability to comprehend syntactically-constrained sentences and the ability to judge their grammaticality. This dissociation can be found in two distinct populations, agrammatic aphasics and commissurotomy patients. Moreover, the presence of this dissociation in the intellectually impoverished right hemisphere suggests that grammaticality judgments may not depend on a developed intellectual capacity as much as the interpretation of sentences for understanding of meaning. The processing underlying grammaticality judgments may be automatic and data-driven and as a consequence, be independent of the adequate functioning of other cognitive systems, such as those involved in an inference task, the kind of task these same kind of right hemispheres fail at carrying out. Thus, interpretation of syntactically constrained sentences may require more interactive processing and depend crucially on more advanced inferential capacities.

MOTOR CONTROL

The capacity to carry out the simplest kind of visually or tactually guided movement has fascinated and perplexed brain scientists for years. Understanding the basic anatomy and physiology of motor control has served as one source of insight into how discrete movements are executed. When considering more integrative questions such as the problem of organizing a movement or the problem of how sensory coordinates are mapped on to motor coordinates, the challenge of the problem of motor control becomes profound especially in the human being.

The neurologic clinic has been the source of many observations and in particular the syndrome of apraxia has been well describe. In brief, patients with disturbances in language function are frequently unable to carry out verbal motor commands as are patients with dementia. It has been assumed the disorder (ideomotor apraxia) reflects a problem of comprehension of the task requirement since verbally requested movements can all be carried out either spontaneously or imitation, thereby indicating the basic motor programs for the movement in question are intact (Nass and Gazzaniga, 1987). There are still other disorders that have been reported including the syndrome of ideational apraxia where movements are attempted but the meaning of elements in a sequential task is disrupted. Thus, in lighting a cigarette, the match maybe placed in the mouth and the cigarette is used to strike the matchbox. It has been suggested by many investigators that in human beings the left hemisphere is specialized for organizing complex movements. It has also been argued that the corpus callosum is heavily involved in the left hemisphere's attempts to control the left side of the body. In the following I will first review studies on the specificity of the callosal links. I will also examine the issue of hemisphere specialization for motor function.

Studies on callosal mechanims

Studies on patients with both partial and complete commissure section have allowed for some further observations on the problem of sensory-motor control. In prior studies, it has been shown both in primates and man that the corpus callosum is not an essential structure for the successful completion of an ipsilateral sensory-motor task only involving the proximal musculatures of the shoulder and arm. Thus, a disconnected hemisphere, either left or right can easily direct both the contralateral and ipsilateral arm to a point in space (Gazzaniga et al., 1967). These same studies clearly showed, however, that the corpus callosum was crucial for the successful integration of sensory-motor information involving the more distal musculatures of the hand. In these studies it was shown that a specific visual command presented to either the left or right hemisphere to move a particular finger or form a specific hand posture, could be easily carried out by the contralateral hand. Control of the ipsilateral hand, however, was severely impaired. Related tests carried out in the monkey revealed the same pattern of results. In short, the corpus callosum was considered crucial for cross-hemisphere integration of sensory-motor information involving the hand. What has not been clear is what part of the callosum served as the crucial link. An answer to this question, of course, assumes the callosum is organized in a functional-topic manner.

It has been established for some the time that there are major functional subdivisions of the callosum. The posterior or splenial regions are involved with visual processes. Regions anterior to the splenium are active in transferring auditory and tactual information and still more anterior regions transmit information involved in motor activity. When considering what callosal segments are crucial for integrating sensory-motor information, the modality of the task in question must be considered. For example, if the task is a visual-motor task, splenial fibers could transmit the sensory information and within hemisphere fibers could then communicate to the motor system of each hemisphere. Conversely, if the splenial fibers were sectioned and more anterior fibers were remaining that spared the motor fibers, the motor system could inter-communicate the essential information for interhemispheric communication. At the same time a section that spared the visual fibers but included the fibers communicating tactile information, a sensory-motor task using touch as a stimulus would show disconnection effects. In what follows, I report on a new case, E.B. with a partial callosal disconnection. The results reveal the great specificity of callosal fiber systems.

Case E.B., a 23 year old female, underwent partial callosal section for intractable epilepsy in 1983. The posterior one-half of the callosum was sectioned in one operation and the extent of the section was verified with MRI. Prior to callosal surgery, she had undergone a right occipital resection in an earlier effort to control her epilepsy. This resulted in a left hemianopia that has remained static for 6 years. Because of the preoperative hemianopsia, interfield testing of visual function was not attempted, however, interhemispheric tests on tactile function were carried out. These tests revealed she was unable to name objects placed out of view when palpated with the left hand but could name those palpated with the right hand. She was also unable to transfer stereognostic information from one hand to another, thereby demonstrating that no tactile sensory information could be cross-communicated between the two hemispheres. Additionally, while her left hand was able to retrieve like items in a match-to-sample paradigm, she could not retrieve objects to verbal command with the left hand. The rest of her neurologic history is unremarkable and she currently enjoys good health. The second patient, Case J.W., underwent full callosal section in two stages and the extent of his full section has been verified with MRI.

The capacity of each patient to carry out a simple tactile-motor task was assessed in much the same manner originally employed for split-brain patients (Gazzaniga et. al., 1963). In brief, the subject was asked to close the eyes while each finger was lightly touched by the experimenter in either the proximal or distal phalanx. The within-hand task required the subject to touch the point of stimulation with the thumb of the same hand. Subsequently, the between-hand condition was run. Here a point was stimulated in the same fashion on one hand and the subject was required to find the corresponding point on the opposite hand with the thumb of the opposite hand. Eighteen trials were carried out for each condition. For a response to be scored as correct, the exact phalanx had to be touched. In practice most errors were responses to the wrong finger. Prior to each test run, practice trials were run with the eyes open. The full task was carried out on several occasions in each patient over a period of years. The results reported here were collected two years after surgery on E. B. and five years after the final callosal surgery on J.W. The pattern of response capacity has not changed over either patient's postoperative course.

Both subjects were easily able to respond with perfect accuracy when stimulus and response were all within a hand. In the between-hand condition, Case J.W., the fully sectioned patient, was unable to cross-integrate the information in either direction (5/18 left to right and 2/18 right to left), a result consistent with other fully sectioned patients. Case E.B. however, the patient with only a partial section, showed a unique pattern of results. While she was able to cross-integrate information from the right hand to the left (17/18) she performed significantly more poorly when trying to cross-integrate information from left to right (6/18; $\chi^2=14.56$, $p<.001$).

The results confirm and extend earlier findings. The corpus callosum is clearly active in the cross-integration of sensory and motor information. When the structure is sectioned completely, sensory information arriving and being processed in one hemisphere's somato-sensory cortex remains isolated to that hemisphere. Further, when it is transmitted to the opposite hemisphere, the present results suggest the transmitted information traverses over highly specific callosal pathways. In the present instance with Case E.B., it appears that the callosal surgery included fibers that were responsible for transmitting the crucial motor information from the left hemisphere to the right. At the same time the surgery was not extensive enough to section the fibers that were responsible for allowing integration of motor information from right to left.

It should be noted the corpus callosum varies in shape and size to such an extent that it could almost be viewed as a fingerprint for any one individual brain (Oppenhiem et al., 1987). Given that variation, and given that the exact extent of the surgical section is a matter of chance, it seems highly unlikely that the kind of striking dissociation seen here will easily occur. Nevertheless, the present results are consistent with other studies that affirm the view that careful assessment of the functional capacity of remaining neuronal systems following partial commissurotomy yield rich insights into how specific brain systems are in the kinds of information they encode. In the present context, the results also suggest each hemisphere can access motor programs that allow for discrete distal response for the contralateral hand but are unable to access programs for the ipsilateral hand. In order to control the ipsilateral hand, either a message has to be sent to the opposite hemisphere via the motor pathways or the sensory pathways must be intact so each hemisphere receives the initial stimulus.

Hemisphere specialization in motor control

It is common place to think that the cortex is involved in the planning of complex movements. The simple act of picking up an apple proves to be replete with problems of control, estimation, sensitivity to feedback and all the rest. When a simple act must be done in a proper sequence, the problems appears even more complex. There have been a variety of suggestions about the cortical areas involved in storing motor programs. As already mentioned it is commonly argued that left hemisphere is specialized for this kind of activity. Yet, once again the work on split-brain patients raises problems for a simple interpretation.

Split-brain patients with extensive language in their right hemisphere can carry out sophisticated motor activities. It is also the case that split-brain patients with little or no language in their right hemisphere can also carried out complex motor activities either by imitation or in response to sensory stimulation. These data have argued against the notion that the left hemisphere is the repository of all motor engrams for complex movements. The results from these patients suggest that for many types of motor activities, each hemisphere seems to possess the necessary motor plans.

Secondly, it should be noted that current theories of motor control suggest that brain structures quite peripheral to cortex are involved in motor programming. Thus, patients with cerebellar lesions who evidence no paralysis can be quite impaired on simple motor activities such as reaching to a point in space. Here the cortex is completely intact, the basic motor system is intact but somehow the programs that manage accurate movements are disrupted. Disorders of movement have also been noted in patients with multiple sclerosis where the major pathology is in the spinal cord. While there can be some paralysis associated with this disease, it does not explain the extent to which these patients lose control of their ability to carry out simple movements.

These and other considerations argue for the fact that much of the management system for motor activity is carried out in peripheral structures. It is as if the human cortex merely organizes the constant series of possible responses that can be made and then dispatches the general instructions to sub-cortical systems for much of the moment to moment management of a motor response. This general framework, of course, does not rule out the importance of cortical mechanisms. It was clear from the disconnection work reported above that access to sub-cortical sites would appear to be highly specific and cortically controlled. Still, the role of sud-cortical systems can not be overemphasized.

In this light, it is interesting to consider, from a cognitive perspective, what is being organized at the cortical level and how it might vary in terms of cortical organization. Certainly a key feature for a sustained, cognitively driven activity is the capacity for the proper sequencing of a set of responses. This higher order dimension to motor programming, has generally been associated with the left hemisphere. It thus came as a great surprise to us to discover the capacity can vary widely in the commissure sectioned patient. We are discovering that any given test in the cognitive domain may sometimes find one patient performing better out of one hemisphere, and another patient perpormed better out of the other.

Perceptual Studies

Deducing the nature of cortical organization and how it relates to cognitive and perceptual representational systems is a task that receives assistance from many quarters. One of the major problems has been to try and identify brain processes that are associated with perceptual-cognitive processes as opposed to sensory processes. This distinction has always been honored in a neurologic setting through the appreciation of the phenomenon of agnosia. With this disorder, patients reportedly have intact sensory systems put are unaware of what seen objects are used for. For example, patients can see an apple, but not know what is until they touch it. Upon touching an object they are instantly capable of naming it and describing it.

Additionally, research on animals, in particular on animal visual systems has also provided support for the idea that sensory processes can be dissociated from one another and from perceptual processes. Here, using largely anatomical and electrophysiological techniques, visual processes such as motion detection, color detection and other primary features of visual perception are localized to different brain structures with the different channels beginning to be identified in the retina and continuing into association cortex. With these advances in animal research where experimental methods allow for controlled intervention and specificity, the idea of being able to dissociate sensory and perceptual processes takes on added importance (see Zeki, 1987).

The patients that have allowed for observations of this kind in the commissure sectioned population are those that have undergone posterior callosal section. This surgery interupts the callosal connections that interconnect the primary visual areas of the brain. The callosal fibers that maybe involved in more perceptual or gnostic aspects of stimulus processing may well still be intact. For present purposes, two paradigmatic cases of two different kinds of disconnection will be reviewed.

Case J.W. was operated on in two stages. The posterior half of the callosum was sectioned first and we were able to examine his capacity to transfer visual information between the two half brains before the remaining anterior half of the callosum was sectioned (Sidtis et al,1981). In the first weeks after the section, J.W. was easily able to name and report all stimuli presented to the right visual field but very impaired at reporting left field stimuli. Starting around the sixth post-operative week, however, J.W. began to name line drawings of common objects presented in the left visual field. What was so interesting about his ability to name these stimuli was that a careful analysis revealed that the right hemisphere was somehow not sending over to the left the actual image of the stimulus. Rather, it appeared the associated gnostic aspects of the stimulus were being activated in the right brain and that these were some how being communicated to the left brain through the remaining anterior callosum. Similar findings have recently been reported by Sugishita et al., (1986 ; 1987) in a patient with posterior section of the callosum. In a long term follow up of this patient, these investigators reported that over time, the remaining callosal fibers became able to transfer gnostic information.

When J.W. under went section of the remaining callosum, he was and has remained unable to name any left field stimuli. In a subsequent MRI, he has been found to have a complete callosal section with the unapproached anterior commissure remaining intact. With the full section, J.W. does not transfer any perceptual information between the hemispheres. Color, pattern, and brightness information can not be cross-compared, thereby leaving but one observation of interhemispheric integration. Under conditions of sustained stimulation some crude spatial information can be integrated between the disconnected half brains (Holtzman, 1984).

Case V.P., however, allows for different insights that also emphasized how specific neural systems seem to be involved with specific cognitive and perceptual functions. Her MRI revealed sparing of fibers in both the splenium and the rostrum of the corpus callosum. Sparing in the splenium suggests the possibility that visual pattern and color information might transfer between the two hemispheres. Yet in test after test in V.P. there is no such indication. It is too soon to tell whether the failure of simple transfer reflects regional differences of function within the splenium or whether it is related to the number of fibers spared, or both.

The sparing of fibers within the rostrum predicts no known interaction, since the function of the anterior commissure has remained elusive to investigation. Yet, in a series of studies carried out in collaboration with Kutas and Hillyard, there are intriguing clues as to a possible function, and further, into how the cortex codes information. First, it turns out V.P. is able to tell whether or not two words, one projected to each half brain are related. Thus, if the word “car” is flashed to one half brain and “tire” to the other, V.P. correctly responds “yes”. If the words had been unrelated, she would correctly have responded “no”. In follow up studies, it appears the nature of the transferred code was phonologically-based since, homophone foils disrupt her accuracy.

Further tests on V.P. have revealed a most remarkble interaction that was not seen in J. W. The task required V.P. to judge whether or not two words, one presented to each visual field, rhymed. There were four conditions. The words either a) did not look or sound alike, b) looked alike but did not sound alike, c) sounded alike but did not look alike, or d) both looked and sounded alike. V.P. is only able to judge correctly whether the words rhyme when the words both look and sound alike. Such a finding suggests the highly specific way in which the cortex encodes information. It appears that the visual system which is still marginally interconnected by some fibers can send some kind of verifying signal that is useful if information has already been transmitted through another modality. Without that bit of redundancies in the system, the information transferred appears to be of no use.

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