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LOGIC AND CEREBRAL HEMISPHERIC INTERACTION

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Abstract

In this paper we examine the weakest *formal languages* permitting a characterization of:

1. Certain functional asymmetries which exist between the left and right cerebral hemispheres; and
2. 'Interpretation' in natural languages.

Correlations between the weakest formal languages required provide a minimal framework for exploring hemispheric interaction, and allow formulation of constraints on the representation of certain types of information in the brain.

We present arguments supporting our hypotheses that:

1. If the left hemisphere has a 'language', that language is extensional.
2. If the right hemisphere has a 'language', that language is intensional.

These hypotheses have particularly interesting consequences for the representation of natural languages in the brain. They require that the "semantics" of natural language be a function of the left hemisphere, and the "pragmatics" of natural language be a function of the right hemisphere.

The human brain has anatomically distinct cerebral hemispheres which differ in morphology and function. Despite the differences, each hemisphere has an independent capacity for learning, emoting, thinking, and acting (Gazzaniga, 1965; Gazzaniga, 1967; Sperry and Gazzaniga, 1967); and each hemisphere has natural language potential (Geschwind, 1965a; Geschwind, 1965b). Fiber bundles connect the hemispheres enabling them to communicate and to act together in complex behaviors.

Such communication and hemispheric interaction may be treated as 'language'; thus, the brain may be regarded as having a 'language'. We speculate that if the brain has a 'language' each hemisphere must have a fragment[1] of that 'language' which is itself a 'language'. We then employ the useful but unconfirmed procedure of characterizing such hemisphere 'languages' with FORMAL LANGUAGES, arguing for certain formal characteristics required by the existence of certain functional asymmetries between the hemispheres. Correlations between the FORMAL LANGUAGES permitting a characterization of (1) the hemisphere 'languages', and (2) 'interpretation' in natural languages provide a minimal framework for exploring hemispheric interaction and allow formulation of constraints on the representation of certain types of natural language information in the brain.

1. Bases of the speculation

1.1 The hemispheres have both morphological and functional asymmetries. Geschwind and Levitsky (1968) have demonstrated that pronouced left-right morphological asymmetries exist in the temporal speech region, gyrus of Heschl, and *planum temporale*. Asymmetries are present at birth, suggesting that these reflect intrinsic and not acquired differences (Witelson and Pallie, 1973).

Pronounced functional asymmetries also exist between left and right hemispheres. The evidence of these differences derives from several sources:

> Studies of patients who have undergone surgical section of the neocortical commissures. Within limits of their underlying diseases, these patients have allowed examination of the functioning of one hemisphere independent of the functioning and knowledge of their other hemisphere (Gazzaniga, 1967; Gazzaniga, 1970; Gazzaniga, 1973; Posner and Mitchell, 1967; Sperry and Gazzaniga, 1967).
>
> Studies of patients and subjects who have undergone unilateral intracarotid infusion of amobarbital. The technique demonstrated by Juhn Wada transiently, reversibly disrupts functioning in the hemisphere ipsilateral to the injection (Bogen and Gordon, 1969; Gazzaniga, 1973; Wada and Rasmussen, 1960).
>
> Studies of patients with focal disease or trauma, which permit correlations of focal cortical lesions with impairments of specific functioning (Eisenson, 1962; Geschwind, 1965a; Geschwind, 1965b; Geschwind, 1967; Smith, 1973).
>
> Subjects studied with special techniques developed to selective stimulate one or the other cerebral hemisphere. The techniques include dichotic listening, i.e, simultaneously presenting different auditory stimuli to each ear (Kimura, 1967; Milner, 1962; Milner, Taylor and Sperry, 1968) and tachistoscopic presentation, i.e, selectively presenting stimuli in one visual hemi-environment (Gazzaniga, 1970; Nebes, 1973; Levy, Trevarthen, and Sperry, 1972).

The evidence from these sources indicates in general that the left or 'major' hemisphere is natural language-strong: it can name (Geschwind, 1967) and relate entities (Luria and Tsvetkova, 1960) and interpret discrete configurations in sequences, but it performs poorly in spatial construction and certain types of problem solving (Gazzaniga, 1970). This evidence has also been taken as indicating that the right or 'minor' hemisphere is natural language-weak: although it cannot name (Gazzaniga, 1967), it can classify by property[2] (Gazzaniga, 1970), process definite descriptions (Eisenson, 1967; Gazzaniga, 1967), and interpret temporal and spatial configurations (Milner, 1967, Smith, 1973). It performs well in temporal and spatial construction and problem solving (Gazzaniga, 1970); it has substantial natural language comprehension and independently of the left hemisphere "…can sustain auditory comprehension and arithmetic reasoning" (Smith, 1973).

Considerable evidence demonstrates that sensory stimuli are analyzed in qualitatively different ways by each hemisphere, suggesting fundamental differences in neuronal connectivity. These qualitative differences appear consistently in each sensory modality. Using dichotic presentation of melodies, Kimura (1964) has reported that in normal subjects the right hemisphere excels in processing and recognizing melodies. Shankweiler (1966) has reported that following right temporal lobectomy, patients show impaired perception of dichotically presented melodies in the left ear (right hemisphere). Gordon (1970) has reported that dichotically presented chords are better recognized by the right hemisphere, while rhythms are better recognized by the left. Halperin et al (1973) under dichotic listening conditions in normal subjects have studied the ability to recognize transitions imposed on a continuing stimulus. They report that so long as the number of transitions was less than two the right hemisphere excelled at recognition however when the number of transitions was two or more the left hemisphere excelled. These various observations suggest that the right hemisphere excels in the analysis of complex or context sensitive auditory stimuli and that the left hemisphere excels in temporal analysis of rapidly changing sequences of stimuli.

Using tachistoscopic presentation of arrays of dots, Nebes (1973) studied a group of commissurotomized patients. All were "significantly more accurate on displays in the left half-field than in those in the right suggesting that in man the right hemisphere is more competent than the left in perceiving the overall stimulus configuration." Milner and Taylor (1972) studied these same patients and report superiority in the delayed matching of tactile patterns by the right hemisphere "…thus demonstrating right hemisphere specialization for the perception and recall of spatial patterns".

These observations suggest that the left hemisphere processes stimuli by sequential analysis of its detail and transitions; in contrast the right hemisphere deals preferentially with the overall pattern of constant or unvarying stimuli. Milner and Taylor (1972) have demonstrated that complex patterned stimuli can be remembered without verbal coding thus establishing the existence of non-verbal memory. This observation disconfirms the hypothesis that the left hemisphere superiority for language rests upon memory.

1.2 Despite this lateralization of functions each hemisphere has independent capacity for learning, emoting, thinking, and acting (Gazzaniga, 1965, 1967; Sperry and Gazzaniga, 1967, Smith, 1973). Two results are of particular interest at this point:

> Studies with "split-brain" patients demonstrate that one hemisphere may be embarrassed without the other hemisphere being embarrassed or even aware that the other hemisphere is embarrassed (Gazzaniga, 1970).
>
> A study using intracarotid amobarbital demonstrated that when a patient's left hemisphere is anaesthetized, the right hemisphere can remember and later identify an object presented to it, although the patient is unable to identify the object by name (Gazzaniga, 1973).

1.3 Certain complex processes require hemispheric interaction. For example "split-brain" patients perform poorly on cross-matching tests which require that one hemisphere know what the other is doing. More complex behavior may require integration of asymmetric functions. Bogen and Bogen (1969) have reported an interesting example of asymmetric function integration: if a patient is singing a song as his right hemisphere becomes anesthetized with intracarotid amobarbital, he becomes amelodic, but continues with the proper lyrics and rhythm.

In such complex behaviors the cortices communicate principally through the *corpus callosum*, a fiber tract which transfers but does not 'translate' information. Absent evidence of left-right receptor asymmetry, each hemisphere must receive the same types of information, and functional asymmetries must be a result of central processing differences. Hemispheric interaction thus requires that the hemispheres have in common at least a partial representation of the information they process.

1.4 If the brain has a 'language' then from §1.1 follows that each hemisphere has a fragment of that 'language' and that these fragments are not identical. From §1.2 follows that each fragment must itself be a 'language'. The minimal solution of these conditions and the restriction in §1.3 requires that the 'languages' have an equivalent syntax.[4] In support of this position Gazzaniga and Hillyard (1971) have reported that each hemisphere can interpret the operation of negation.

The minimal requirements of these 'languages' and the 'languages' themselves can be characterized formally. In the next section we describe the construction of FORMAL LANGUAGES and apply that procedure to each hemisphere 'language' in turn.

2. Formal languages

Alonzo Church has proposed that a LOGIC (a SYNTAX) include a set of PRIMITIVES (a LEXICON) and a definition of well-formedness (a GRAMMAR); and that a LOGIC WITH AN INTERPRETATION be a FORMAL LANGUAGE (Church, 1956). The general procedure for the construction of a formal language requires a definition of the LOGIC and an INTERPRETATION of that LOGIC.

To facilitate the development of the necessary FORMAL LANGUAGES, we assume Church's program for a FORMAL LANGUAGE (Church 1956) with a syntatical TERM LOGIC[5] and additionally incorporate Kripke's analysis of naming and description (Kripke, 1972) into the INTERPRETATION. To develop a partial characterization of the hemisphere 'languages' we investigage a minimal formal treatment of a paradigmatic function of each hemisphere using a function well-documented in the neurological and psychological literatures and well-known to the philosophy of logic: naming and definite description.[6]

As noted in section §1.1 the left hemisphere can name and interpret the process of naming. The right hemisphere can neither name nor interpret the process of naming; however it can interpret definite description. The claims about left hemisphere function are supported by the following evidence:

i. "Split-brain" patients can name objects presented to the right hand (left hemisphere) but when objects are presented to the left hand (right hemisphere) the subject cannot name the object although he can use it properly. If pressed to name the object in the left hand the subject misnames wildly (Gazzaniga, 1970) since the left hemisphere initiates the naming but is ignorant of the object. Proper names occur normally and are used correctly in left hemisphere speech (Gazzaniga, 1970).

ii. Certain left hemisphere lesions disrupt naming and the occurrence of names in speech (Geschwind, 1967; Green, 1969). One particularly interesting case involved a patient who when presented with photographs of various familiar people could not name any person but could characterize each by definite descriptions (Whitaker, 1969).

The claims about right hemisphere function are supported by the following additional evidence:

i. "Split-brain" patients can identify (i.e, locate and choose) the proper object by definite description but cannot name the object selected (Gazzaniga, 1967).

ii. Right hemisphere anaesthesia with intracarotid amobarbital produces no noticeable disruption of naming. Left hemisphere anaesthesia disrupts naming however the subject can identify a person or object correctly by pointing but not by name (Gazzaniga, 1973).

iii. Certain right hemisphere lesions may disrupt a patient's ability to recognize people although the patient will correctly use the names of people he has failed to recognize in spontaneous speech (Jackson, 1876).

The implicit claim of asymmetric distribution is further supported by results from a modified version of the Posner physical identity-name identity test (Posner and Mitchell, 1967). Gazzaniga (1970) reports that tests with six normal subjects indicate both hemispheres are equally proficient (fast) in judging two stimuli physically identical or not (e.g. '**AA**' vs '**AB**'); the left hemisphere is significantly more proficient (faster) than the right hemisphere in judging two stimuli name-identical or not (e.g. '**Aa**' vs '**Ab**'). These functional asymmetries indicate profound differences.

2.1 *The representation of naming and definite description.*

'Naming' requires no specific syntatic apparatus; 'definite description' in standard treatments requires a syntatic DEFINITE DESCRIPTION OPERATOR, ι (Whitehead and Russell, 1910). From this it follows that the LOGIC for the left hemisphere contains NAMES as TERMS (in addition to other as yet unspecified linguistic predicates); the LOGIC for the right hemisphere contains DEFINITE DESCRIPTIONS as TERMS (in addition to other as yet unspecified predicates relating context and possible worlds).

By virtue of their syntatic form the LOGICS for both the left and the right hemisphere contain a certain minimal set of shared OPERATORS, which included negation, conjunction and OPERATORS required to define and process quantification (Carnap, 1961).The interpretation for these OPERATORS may be hemisphere-specific. In addition to this minimal set of shared OPERATORS the LOGIC for the right hemisphere must contain at least a DEFINITE DESCRIPTION OPERATOR, ι .

2.2 *Interpretation of naming and definite description.*

Kripke (1972) argues that a name is a RIGID DESIGNATOR, that is, any act or event of naming some INDIVIDUAL, x, by $\ulcorner x \urcorner$ always designates x without regard to CONTEXT. Kripke's argument may be represented as an argument that (1) is a theorem of the system of naming:

$$(1) \qquad \wedge x \wedge \phi \, [\, \ulcorner x \urcorner \ \phi \, x \ \supset \mathbf{L}(\ulcorner x \urcorner \ \phi \, x\,)\,]$$ [7]

where ϕ represents every true predicate which holds of an INDIVIDUAL and its name, and **L** represents logical necessity.

From (1) it follows that the system of naming contains a PREDICATE (or OPERATOR) of logical necessity **L**. By the definition of logical necessity (Hughes and Cresswell, 1968), (2) must also be a theorem of that system:

$$(2) \qquad \wedge\phi \; (((\phi \supset \varphi) \supset \mathbf{L}(\phi \supset \phi)) \bullet ((\phi \bullet {\sim}\phi) \supset \mathbf{L}(\phi \bullet {\sim}\phi)))$$ [8]

If both (1) and (2) are theorems of the system of naming, (3) must also be a theorem of that system:

$$(3) \qquad \wedge\phi\ (\phi \supset \mathbf{L}\phi) \equiv (((\phi \supset \phi) \supset \mathbf{L}(\phi \supset \phi)) \bullet ((\phi \bullet \sim \phi) \supset \mathbf{L}(\phi \bullet \sim \phi)))$$

If (3) is a theorem of the system, that system is extensional by definition (Hughes and Cresswell, 1968).

Kripke (1972) further argues that no theorem of the form (4) is true in a system of definite description in which (5) is also a theorem:

$$(4) \qquad \wedge x\ \exists y\ \wedge\psi\ [y\ \psi\ x\ \supset\ \boldsymbol{O}(y\ \psi\ x)\ ]$$ [9]

where ψ represents '*is a definite description of*' and ***O*** represents some PREDICATE or OPERATOR.

$$(5) \qquad \wedge\psi\ (((\psi \supset \psi) \supset \boldsymbol{O}(\psi \supset \psi)) \bullet ((\psi \bullet \sim\psi) \supset \boldsymbol{O}(\psi \bullet \sim\psi)))$$

In other words the relationship between naming and the thing named is a LOGICAL relationship[10] holding of necessity; while the relationship between a definite description and the thing described is empirical and is dependent on the situation (CONTEXT).

Kripke's argument thus requires that the system of naming be extensional and that the system of definite description be intensional.[11] If the system of naming is extensional, the minimal LOGIC for the left hemisphere requires an EXTENSIONAL INTERPRETATION; if the system of definite description is intensional, the minimal LOGIC for the right hemisphere requires an INTENSIONAL INTERPRETATION. The two FORMAL LANGUAGES which characterize the hemisphere 'languages' thus substantially differ in INTERPRETATION.

Since the two systems share a syntax and since an extensional system may be embedded in an intensional system the two systems may have common OPERATORS. However the LOGIC for the right hemisphere is not required to have an EXTENSIONAL INTERPRETATION of these OPERATORS; and further an intensional OPERATOR such as ι will be treated as a simple extensional PREDICATE in the LOGIC for the left hemisphere.

2.3 *Intensional systems*

Following the tradition of Leibniz (1960), current logical theories use intensional systems to 'conceptualize'. In such systems INTENSIONS are processes using PROPERTIES to determine correspondences across alternative situations (POSSIBLE WORLDS). If only the LOGIC for the right hemisphere has an INTENSIONAL INTERPRETATION, the right hemisphere must interpret 'abstract' words and 'concepts' including propositional attitudes (e.g. "*believe*", "*try to*", etc.). If this be the case appropriate damage in the right hemisphere will be associated with disruptions of interpretation of 'abstract' words and 'concepts'. Eisenson (1962, 1967) has reported that in comparisons of normal subjects and subjects with right hemisphere lesions those with right hemisphere lesions experience marked difficulty in defining 'abstract' words, although they have no difficulties with 'concrete' words, and they score significantly lower in tests requiring either multiple-choice or open-ended sentence completion with 'abstract' words.[12]

This evidence together with the arguments presented allow us to propose the following hypotheses:

I. The language (logic and interpretation) for the left hemisphere must be extensional (and not intensional).

II. The language (logic and interpretation) for the right hemisphere must be intensional (and not extensional).

These two hypotheses subject to empirical confirmation have important consequences particularly for the representation of natural languages in the brain.

3. Natural languages and the brain

In the tradition of C.W. Morris (1938), a sign system is characterized through "formal relations of signs to one another" (the *syntactical dimension*), through "relations of signs to objects to which the signs are applicable" (the *semantical dimension*), and through "relations of signs to their interpreters" (the *pragmatical dimension*).

Natural languages are particular cases of sign systems. A formal treatment of natural language requires a syntax and an interpretation with respect to reference and sense. Recent formal treatments employ more precise definitions of Morris's notions. In these treatments:

> A *syntax* relates TERMS to TERMS. Syntax deals with linguistic expressions alone (Carnap, 1971; Peirce, 1931).
>
> A s*emantics* relates terms and reference. Semantics deals with linguistic expressions and the objects to which they refer (Carnap, 1971; Tarski, 1936).
>
> A *pragmatics* relates TERMS, reference users and contexts. Pragmatics deals with linguistic expressions, the objects to which they refer, the users of the expressions, and the possible contexts of use (Bar-Hillel, 1954; Montague, 1972; Peirce, 1931).[13]

The semantics and the pragmatics must be discrete. Moreover, by definition, the semantics is extensional (Church, 1964). Montague (1972) has demonstrated that a pragmatics is reduceable to an intensional logic. Thus it follows that if hypothesis I is correct, the interpretation of the semantics of a natural language must be a function of the left hemisphere; and if hypothesis II is correct, the interpretation of the pragmatics of a natural language must be a function of the right hemisphere.

4. Implications

The conclusions of section §3 allow a number of additional proposals. These proposals contain several interesting ideas but must be taken with a grain of salt.

Perlmutter and Oresnik (1973) have argued against language-specific syntactic processes. Daly, Hester, and Scott (1973) have argued against language-specific semantic/pragmatic processes. Without language-specific processes, one way languages might differ is in interpretation of verbs as extensional or intensional predicates. Under such a proposal, comparisons of the disruptions of LANGUAGE across languages correlated with lesions of a particular area of the brain should reveal different disruptions in different languages. In the bilingual or multilingual speaker, a single lesion might produce quite different disruptions in his various languages, perhaps leaving one language relatively more intact than others. Lesions, in our view, disrupt logic and manifest in behaviors such as how a person uses language.

Studies with animals (Levine and Mullins, 1973; Harris and Levine, 1965) have demonstrated hormonally induced differences in neuronal organization at the level of the hypothalamus. Analagous differences should exist at the cortical level. Further these same types of differences should appear in humans. If analogous induced differences occur in human cortex there should at least be differences in language (interpretation) processes which correlate with maturation and gender.

5. Conclusions

Although our characterization of the hemisphere 'languages' remains incomplete, our conclusions allow two types of testable hypotheses:

> Hypotheses involving relationships between FORMAL LANGUAGES and hemisphere 'languages'; and
>
> Hypotheses involving the particular characterization of the hemisphere 'languages' and thus relationships between hemisphere 'languages' and interpretation in natural languages.

Disconfirmation of hypotheses of the first type would refute any characterization of hemisphere 'languages' as FORMAL LANGUAGES. Disconfirming evidence would include a demonstration that the right hemisphere has a 'language' which contains no LOGICAL ELEMENT, or, trivially, that the right hemisphere has no 'language'. Any demonstration that a 'language' has no LOGICAL ELEMENT entails demonstrating that the 'language' has no FORMAL PROCESS.

Disconfirmation of hypotheses of the second type would refute our characterization of hemisphere 'languages' but would not refute our general approach (i.e, would not refute any characterization of the 'languages'). According to our hypotheses INDIVIDUALS will be treated as atomic entities in the left hemisphere as 'consisting of properties in the right hemisphere. In this case disconfirming evidence would include a demonstration that individuals are treated as identical formal entities in both hemispheres (Church, 1964).[14] [15]

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NOTES

1 We understand "fragment" to mean specifically that part of the "communicative function particular to the hemisphere."

2 Gazzaniga (1973) has suggested that the right hemisphere can classify words by property (e.g. ±animate, ±human, etc) and apparently can also select ‘possible words’ (i.e, accidental lexical gaps) from sets of nonsense words.

3 The asymmetries which occur in each modality should reflect analogous developmental stages. Pettigrew and Freeman (1973) have demonstrated relationships between early visual environment

and the organization of higher level cells in the visual system of the cat. Similar relationships between early environment and the organization of higher level cells should occur in each sensory modality.

[4] We understand equivalent syntax to be at least equivalent in weak generative capacity. In this approach a formula might be either well-formed in both LOGICS, but interpretable in only one LOGIC, or well-formed in both LOGICS, and interpretable in both LOGICS, but interpreted differently in each LOGIC.

An alternative and more powerful approach would employ a common META-LANGUAGE. This solution is unacceptable for several reasons:

> i. Any META-LANGUAGE must be constrained to preserve experimentally demonstrated functional asymmetries. The META-LANGUAGE constraints must define disjoint META-LANGUAGE fragments in the LANGUAGE for the left hemisphere, but not in the LANGUAGE for the right hemisphere, and further, such that spatial, non-discrete processes are interpretable in the LANGUAGE for the right hemisphere, but not in the LANGUAGE for the left hemisphere. Disjoint META-LANGUAGE fragments do not allow the necessary inter-hemispheric communication, by definition.
>
> ii. Each hemisphere would be required to 'translate' its own 'language into the META-LANGUAGE before information could be transmitted across the corpus callosum. There is no evidence of such paired functions in the brain, neither is there evidence for the loss or disruption of only half of such a capacity. Thus there is no evidence for the existence of either a META-LANGUAGE or a META-LANGUAGE capacity.

[5] The hypothesis that the languages for the hemispheres have a common syntax, and that this can be modelled in a TERM LOGIC, is testable: this constraints the co-occurrence of PRIMITIVES of the LANGUAGE. For instance, although this allows predication of a TERM, it does not allow predication of an OPERATOR. By this hypothesis, if a PRIMITIVE is an OPERATOR in the LOGIC for one hemisphere, but a PREDICATE in the LOGIC for the other hemisphere, that PRIMITIVE cannot serve alone as a logical object of a higher predicate.

[6] These particular and restricted notions of naming and definite description take a name to be a proper name, and a definite description to be a description of the form 'the x such that ψ (x)', for example, "the man who destroyed Hadleyberg".

[7] That is, for all INDIVIDUALS (x), and for all relations holding of "...*names*…", ⌐x¬ names x implies it is necessarily true that ⌐x¬ names x. In this situation, "*names*" is a transitive verb.

[8] (2) is designed to insure that the equivalence between (1) and (2) holds only if the antecedent in (1) is true.

[9] For all INDIVIDUALS (x), there is some y such that for all relations holding of "*a definite description of ... as* ... ", a definite description of x as y implies (possibly, etc.) the definite description of x is y.

[10] 'Logical relationship' in the classical sense, that is, 'logically true'.

[11] That is, naming is an extensional process; and a system which models only the process of naming, an extensional process, is an extensional system. An intensional system may contain particular extensional processes, but the terms which correspond to those processes must have a rigid

interpretation (i.e, that interpretation must be an extension, and that extension must be the same in all contexts in which it '*exists*').

[12] If the phenomenon tested is in fact correlated with 'abstract' (Benton, 1973).

[13] In this framework, "*semantics*" means "extensional semantics'*; "*intensional semantics*" includes "*pragmatics*". We recognize these distinctions to avoid confusion with similar linguistic terminology.

[14] One possibly related set of observations concerns developmental stages in children. Kohlberg (1969) has reported that children first treat all possible individuals as real, later distinguish between real and unreal individuals, and still later, come to regard unreal individuals as internal in origin. The distinction between real and unreal individuals corresponds to a distinction between individuals with a reference, and (possible) individual concepts. His data suggest that children distinguish between real and unreal individuals only after much of the corpus callosum has myelinated. Perhaps for children, "monsters" are possible individuals, that is, unreal sets of properties.

[15] Our characterization additionally predicts hemispheric differences at least in:

i. Interpretation of the concept of 'time'.

ii. Interpretation of the concept of (mathematical) 'number'.

iii. Interpretation of description.

This characterization requires hemispheric differences in the organization of memory.

BIBLIOGRAPHY

Bar-Hillel, Y. 1954. Indexical expressions. *Mind*, **6**:359.

Benton, AL. 1973. Personal Communication.

Bogen, JE and Bogen, GM. 1969. The other side of the brain III: the corpus callosum and creativity. *Bull Los Angeles Neurological Society*, **34**:191.

Carmon, A and Nachshon, I. 1971. Effects of unilateral brain damage on perception of temporal order. *Cortex*, **7**:410.

Carnap, R. 1934. Logical Syntax of Language. Vienna.

Carnap, R. 1961. On the use of Hilbert's ε-operator in scientific theories. In Y Bar-Hillel *et al*. (eds.) Essays on the Foundation of Mathematics. Amsterdam: Magnes Press.

Church, A. 1956. Introduction to Mathematical Logic: I. Princeton: Princeton University Press.

Church, A. 1964. The need for abstract entities in semantic analysis. In JJ Katz and JA Fodor (eds.) The Structure of Language. Englewood Cliffs: Prentice-Hall.

Church, A. 1971. A formulation of the logic of sense and denotation. In P Henle *et al.* (eds.) Structures, Methods and Meaning. New York: Liberal Arts Press.

Church, A. 1973. Outline of a revised formulation of the logic of sense and denotation. *Nous*, **7**:23.

Daly, DD. 1973. Cerebral localization. In AB Baker (ed.). Clinical Neurology. New York: Harper and Row.

Daly, DM, Hester, TR, and Scott, JR. 1973. Some arguments for language-specific logical processes. Handbook of the International Linguistics Association. (18th Annual Conference on Linguistics. Arequipa, Peru. **18**:22). New York: ILA

Eisenson, J. 1962. Language and intellectual modification associated with right cerebral damage. *Lang Speech*, **1**:49.

Eisenson, J. 1967. Discussion. In C Millikan and F Darley (eds.). Brain Mechanisms Underlying Speech and Language. New York: Grune and Stratton.

Frege, G. 1882. *Uber Sinn und Bedeutung*. Zertschriff fur Philosophie und Philosophischw Kritik. **100**:25 translated in H Feigel and W Sellers (eds.) 1949. Readings in Philosophical Analysis. New York: Appleton-Century-Crofts.

Gazzaniga, M. 1965. Psychological properties of disconnected hemispheres in man. *Science*, **150**:372.

Gazzaniga, M. 1967. The split-brain in man. *Sci Am*, **217**:24.

Gazzaniga, M. 1970. The Bisected Brain. New York: Appleton Century Crofts.

Gazzaniga, M. 1973. Personal Communication.

Gazzaniga, M, Bogen, JE., and Sperry, RW. 1965. Observations on visual perception after disconnection of the cerebral hemispheres in man. *Brain*, **88**.

Gazzaniga, M and Hillyard, SA. 1971. Language and speech capacity of the right hemisphere. *Neuropsychol*, **9**:273.

Geschwind, N. 1965a. Disconnexion syndromes in animals and man I. *Brain,* **88**:237.

Geschwind, N. 1965b. Disconnexion syndromes in animals and man II. *Brain*, **88**:585.

Geschwind, N. 1967. The varieties of naming errors. *Cortex*, **3**:97.

Geschwind, N and Levitsky, W. 1968. Human brain: left-right asymmetries in temporal speech region. *Science*, **161**:168.

Gordon, HW. 1970. Hemispheric asymmetries in the perception of musical chords. *Cortex*, **6**:387.

Green, E. 1969. Phonological and grammatical aspects of jargon in an aphasic patient: a case study. *Lang Speech*. **1**:103.

Hall, MM, Hall, GC, and Lavoie, P. 1968. Ideation in patients with unilateral or bilateral midline brain lesions. *J Abnorm Psychol*, **73**:526.

Halpern, Y, Nachoshon, I, and Carmon, A. 1973. Shift of ear superiority in dichotic listening to temporally patterned non-verbal stimuli. *J Acoust Soc Am*, **53**:46.

Harris, GW. 1964. Sex hormones, brain development and brain function. *Endocrinol*, **75**:627.

Harris, GW and Levine, S. 1965. Sex differentiation of the brain and its experimental control. *J Physiol* (London), **181**:379.

Hermes, H. 1965. Term Logic with Choice Operator. New York: Springer-Verlag.

Heubel, DH and Wiesel, TN. 1962. Receptive fields, binocular interaction, and functional architecture in the cat's visual cortex. *J Physiol*, **16**:106.

Hughes, GE and Cresswell, MJ. 1968. An Introduction to Modal Logic. London: Methuen.

Jackson, JH. 1876. Case of large cerebral tumor without optical neuritis and with left hemiplegia and imperception. *Royal London Opthomological Hospital Reports*, VIII.

Kimura, D. 1964. Left-right differences in the perception of melodies. *Qtr J Exp Psychol*, **16**:355.

Kimura, D. 1967. Functional asymmetries of the brain in dichotic listening. *Cortex*, **3**:163.

Kohlberg, L. 1969. Stage and sequence: the cognitive-developmental approach to socialization. In Goslin (ed.) Handbook of Socialization Theory and Research. Chicago: Rand McNally.

Kripke, S. 1972. Naming and necessity. In G Harman and D Davidson (eds.) Semantics of Natural Language. Dordrecht: Reidel.

Leibniz, GW. 1960. Two fragments from Leibniz. In CI Lewis. A Survey of Symbolic Logic. New York: Dover.

Levine, *S*, and Mullins, Jr. RF. 1966. Hormonal influences on brain organization in infant rats. *Science*. **152**:1585.

Levy, J, Trevarthen, C, and Sperry, RW. 1972. Perception of bilateral chimeric figures following hemispheric deconnexion. *Brain*, **95**:61.

Luria, AR and Tsvetkova, LS. 1960. The mechanism of dynamic aphasia. *Found Lang*, **4**:296.

Milner, B. 1962. Laterality effects in audition. In VB Mountcastle (ed.) Interhemispheric Relations and Cerebral Dominance. Baltimore: Johns Hopkins Press.

Milner, B. 1967. Brain mechanisms suggested by studies of temporal lobes. In C Millikan and F Darley (eds.). Brain Mechanisms Underlying Speech and Language. New York: Grune & Stratton.

Milner, B and Taylor, L. 1972. Right-hemisphere superiority in tactile patterns-recognition after cerebral commissurotomy: evidence for non-verbal memory. *Neuropsychol*, **10**:1.

Milner, B, Taylor, L, and Sperry, RW. 1968. Lateralized suppression of dichotically presented digits after commissural hemi-section in man. *Science*, **161**:100.

Montague, R. 1970. English as a formal language. In B Visentini *et al*. (eds.). Linguaggi nella società e nella tecnica. Milan: Edizioni di Comunitá.

Montague, R. 1972. Pragmatics and intensional logic. In G Harman and D Davidson (eds.) Semantics of Natural Language. Dordrecht: Reidel.

Morris, CW. 1938. Foundations of the theory of signs. In the Encyclopedia of Unified Science. **1**:2. Chicago: University of Chicago Press.

Nebes, RD. 1973. Perception of spatial relationships by the right and left hemispheres in commissurotomized man. *Neuropsychol*, **11**:285.

Peirce, CS. 1931. Collected Papers. Cambridge: Harvard University Press.

Perlmutter, DM and Oresnik, J. 1973. Language particular rules and explanation in syntax. In SR Anderson and P Kiparsky (eds.). Festschrift for Morris Halle. New York: Holt, Reinhart, and Winston.

Pettigrew, JD and Freeman, RD. 1973. Visual experience without lines: effect on developing cortical neurons. *Science*, **182**.

Posner, MI and Mitchell, RF. 1967. Chronometric analyses of classification. *Psychol Review*, **74**:392.

Shankweiler, D. 1966. Effects of temporal-lobe damage on perception of dichotically presented melodies. *J Comp Physiol Psychol*, **62**:115.

Sperry, RW and Gazzaniga, M. 1967. Language following surgical disconnection of the hemispheres. In C Millikan and F Darley (eds.) Brain Mechanisms Underlying Speech and Language. New York: Grune and Stratton.

Tarski, A. 1936. Grundlegung der wissenschaftlichen Semantik. *Actes du Congres International de Philosophe Scientifique*. Pans.

Wada, J. and Rasmussen, TR. 1960. Intracarotid injection of Sodium Amatyl for the lateralization of cerebral speech dominance, experimental and clinical observations. *J Neurosurg*, **17**:266.

Whitaker, H. 1969. On the representation of language in the human brain. *Working Papers in Phonetics #12*, UCLA.

Whitehead, AN and Russell, BAW. 1910. Principia Mathematica: I. Cambridge: Cambridge University Press.

Witelson, SF and Pallie, W. 1973. Left hemisphere specialization for language in the newborn: neuroanatomical evidence of asymmetry. *Brain*, **96**:641.

Appendix A