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Cerebral asymmetry during visual pattern recognition: A dynamic model

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City University of New York, 1987

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CEREBRAL ASYMMETRY DURING VISUAL PATTERN RECOGNITION: A DYNAMIC MODEL

by

WENDY EISNER

A dissertation submitted to the Graduate Faculty
in Psychology in partial fulfullment of the
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Abstract

CEREBRAL ASYMMETRY
DURING VISUAL PATTERN RECOGNITION:
A DYNAMIC MODEL

by

WENDY EISNER

Adviser: Professor Stanley Novak

The current study explored pattern and magnitude of asymmetry during spatial frequency recognition. Effects of (a) frequency, gender, and stimulus familiarization on processing and (b) asymmetry magnitude and frequency range on proficiency were examined.

Ten male and 10 female dextral young adults performed a same/different recognition task to black-and-white checkerboard stimuli (1-3.9 cycles per degree [cpd]) in which 2 cpd was the standard. Each stimulus pair was successively presented parafoveally for 150 ms in either the right (RVF) or left visual field (LVF). Absolute accuracy (percent correct), sensitivity (d'), and relative accuracy (visual field advantage index [VFAI]) were used to measure recognition.

In the VFAI data, a LVF advantage emerged at F1 (1.4 cpd) and F3 (2.3 cpd), and a RVF advantage, at F2 (1.7 cpd) and F4 (2.8 cpd). In the percent correct and d' data, significant Frequency x Visual Field interactions were

found. These results suggest an effect of frequency on direction of advantage determined predominantly by sensitivity and dependent on the Frequency x Task Difficulty interaction. The above-described VFAI pattern varied with stimulus familiarization.

Gender differences emerged that suggest possible bases of male superiority in visuospatial, and female superiority in facial, processing reported in the literature. The former may be due to males' maintaining higher criteria to RVF presentations, and having greater sensitivity to LVF presentations, than females; the latter, to the females' capacity to select the most efficient processing mode for a given stage of stimulus familiarization when processing 2-3 cpd, the most salient frequencies of facial stimuli.

The VFAI data and the correlations between magnitude of advantage and absolute accuracy suggest that the successful solution of difficult tasks entails qualitatively and quantitatively different processing than that of easy ones. The former demand use of the hemisphere opposite to that used by the latter within the same frequency range and a greater amount of unilateral activity than that used by the latter. Post-hoc analyses of the significant frequency effects found in the percent correct and d' data suggest that task difficulty is a more salient determinant of recognition accuracy than frequency range.

The current experiment is compared with Previc's (1982) and Sergent's (1982a). Suggestions concerning (a) modification of the spatial frequency model of hemispheric specialization (Sergent, 1982a), (b) emergent processing level and underlying neural mechanisms of such specialization, and (c) the design of future research on this topic are presented.

In sum, the nature of a given Spatial Frequency x Visual Field effect depends on stimulus, subject, and task characteristics; time (degree of stimulus familiarization and processing stage); and dependent variable. Hence, the most accurate way of conceptualizing about this effect is in terms of one hemisphere's being specialized for recognizing a given frequency range, not in an absolute sense, but rather under specified conditions.

ACKNOWLEDGEMENTS

Intellectual creativity is not qualitatively different from creativity at any level of organization in nature: Ideas, plants, minerals, and animals alike require conditions conducive to conception and growth to reach maturity.

For example, the following practical, emotional, and intellectual conditions were required for my writing the current thesis: funding; motivation; guidance and feedback from experienced researchers in this field; library services for the literature search; laboratory and computer facilities for slide generation, data collection, data analysis, and word-processing; and a subject pool.

I consider myself extremely fortunate in that, both professionally and personally, I received the inspiration and nourishment I needed to complete the current work. Concerning my thesis committee, I have always felt that every one of its members, namely, Dr. Stanley Novak, my mentor; Drs. Gerald Turkewitz and Martin Chodorow, my in-house readers; and Drs. James Gordon and Vance Zemon, my outside readers, was extremely generous: They each seemed to give and share all that they knew concerning any given problem.

Further, they were always available when I called them; they gave my concerns their total attention; they listened to my questions carefully and considered them deeply and fully. Finally, they all possess wonderful senses of humor, maintained an overall perspective throughout the long and

arduous process of completing my thesis, and expressed confidence in my intellectual abilities. (They were able to "see the forest for the trees" when I felt caught climbing a single tree!) These qualities were extremely helpful at moments of utter exhaustion, frustration, and doubt intrinsic to the task-at-hand.

Considering each committee member individually, I would like to thank Stan for his responsiveness to my mode of working; he respected my need to think and work independently at a self-defined pace. Further, at many critical moments during the genesis of this thesis, such as the written and oral presentations of the topic proposal and the interpretation of data, Stan provided me with valuable perspectives and insights that helped direct my work.

Finally, I appreciate Stan's assistance with the practical aspects of my research: (a) He trained me in the technical aspects of electrophysiological research and, hence, contributed to the "sister" study of the current one; and (b) he was instrumental in the assignment of lab assistants when necessary and my attaining an award that granted me one year of research without teaching.

Second, I would like to thank Gerry for his overall intellectual direction: (a) The initial conception of the current study was a direct outgrowth of his lateralization and facial recognition research, and (b) I found that working with Gerry involved entering the world of lateralization research: He continually introduced me to and informed me of investigators, meetings, lectures, and publications concerning this topic. The net result of his earnest enthusiasm, genuine curiosity, and spirit of cooperation with respect to lateralization research is to connect the physically separate labs devoted to this topic into one intellectually continuous lab.

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proposal; he translated my ideas into the paradigm that I ultimately adopted. I further appreciate his input concerning visual evoked potential technology to the design of the "electrophysiological version" of the current psychophysical study. In a more pragmatic vein, I would like to thank Vance for lending me the slides that I used to generate my stimuli.

Concerning contributors to my thesis other than my committee members, I would first like to thank the following parties who offered financial support for this project and, hence, in the most fundamental sense, made it possible: the Biopsychology program of CUNY; the Helena Rubenstein Foundation; and my parents, Nate and Fran Eisner.

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I would next like to thank another group of people who helped realize this project, namely, the subjects. Relatives, friends, and Hunter College undergraduates (members of my own as well as my colleagues' classes) generously volunteered to partake in either the pilot studies or the experiment proper, and I am most thankful for their cooperation, patience, and even enthusiasm!

I am also deeply grateful to a long list of relatives, friends, and colleagues who provided me with moral support for the duration of this demanding undertaking. Although I cannot name them all due to space limitations, I thank each of them for helping me see the light at the end of the tunnel when I could not and convincing me that I would reach that light when I did not feel that I would.

I would like to specifically mention a few of these people. Family members include: my parents (named above); my sister, Ms. Susan Eisner; my brother and sister-in-law, Dr. Mark Eisner and Mrs. Tricia Beatty-Eisner; my aunt, Mrs. Selma Gordon; my cousins, Dr. Frederica Linick, Ms. Barbara Linick, Ms. Jennifer Linick, Dr. Sid Horowitz, and Mrs. Nina Bennett; and my "in-laws," Mr. Bill Beatty and Mrs. Ronnie Beatty.

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I would like to conclude my acknowledgements by noting that it is extremely difficult to draw the line concerning the contributors to a project as complex as the current one. Its conception was due to many sources prior to the day in 1984 when I began writing my thesis topic proposal; likewise, the sources of emotional support enabling me to complete this project existed prior to that date.

For example, my interest in the interface of visual perception and cognitive processes dates at least back to my undergraduate education when I read Immanuel Kant's discussion concerning his notion that concepts without percepts are empty, and percepts without concepts are blind, and sources of support for my research interests likewise date back to my undergraduate professors, including: Dr. Anne Congleton, Dr. Ingrid Stadler, Ms. Alice Wingwall, and Dr. Whitney Chadwick.

Further, in citing the people whom I have known personally during the course of my research as the "conditions conducive to the conception and growth" of my thesis, I have overlooked other factors that also constitute these conditions. For example, certain articles, like those of Dr. Brenda Milner, were as instrumental in the development of the current work as were my discussions with people mentioned above. Hence, I would like to acknowledge all those investigators who built and currently constitute the research traditions concerning cerebral asymmetry, the visual system, and recognition memory.

Two other factors besides people I knew personally that nourished the development of my thesis provided me with emotional support: (a) the repetoires of classical and romantic chamber music and (b) the companionship of my dog, Munchkin. Both helped me continue during the solitary and, at times, seemingly endless period of writing my thesis.

While writing these acknowledgements, the following song lyrics have been running through my mind: "the wind beneath my wings." I have felt that everyone and everything I have cited herein have provided me with the elements I required to proceed with this project. I acknowledge and appreciate that they have been "the wind beneath my wings," and I dedicate this work to all of them.

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[1] INTRODUCTION

> "Even though some of the objects have been presented previously, the monkey, nonetheless, examines such objects as if they were being presented for the first time." (Klüver & Bucy, 1938, p. 39)

> "One patient . . . identified a bicycle as a pole with two wheels, one in front, one in back." (Hécaen & Albert, 1978, cited in Kolb & Whishaw, 1985, pp. 213-214)

The above two descriptions refer to behavior typical of visual agnosia or psychic blindness (Klüver & Bucy, 1938). This recognition disorder, first observed by Brown and Schafer (1888, cited in Gross, 1973), is characterized by (a) normal perceptions accompanied by abnormal comprehension of the meaning of those perceptions, that is, a dissociation between an object and its context or use (Teuber, cited in Benson, 1984) and (b) discontinuity of experience.

So striking is this recognition dysfunction that one cannot help but appreciate the fragility and complexity of the capacity to recognize and wonder how recognition works in normals. How the visual and mnestic systems of the human brain are functionally organized to yield the capacity to know that one has seen a given patterned stimulus on a prior occasion is the fundamental question of this study.

Lesion studies, the precedent research concerning visual pattern recognition, did not systematically manipulate stimulus and subject characteristics. Stimulus patterns ranged from abstract designs to representational faces (Milner, 1968); the subjects, from adolescent to middle-aged. The current study, on the other hand, varied only the size (spatial frequency) of pattern elements in checkerboard stimuli and analyzed gender differences in young adults to test the aspects of pattern recognition processing and proficiency specified in the following five hypotheses:

1. The human cerebral hemispheres are specialized for spatial frequency processing (Sergent, 1982a).

2. Gender differences in proficiency, and lateralization patterns and magnitude during visuospatial processing exist (de Lacoste-Utamsing & Holloway, 1982; Turkewitz & Ross-Kossak, 1984).

3. Low spatial frequencies are sufficient for accurate pattern recognition (Harmon, 1973).

4. Lateralized processing during pattern recognition correlates with improved accuracy (Ross & Turkewitz, 1982).

5. Lateralized processing during pattern recognition is a function of stimulus familiarization (Ibid.).

The significance of studying visual pattern recognition is three-fold. First, information concerning how the interaction among cerebral organization, subject characteristics, and stimulus parameters mediates pattern recognition in normals can be used clinically to help localize sources of recognition deficits in abnormals.

Second, this study in conjunction with a planned subsequent one using event-related potentials (ERPs) recorded over parietal, occipital, and temporal sites can help specify the processing level at which hemispheric asymmetry for spatial frequency recognition emerges. Third, the current findings have implications for recognition processing and proficiency vis-à-vis more complex patterned stimuli such as faces.

The following three subsections of the Introduction thoroughly define the terms <u>hemispheric specialization</u>, <u>pattern</u>, and <u>recognition</u> so that the notion of hemispheric specialization during pattern recognition processing (discussed in the fourth subsection) can be better understood. Included therein are the evidence and counterevidence for each of the five above-listed hypotheses. The fifth and final section concerns the methodological approach selected to test the current hypotheses. It describes and provides the rationale for the experimental design, procedure, and data analysis; it also states the expected results.

Although the entire Introduction should be read for maximal understanding of the five hypotheses being tested, the following five subsections may be read for a minimal understanding:

Hypothesis	1	-	Subsection	1.4
"	2		"	1.1/4
"	3		"	1.2/5
"	4		"	1.1/6
"	5		"	1.1/9

1.1] HEMISPHERIC SPECIALIZATION

"What, how, and whence" are the three fundamental questions requiring answers to adequately define the term hemispheric specialization, according to the neuroscientist H.- L. Teuber (1974). Thus, the following topics that address these questions are discussed herein:

1. Its dual usage, sometimes as an absolute concept, and other times, as a relative one.

2. The primary models of cerebral organization with which it is consistent.

3. The specific behavioral dichotomies to which it traditionally refers.

4. Gender differences in hemispheric specialization.

5. The fundamental models of interhemispheric interaction.

6. Its adaptive advantages.

7. Its evolution.

8. Its ontogenetic development.

9. Its sensitivity to familiarization effects.

10. A critique of two aspects of lateralization research: the dichotomania position and stimulus control.

1/ Absolute and Relative Connotations

"Nous parlons avec l'hémisphère gauche."
(Broca, 1863, cited in Kolb & Whishaw, 1985, p. 311)

The concept of unilateral cerebral dominance originated in 1836 when a physician named Marc Dax reported an association between the left hemisphere (LH) and speech (Nielsen, 1937; see Springer & Deutsch, 1985, chap. 1, for historical overview of clinical evidence for cerebral asymmetries). The formal study of this concept is attributed to the surgeon Paul Broca who, in the 1860s and 1870s, systematically and extensively examined language mediation by the LH.

Both the terminology and their conceptual referents in the nineteenth and twentieth century literature on this topic are loosely defined and ambiguous. Such terms as specialization, advantage, and superiority are used interchangeably to refer to one or more of the following three meanings: competence, relative dominance, and relative proficiency.

Competence, Relative Dominance, and Relative Proficiency

The competence notion is an all-or-none concept, that is, the "specialized" hemisphere can mediate a particular skill that the "unspecialized" hemisphere cannot. In contrast, the dominance and proficiency notions are graded, that is, both hemispheres can mediate a given skill. Dominance denotes that the specialized hemisphere contributes a greater proportion of activity than the unspecialized one (Bever, 1975); proficiency, that the specialized one performs a given task better than the unspecialized one.

Hence, the former view connotes that one hemisphere does all of the "labor" and the other does none in a given task. The latter two, on the other hand, propose that both hemispheres divide the labor between them; the one that does more or better work is referred to as specialized for that task. According to these latter two relativist definitions,

> "the essence of hemispheric specialization is only that each hemisphere is more involved and possibly more efficient than the other in mediating some . . . tasks . . . . The demonstration of the existence of hemisphere specialization only requires that the relative contribution of the hemispheres in mediating that task can be shown to be unequal." (Witelson, 1985a, p. 38)

Examples of these three meanings follow. In the assertion that the right hemisphere (RH) is putatively specialized for the holistic type of cognitive strategy, and the LH, for the analytic type, specialization connotes:

1. The RH is capable of mediating holistic, and incapable of mediating analytic, processing; conversely, the LH is capable of analytic, and incapable of holistic processing (the competence sense).

2. Both the RH and LH are capable of both strategy types, but the RH's degree of involvement during holistic processing is relatively greater than that of the LH, and the LH's degree of involvement during analytic processing is relatively greater than that of the RH (the dominance sense).

3. Both the RH and LH are capable of both strategy types, but the RH's performance in holistic processing exceeds that of the LH, and the LH's performance in analytic processing exceeds that of the RH (the proficiency sense).

Historically, clinical data, such as the lesion studies of Broca (cited in Springer & Deutsch, 1985, chap. 1) and the commissurotomy studies of Bogen, Gazzaniga, Sperry and their colleagues (1960s, cited in Springer & Deutsch, 1985, chap. 2) have fostered the former absolutist notion. In contrast, data from normals have fostered the latter two relativist notions. A standard definition of hemispheric specialization has not been stipulated by these different research groups. It should be noted that the relative proficiency concept is the one adopted in the current study.

Synonyms for Hemispheric Specialization

It is also important to note that, throughout the literature, the terms asymmetrical and lateralized are used synonomously with the phrase the hemispheres are specialized. Asymmetrical denotes that a given function or structure is not shared by the homotopic area in the contralateral hemisphere; conversely, symmetrical functions or structures are mirror images of one another (Kolb & Whishaw, 1985, p. 161). When the phrase functional asymmetry is used without further explanation, it connotes RH specialization for nonverbal, and LH specialization for verbal, processing (Kimura, 1973; Milner, 1971).

In addition to meaning functionally or structurally different between hemispheres, the term lateralized is used with respect to stimulus presentation; lateralized input is a stimulus presented to one cerebral hemisphere at a time.

2/ Relationship to Primary Models of Cerebral Organization

> "Every part of the brain is involved in language with each part making some special contribution. The relevant question was not where language is localized

> but what contribution is made by each part of the cortex." (Hughlings-Jackson, paraphrased in Kolb & Whishaw, 1985, p. 317)

Depending on whether a given hemisphere and the behavior that it mediates are respectively viewed as unitary (macro level) or multiple (micro level) systems, the hemispheric specialization (also called lateral asymmetry) model of cerebral organization can be categorized as either a functionally localized or aggregate field type of brain organization. The functional localization model postulates that a single behavior is mediated by neural activity within a single cerebral locus. In contrast, the aggregate field (also called mass action and sensorium commune) model proposes that a single behavior is mediated by activity in many cerebral loci.

Although these two models seem to be conflicting, they may, in fact, be complementary: The former may be true with respect to lower processing levels (sensory), and the latter, to higher ones (perceptual and cognitive).

From the viewpoint that a single hemisphere (a) is a single cerebral locus and (b) may mediate a particular behavior, hemispheric specialization is consistent with functional localization, that is, the control of a given behavior is localized to one lateral half of the brain. From the opposing viewpoint that different regions of both hemispheres contribute to the processing of a given behavior, hemispheric specialization is consistent with aggregate field theory. (Proponents of the latter view criticize those of the former for being reductionistic.)

Brief backgrounds and sources of evidence for each of these models are provided herein to clarify this aspect of hemispheric specialization.

The Functional Localization Model

Historically, (a) phrenology (Gall, 1810, cited in Kandel, 1981a) was the conceptual forerunner of the functional localization model and (b) linguistic and sensory data have been cited to support it vis-à-vis regional and cellular processing levels, respectively.

Concerning the linguistic data, postmortem examination of aphasiac brains revealed severe anterior LH damage (Broca, 1861, 1863, 1865, cited in Kolb & Whishaw, 1985, chap. 13, p. 442). Also, postmortem examination of normal human brains showed that the planum temporale, a language-mediating structure, is larger in the LH than in the RH (Geschwind & Levitsky, 1968). Hence, these data have implicated a single brain locus, the LH, as the substrate of a single behavior, language.

Concerning the sensory data, Mountcastle (1957, cited in Kandel, 1981b) demonstrated with single-unit recordings that cat somatosensory cortex is organized in a columnar fashion such that all neurons that selectively respond to the identical submodality (e.g., joint position and hair movement) are physically located in the same vertical column. He thus showed electrophysiologically that those cells with the same function are grouped within the same structure.

The same type of cortical architecture has since been demonstrated in cat, monkey, and human visual cortex (Hubel & Wiesel, 1962, 1968). Hence, the sensory, like the linguistic, data have implicated a single brain locus (in the sensory case, the cortical column) as the substrate of a single behavior (in the sensory case, sensitivity to a particular stimulus dimension).

The Aggregate Field Model

Historically, the scientist Flourens (early nineteenth century, cited in Kandel, 1981a) formulated the notion that all sensory and motor functions are coextensive in the cerebrum. This idea provided the basis for the related notion that all cognitive functions are located throughout the cortex. The classic learning and memory studies of Lashley (1950) and the recent ERP studies of Gevins and his colleagues (1981, 1983, 1985) have yielded evidence for this theory.

Lashley showed that the extent or mass, rather than the location, of a lesion correlated with the degree of impairment during maze-learning in rats; hence, the term mass action. He also concluded, after decades of trying to localize the engram (the neural correlate of memory) in that species, that the engram is represented throughout a given region, rather than within a single, specific location. Hence, these data supported that notion that more than one area mediates learning and memory behaviors.

Gevins et al. showed that during a visual search task, simultaneous and sequential temporal patterns in many brain regions along both the anterior-posterior and lateral meridians characterized the neural ensemble activity. These researchers concluded that perceptual and cognitive tasks are nonunitary behaviors consisting of multiple stages that occur at different cerebral loci. The unique contribution of these data to the aggregate field model is the breakdown of a given behavior into a network of constituent sub-behaviors each of which is processed in different places in the brain at different times.

Just as Gevins et al. demonstrated that a visuoperceptual task is not mediated by one entire hemisphere, so did Broadbent (1974) postulate that language is not a homogeneous, indivisable behavior mediated solely by the LH. Rather, he viewed language as a compound of such qualitatively different aspects as phonetics, syntax, and semantics that are each processed in different regions of both cerebral hemispheres.

Like Broadbent, Lenneberg (1967) proposed that language is not entirely controlled by the LH:

> "It is not so much one . . . specific aspect of the brain that must be held responsible for the capacity of language acquisition, but the way the many parts of the brain interact. Thus, it is the mode of function rather than specific structures that must be regarded as the proper neurological correlate of language." (p. 170)

Lenneberg also suggested that the reason language could not be mediated by a single cerebral region is that language is part of cognition, and the various cognitive functions involved in language are widespread throughout the cerebrum.

Lenneberg explicity stated his view of language as a compound of cognitive functions:

> "Language is a manifestation of species-specific cognitive properties. There is evidence that cognitive function is a more basic and primary process than language, and that the dependence relation of language upon cognition is incomparably stronger than vice versa . . . . The cognitive function underlying language consists of an adaptation of a ubiquitous process (among vertebrates) of categorization and extraction of similarities. The perception and production of language may be reduced on all levels to categorization processes . . . . Words label categorization processes (p. 374) . . . . [Language is a] mode of calculating with categories." (p. 377)

The viewpoints of Gevins et al., Broadbent, and Lenneberg have radical implications for the notion of hemispheric specialization; the hemisphere is seen not as a unitary locus that mediates a unitary behavior, but rather as a conglomerate of many loci that mediate different behaviors.

This model, although apparently contemporary (in addition to its proponents cited herein, Allen [1983] and Le Doux [1983] have argued on its behalf), was actually suggested by earlier electroencephalogram (EEG) research. In 1939, Raney proposed that hemispheric specialization for a given behavior denotes not that the entire hemisphere mediates that behavior, but rather that a particular intrahemisheric region mediates a specific processing stage of that behavior.

Currently, hemispheric specialization is unsystematically aligned with either the functional localization or aggregate field model of cerebral organization. The circumstances under which it should be viewed according to one or the other model need be specified.

3/ Behaviors for Which the Human Brain is Laterally Specialized

> "If . . . it should be proven . . . that the faculty of expression resides in one hemisphere, there is no absurdity in raising the question as to whether perception -- its corresponding opposite -- may be seated in the other." (Hughlings-Jackson, cited in Springer & Deutsch, 1985, p. 13)

The purpose of this subsection is to specify the traditional behaviors for which the cerebral hemispheres are putatively specialized (see Table 1). It is beyond the scope of this dissertation (a) to describe the methodologies used to identify every one of these dichotomies and (b) to present the evidence and counterevidence for all of them. This information is provided herein with respect to the stimulus type and, to a lesser extent, the processing mode, dimensions in order to show how these dichotomies have been investigated and demonstrated. (Data concerning the other dimensions listed in Table 1 are mentioned in subsequent subsections in relation to particular issues and arguments being presented therein.)

Both normative and clinical studies using a wide variety of behavioral, anatomical, and physiological measures have tested whether the RH is specialized for visuospatial, and the LH for verbal, stimulus types. The evidence is presented herein prior to the counterevidence; the normal data prior to the abnormal; and within each of these

Table 1

Dimensions of Functional Asymmetry

Dimension	Right hemisphere	Left hemisphere
Stimulus type	visuospatial	verbal
	(Gazzaniga et al, 1965)	
Stimulus form	simple	complex
	(Nebes, 1974)	
Task type	"different" judgement	"same" judgement
	(Egeth & Epstein, 1972)	
Task difficulty	easy discrimination	difficult discrimination
	(Patterson & Bradshaw, 1975)	
Learning effects	highly familiar	moderately familiar
	(Goldberg & Costa, 1981; Ross-Kossak & Turkewitz, 1986)	
Processing type	parallel	serial
	(Cohen, 1973)	

(table continues)

Dimension	Right hemisphere	Left hemisphere
Processing strategy	synthetic (spatial integration)	analytic (temporal integration)
	(Levy-Agresti & Sperry, 1968)	
	appositional	propositional
	(Bogen, 1969)	
Processing unit	configuration	feature
	(Nebes, 1974)	
Processing stage	early (sensory)	late (perceptual and cognitive)
	(Hellige, 1980)	
Representational code	diffuse	focal
	(Semmes, 1968)	
Response type	gross motor	fine motor
	(Kimura & Archibald, 1974)	

discussions, the behavioral data are presented prior to the anatomical and physiological. Also, the samples and procedures that yielded these data are briefly described prior to their presentation.

After this discussion, data concerning the correlation between this lateralization pattern and hand preference, and the precedent data concerning hemispheric mediation of information-processing modes, are presented. A brief critique of some of the methods used in lateralization research concludes this subsection.

Normative Data Supporting Lateralized Control of Stimulus Type

Methods

In normals, the behavioral techniques have primarily included the divided visual field and dichotic listening paradigms with accuracy or reaction time (RT) dependent variables. Most anatomical methods have involved the postmortem examination of human cerebra at both the gross morphological (regional measurements) and microstructural (analysis of cellular components' density, interconnections, etc.) levels. Finally, physiological techniques have included those which provide real-time measures or images of electrophysiological and metabolic activity such as: the electroencephalogram (EEG), evoked (EP) and event-related potentials (ERP), regional cerebral blood flow (rCBF), and positron emission tomography (PET).

The divided visual field paradigm (Mishkin & Forgays,

1952) entails the selective activation of a single hemisphere by stimulus presentation in the visual field contralateral to that hemisphere. Hence, stimuli presented in the left visual field (LVF) are initially processed in the RH, and stimuli presented in the right visual field (RVF) are initially processed in the LH. Tachistoscopic presentation is usually used to maximize stimulus control. The same principle, that of projection from a given sensory organ to the contralateral cerebral hemisphere, underlies the dichotic listening procedure used to investigate linguistic processing.

Behavioral Data

The behavioral data yielded by divided visual field studies showing RH superiority in processing visuospatial, and LH superiority in processing verbal, stimulus material include the following. Grey or colored square-shaped stimuli presented to the RH were perceived as lighter than those presented to the LH (Davidoff, 1975). Unstructured visual stimuli presented to the RH elicited faster RTs than those presented to the LH (Jeeves & Dixon, 1970). Accuracy in the enumeration and localization of dot patterns was superior to RH than to LH presentation (Kimura, 1969).

Other behavioral studies have shown that recognition accuracy for nonsense figures presented to the RH exceeded that to LH-presented stimuli (Kimura, 1966). Also, RT to black-and-white photographs of human faces presented to the RH was shorter than that to LH presentation; RT to letter stimuli presented to the LH was shorter than that to RH presentation (Rizzolatti, Umilta, & Berlucchi, 1971). Finally, RH superiority in the processing of line orientation (Fontenot & Benton, 1972) and overlapping figures (Kershner & Jeng, 1972) in tachistoscopic divided visual field studies has also been found (both cited in D. W. Zaidel, 1985).

Anatomical Data

As mentioned above, Geschwind and Levitsky (1968) found that, in 65 out of 100 normal adult brains, the planum temporale (the supratemporal surface of the temporal lobe) in the LH is significantly longer (by 33%) and differently slanted than that in the RH. (In the remaining 35 brains, 11 were characterized by the reverse pattern, and 24, by structural symmetries. It should be noted that no handedness data were available for this sample.)

This region, part of association cortex, is referred to in the LH as Wernicke's area, that is, the posterior language area associated with comprehension functions (based primarily on aphasiac data). Geschwind and Levitsky commented that its larger size in the LH than RH is "compatible with known functional asymmetries" (p. 187).

A second anatomical asymmetry possibly correlated with LH mediation of language was observed by Scheibel et al. (1985). These investigators found that, in normal brain tissue obtained at autopsy from 8 males (6 dextral) aged 58-77 years, dentritic organization in anterior language areas (including Broca's area and associated with motor aspects of linguistic processing, e.g., speech) differed between hemispheres with respect to number of intersections and length of segments. Scheibel et al. are currently investigating the development (from birth to 6 years) and functional consequences of these dentritic asymmetries.

Physiological Techniques and Data

One physiological measure, the EEG, represents spontaneous cerebral electrical activity (1-35 Hertz [Hz]) putatively driven and coordinated by the subcortical "pacemaker," the thalamus in the brain stem. Butler and Glass (1974) found greater alpha (6-14 Hz) suppression, signifying cognitive activity, at central and posterior sites in the LH than RH in dextral adults during verbally mediated (language and arithmetic) tasks.

EPs and ERPs, two other physiological measures, are defined, and the data concerning lateral mediation of visual and verbal material are presented, below (see subsection 4.6 for definition).

A fourth physiological index, rCBF, derived from research by Roy and Sherrington (1890, cited in Kolb & Whishaw, 1985, chap. 14), is used in lateralization research as follows. A gas, xenon 133, is infused into the blood and is thereby transported to the brain. The subject then undertakes a visuospatial or verbal task. Those brain regions that are most active during task engagement contain the relatively highest levels of blood flow and, hence, the greatest xenon 133 density. These regions are identifed by xenon-sensitive monitors placed near the skull.

rCBF measures have indicated that greater metabolic activity existed in the RH than LH when subjects were involved in a picture completion task; in contrast, they showed greater LH than RH activity during verbal processing (Risberg, Halsey, Wills, & Wilson, 1975).

PET, another measure of physiological activity, involves the administration of a radioactive glucose-based tracer ([18F]-FDG) to a subject prior to task engagement. Because glucose utilization indicates metabolic activity, sites of increased glucose utilization, reflected by the emission of positron radiation from the tracers' labelled metabolic product ([18F]-FDG phosphate), represent those brain regions that had been most active during the given task. These emissions are detected by a PET scanner that reconstructs and visually displays the distribution of the tracers in the brain. The most active regions are revealed on this "map."

In dextral subjects, increased glucose utilization was found in the RH during the processing of nonverbal stimuli (musical chords) and in the LH during the processing of verbal stimuli (Mazziotta et al., 1982, cited in Phelps & Mazziotta, 1985).

Clinical Data Supporting Lateralized Control of Stimulus Type

The clinical data concerning lateral asymmetry for stimulus material have been provided primarily by epileptic and lesioned patients subjected to presurgical or surgical procedures. For example, some epileptic patients underwent commissurotomies, a procedure in which some or all of their callosal fibers (those which interconnect the cerebral hemispheres) were severed to minimize or prevent the interhemispheric spread of seizure activity. Historically, van Wagenen (1940s) followed by Bogen, Gazzaniga, Meyers, Sperry, and Vogel (1950s-1960s) (all cited in Springer & Deutsch, 1985, chap. 2) pioneered and developed this technique.

Behvioral Data

Both split-brain and lesioned subjects provided behavioral data concerning visuospatial and verbal processing tested by the divided visual field paradigm. The split-brain experiments showed that a given subject could verbally identify stimuli presented to his/her LH, but could not do so when those same stimuli were presented to his/her RH (Gazzaniga, Bogen, & Sperry, 1965). These data hence corroborated Broca's aphasiac data; both showed that the LH "speaks."

The RH was shown, in split-brain subjects, to excel in such visuospatial activities as: the perception of part-whole relations, pattern formation from block assembly, the copying of designs, the fitting of forms into molds, and the discrimination and recall of tactual and visual forms.

The response patterns in the behavioral data of laterally lesioned subjects implicated (a) RH involvement in a perceptual closure task (DeRenzi & Spinnler, 1966); (b) RH involvement in discriminating and remembering visuospatial, and LH involvement in discriminating and remembering verbal, stimuli (Milner, 1971); and (c) relatively greater RH than LH involvement in the enumeration of dot stimuli (Kimura, 1963; Warrington & James, 1967).

Physiological Data

Electrical stimulation data have provided physiological measures of hemispheric specialization for stimulus type (Milner, Ojemann, Penfield, and Rasmussen, cited in Kolb & Whishaw, 1985, chap. 14). Electrical stimulation refers to a presurgical procedure used to identify the precise site generating epileptic activity to be removed during the impending operation.

In this procedure, stimulation of a given region inhibits the function controlled by that region. Hence, when a region is stimulated and a particular behavior appears deficient, that region putatively controls that behavior. Since subjects were shown to retain their speech capacity during RH stimulation, but to lose their speech capacity during LH stimulation, the LH was implicated as the regional substrate of language (Penfield and his colleagues, 1930s, cited in Ibid.). Ojemann and his colleagues (cited in Ibid.) showed with this technique that the RH mediated line orientation and facial recognition judgements.

Counterevidence for the Above Pattern of Lateralized Control of Stimulus Type

Some counterevidence for RH superiority for processing visuospatial, and LH superiority for processing verbal, stimuli exists. One source of this counterevidence is the rapidly expanding body of literature concerning RH involvement in language. For example, a cross-cultural dichotic listening study showed RH superiority for language (consonant-vowel syllables) in a Navajo Indian sample (Scott, Hynd, Hunt, & Weed, 1979).

Second, a complete definition of language includes its motor (gestural), vocal (prosadic), meaning (semantic), and relational (syntactic) aspects (Benson, 1985a). Primarily behavioral data from both normals and abnormals have implicated the RH in the gestural, prosadic (inflection, timbre), and semantic (comprehension of humor, metaphor, and theme) aspects and the LH in prosadic (speech musculature), semantic (verbal encoding, word definitions, and object naming), and syntactic (grammar) aspects (Thatcher, 1980; E. Zaidel, 1985a).

The RH-mediated gestural aspects also include the evaluation of both nonverbal paralinguistic cues (e.g., facial expression) and the pragmatic (e.g., context, intention) dimension of language (E. Zaidel, 1985a). The RH may be relatively more involved than the left in language comprehension (the input processing level), whereas the LH may be more involved than the right in language production (the output processing level) (Searleman, 1983).

Correlation Between Lateralization Pattern Underlying

Visuospatial and Verbal Processing and Hand Preference

Behavioral and physiological measures have indicated a significant correlation between (a) lateralization pattern mediating visuospatial and linguistic processing and (b) hand preference. However, the percentages of right-handers (90% of the human population) and left-handers (10% of all humans) who demonstrate RH control of visuospatial, and LH control of verbal, processing vary with method used to investigate lateralization patterns.

Methods Used to Test Lateralization Patterns

The Wada and dichotic listening tests are the two most common methods used for this purpose. The latter method was described above. The former is a presurgical procedure administered to identify language areas of the brain so that they may be spared, if possible, during forthcoming surgery.

This procedure entails the injection of a barbituate, sodium amobarbitol, into the carotid artery in the neck. The drug is then carried by the blood to the ipsilateral cerebral hemisphere where it temporarily anesthesizes its target sites and, hence, inhibits the behaviors mediated by those sites. If a given subject retains the capacity to answer questions and to count, then the anesthesized area is not implicated as a language area; if, however, the subject's performance is deficient, then the anesthesized area is identified as a language-mediating region.

Statistical treatment of the Wada Test data has determined that 95% of the right-handers and 70% of the left-handers in the population are RH dominant for visuospatial processing and LH dominant for linguistic processing. Of the remaining 30% of the sinistral group, 15% are RH dominant for language and 15% are "nondominant" (they bilaterally represent linguistic stimuli) (Rasmussen & Milner, 1977, cited in Springer & Deutsch, 1985, chap. 1). In contrast to these physiological data, the behavioral dichotic listening data showed that a smaller percentage (80%) of the right-handers tested demonstrated the "RH-visuospatial/LH-verbal" lateralization pattern.

This discrepancy between the data yielded by these two methods may be due to two factors: (a) The Wada Test measures the given behavior in subjects with varying degrees of cerebral abnormality and (b) the Wada and dichotic listening tests do not both measure the identical process.

The first point is discussed in the Critique subsection below. Concerning the second point, the physiological measure may be tapping the speech production aspect of linguistic processing more than the behavioral measure; the behavioral measure may be tapping the effects of cognitive strategy on performance more than the physiological measure.

Anatomical Data Concerning Lateralization Pattern and Handedness

Recent anatomical data have shown that the corpus callosa in 42 adult (25- to 65-year-olds) postmortem brains were significantly larger in those of left-handers than in right-handers' (Witelson, 1985b). These data suggest one account of the correlation between bilateral control of linguistic processing and sinistrality: Because a larger corpus callosum suggests a greater degree of interhemispheric communication, the probability of bihemispheric behavioral control in left-handers exceeds that in right-handers.

Origins

Finally, the origins of (a) hand preference and (b) its relation to lateralization pattern for visuospatial and verbal processing are not well-understood.

Ontogenetic level. Hand preference is an inherited trait (e.g., if either parent is dextral, the probability that the offspring will likewise be dextral increases by a factor of 1.5 [Boklage, 1984]). However, environmental factors, such as cultural biases against sinistrality, do affect its development and incidence in the population.

Annett (1970, cited in Kolb & Whishaw, 1985, chap. 15) and Levy and Nagylaki (1972, cited in Ibid.) have proposed hypotheses concerning the mechanism underlying the inheritance of hand preference and a given lateralization pattern. Annett's theory, called the right shift theory, states that the majority of humans (the dextral group) inherits the "right shift" factor (i.e., RH dominance of visuospatial, and LH dominance of verbal, processing). In contrast, the minority of humans (the sinistral group) lacks this factor and, hence, displays inconsistent laterality patterns.

Levy and Nagylaki's model suggests that two genes control the traits under examination: One gene determines handedness, and the dextral allele is dominant; the other gene controls hemispheric representation of speech, and the LH allele is dominant.

Phylogenetic level. Although the asymmetrical control of behavior is not uniquely human, hand preference (Springer & Deutsch, 1985, chap .9), language, and the asymmetrical control of language may be uniquely human. (Note. Whether language is a human-specific behavior is a controversial issue, the resolution of which partially depends on one's definition of language. Arguments for and against this point are beyond the scope of this paper.)

The evolutionary origins of hand preference, the cerebral control of language in the hemisphere contralateral to the dominant hand (Broca's Rule, 1861, cited in Springer & Deutsch, 1985, chap. 1), and the high variability characterizing these two traits are not well-understood. Why hand preference has existed in humans since at least the time of Homo habilis two million years ago (Lewin, 1986), and how its emergence relates to the lateralized control of language and visuospatial processing require further investigation.

One hypothesis has been proposed concerning control of the preferred hand and language by the same cerebral hemisphere (the LH in most humans) (Kimura, 1979; Kimura & Archibald, 1974). This hypothesis states that the capacity for fine temporal resolution typical of the LH underlies its capacities for serial processing, fine motor control, and such aspects of language as auditory pattern discrimination and encoding. According to Kimura, fine motor control and language are closely related; the former may have been the precursor of the latter in the sense that manual gestures were used prior to vocalizations for the purposes of communicaton and expression. Evidence for this theory is discussed in subsection 1.1/7 below.

Lateralized Control of Processing Modes

In addition to possessing differential sensitivity to stimulus type, the cerebral hemispheres putatively have unique processing characteristics. The RH is hypothesized to be a synthetic and parallel processor capable of operating upon stimulus configurations; the LH is viewed as an analytic and serial processor which operates upon stimulus features (Bogen, 1969; Cohen, 1973; Levy, 1974, cited in Bryden, 1982; Levy-Agresti & Sperry, 1968; Nebes, 1974). The RH mode, characterized by the simultaneous processing of different aspects of a stimulus array, requires proficient spatial integration. In contrast, the LH mode, characterized by the sequential processing of inputs, requires proficient temporal integration.

Clinical Evidence

Clinical evidence for these two different processing modes exists. For example, when patients with constructional apraxia were instructed to copy the

Rey-Osterrieth figure, those with LH damage drew oversimplified figures in which the internal details were minimized or eliminated, and the configuration was emphasized. Those with RH damage, in contast, copied the details more precisely than the outline and drew in an item-by-item fashion (Kirk, 1985; Robertson & Delis, 1984).

The initial conception that the hemispheres differ with respect to the synthetic and analytic processing modes derived not from direct evidence, but by inference from the lesion data of Semmes (1968, cited in Kolb & Whishaw, 1985, chap. 14). Semmes observed that small RH lesions correlated with no obvious behavioral deficits, whereas small LH lesions correlated with a variety of specific deficits; large lesions in both hemispheres correlated with many deficits. She explained these differential lesion effects in terms of hemisphere-specific neural organizations.

Semmes reasoned that, in the RH, (a) the neural substrate of any given behavior was a widespread region, and (b) a variety of different behaviors were controlled by that large functional field. Hence, a small lesion representing highly localized damage had no behavioral effects because extralesion intrahemispheric intact regions remained capable of behavioral control. A large lesion, in contrast, did affect all those behaviors mediated by the entire diffuse region which had been damaged.

In the LH, according to Semmes, the neural substrate of any given behavior was a highly localized region. Hence, any given behavior entirely controlled by a small, damaged region displayed abnormality. Further, because a large region represents the summation of a number of small fields, each of which controls a specific behavior, all of those behaviors displayed abnormalities in conjunction with large lesions.

Semmes concluded from the differential pattern of behavioral deficits associated with different-sized unilateral lesions that the RH was diffusely organized, and the LH, focally organized. She hence provided the data set and interpretations which formed the foundation for the earliest conceptualization of the RH as a synthetic processor and the LH as an analytic processor.

Anatomical Evidence

Gur et al. (1980), using the xenon 133 inhalation procedure, found interhemispheric differences in the amounts of gray and white matter in the brains of 36 dextral male undergraduates. The pattern of these differences is consistent with Semmes' model.

These investigators observed that the ratio of gray to white matter in the LH is greater than that in the RH, and conversely, the ratio of white to gray matter in the RH is greater than that in the LH. Although their results pertained to anterior brain regions, McHenry et al. (1978, cited in Ibid.) and Meyer et al. (1978, cited in Ibid.) reported the same pattern of results for posterior regions.

Gray matter (the somatic and nonmyelinated fibrous components of neurons) and white matter (their myelinated fibers) each contain unique communicative properties; the former is characterized by relatively short-distance, and the latter, relatively long-distance, interneuronal communication. Hence, Gur et al. interpreted their results to indicate that within-regional (intramodal) information transfer in the LH exceeds that in the RH, and across-regional (intermodal) transfer in the RH exceeds that in the LH.

Gur et al. noted that their data support Semmes' model of the LH as focally organized and the RH as diffusely organized. In addition, they suggested an association between (a) focal organization and intramodal processing and (b) diffuse organization and intermodal processing. Their data, hence, imply that the LH is "wired" for fine sensorimotor processing, whereas the RH is preadapted for behaviors requiring multimodal coordination.

Counterevidence

Although much data support the "RH-as-parallel and LH-as-serial processor" model originally suggested by Semmes' work, some counterevidence does exist. Lewine and Elias (1985), for example, found the reverse pattern in normal dextrals in a RT visual search task with letter stimuli. Tucker, Novelly, and Isaac (1984) likewise found the reverse pattern among abnormals (with unilateral temporal and hippocampal resections) in a recall task involving visuospatial stimuli (colored circles).

Critique of Some Methods Used in Lateralization Research

All of the above-described data are considered, from the "convergent evidence" point of view, to provide convincing evidence for the hemisphere-mediated behavioral dichotomies. From a second point of view, however, they are thought to present weak evidence. The former argues that because this effect emerges when measured by many different methods, it is probably real. The latter states that some methods used to yield these data have drawbacks, discussed immediately below, that undermine their validity.

Divided Visual Field Studies

The divided visual field paradigm has been criticized on two grounds. First, a subject's response (accuracy or RT) is not a pure index of activity in the selectively activated hemisphere; hence, the interhemispheric comparisons of those responses are not true measures of hemispheric advantage. The response is confounded in two respects: (a) It represents bihemispheric activity, and (b) it represents cognitive and motor, in addition to sensory, activity. Second, a high degree of interlaboratory variability exists with respect to stimulus display and task-related parameters (Bogen, 1985).

Concerning the first point, (a) stimulus presentation in one visual field only initially selectively activates the contralateral hemisphere: After sensory reception, the neural representation of that stimulus is processed in both hemispheres; and (b) the task is often confounded: Although it appears to be purely sensory, it actually entails cognitive and/or motor processing that contribute(s) to the response (Heister, 1984; Sergent, 1983a; Witelson, 1985a). Similarly, the behavioral response is not purely sensory: It represents not the sensory stage of processing, but rather the output of the entire processing sequence.

Concerning the second point, the only standardized aspect of the divided visual field procedure is selective "initial" hemispheric activation. However, even that aspect is not truly standardized. For example, a subject's fixation on the central point to the right or left of which stimuli are presented is sometimes poorly monitored. His/her responses are interpreted to represent unilateral activation when they, in fact, represent bilateral activation.

All other methodological controls, including stimulus type, luminance, contrast, size, duration, retinal site of stimulation, set size, instructions, task difficulty, and practice trials also vary from experiment to experiment. Hence, although the behavioral data from different divided visual field studies are considered to be indices of the same processes, they, in fact, often measure significantly different processes.

Clinical Studies

The validity of the clinical data concerning hemispheric specialization for the above-listed behaviors has been questioned on theoretical and methodological grounds.

Criticisms of theory. The logic underlying the interpetation of clinical findings is the following: (a) If the brain is damaged at site X, and (b) if behavioral deficit Y is observed, then (c) site X controls behavior Y. For example, in the case of the constructional apraxic patients cited above, those with LH damage tended to omit details in their drawings; hence, the LH was concluded to be the site mediating feature analysis. This line of reasoning has been labelled the transparency principle, a name derived from the fact that a deficit due to focal damage makes transparent the structure of normal processing (E. Zaidel, 1985b).

This logic is too simplistic because, in reality, although a behavioral deficit may be associated with a lesioned site, it may also be controlled by some other unidentified damaged cerebral sites. Hence, the normal behavior may be partially controlled by those other sites (Kertesz, 1983, chap. 1; Springer & Deutsch, 1985). The reason that the deficient behavior cannot be entirely attributed to the single damaged site is that a lesioned brain is not equal to a normal brain except for the lesion. On the contrary, the putatively intact areas of a lesioned brain are often abnormal.

Some of these abnormalities arise from compensatory structural and functional changes that tend to occur after damage. Also, in the case of war-injured lesioned subjects, these abnormalities have been found to be due to missle damage at a distance from the focal lesion. This second example is especially important because some of the major evidence concerning hemispheric control of behavior, including that of Semmes, was derived from war-injured subjects. A corollary problem resulting from the fact that the functional organization of the abnormal brain may significantly differ from that of the normal one is that the behavioral data of the former may not be generalizable to the latter.

Criticisms of method. The primary methodological criticism of the clinical data is that a high degree of intersubject variability exists both within and across studies (Young & Ratcliff, 1983). When experimental groups are formed and comparisons between experimental results are made, lesioned subjects are often not precisely matched with respect to (a) site and extent of damage and (b) medication history.

Regarding the first criterion, subjects are sometimes typed as having the same functional abnormalities when they actually have qualitatively different ones. This problem occurs, for example, when subjects with disconnection syndromes caused by damaged fibers between two sites are grouped with subjects who have damage within those sites.

Concerning the second criterion, drugs are often not treated as an independent variable and, hence, confound the results. Subjects' responses, both within and between experiments, are often compared without controlling for differences in the type, dosage, and time period over which medications have been administered.

4/ Gender Differences in Proficiency and Asymmetry During Visuospatial Processing

> "We are finding that depending on the particular intellectual function we are studying, women's brains may be more, less or equally diffusely organized compared with men's. No single rule holds for all aspects of thinking." (Kimura, 1985, p. 56)

One hypothesis being tested in the current study states that gender differences exist in (a) performance and (b) direction and magnitude of asymmetry in a divided visual field pattern recognition task. This hypothesis derives from three other ones: (a) Males are superior to females in almost all visuospatial tasks except facial recognition (in that task, the reverse superiority holds); (b) pattern of asymmetry differs between the male and female brain; and (c) magnitude of asymmetry in the male brain exceeds that in the female brain.

This subsection presents the following information concerning these hypotheses: (a) Some comparative, as well as normative and clinical human, data concerning the structural aspects of sexual dimorphism in the mammalian brain; (b) some normative and clinical data supporting the gender differences in proficiency hypothesis, and supporting and opposing the gender differences in functional asymmetry hypothesis; and (c) suggestions concerning the origins of these gender differences in visuospatial processing and cerebral functional organization (see De Vries, De Bruin, Uylings, & Corner, 1984; Maccoby & Jacklin, 1974; McGlone, 1980; Springer & Deutsch, 1985, chap. 7, for reviews).

Structural Differences in Male and Female Mammalian Brain

(*Note*. Data concerning sexual dimorphisms in nonhuman primate brain are presented in the final subsection herein concerning phylogenetic origins of human gender differences in visuospatial processing.)

Microscopic Differences

Gender differences have been shown in the following aspects of cerebral cellular morphology: (a) number of neurons in the preoptic area (POA) of rat (Gorski et al., 1980, cited in Hines & Gorski, 1985); (b) length and position of dendrites in the POA of macaque (Ayoub, Greenough, & Juraska, 1983) and hamster (Greenough et al., 1977, cited in Hines & Gorski, Ibid.); and (c) type of synapse in the POA of rat (Raisman & Feld, 1973, cited in Hines & Gorski, Ibid.) (see Swaab & Fliers, 1985, for review). Sexual dimorphism has also been shown in this region in humans; the volume and number of neurons in the male POA exceeds those in the female POA (Swaab & Fliers, Ibid.).

Macroscopic Differences

Human male and female brains also differ at the macroscopic level in the following respects: (a) mean degree of encephalization such that the ratio of brain weight to height in males is larger than that in females (De Vries et al., 1984), (b) overall size of brain favoring the male (Swaab & Fliers, Ibid.), (c) skull thickness favoring the male (Picton, 1984, cited in Friedman, Boltri, Vaughan, & Erlenmeyer-Kimling, 1985), and (d) absolute size of the primary motor and sensory regions favoring the male (Horvath, Ginn, & de Lacoste, 1986). (It should be noted that no significant gender differences in absolute size of association areas were revealed by regional volumetric analysis in this same study.)

With respect to gender differences in cerebral structural asymmetries, cerebral cortex in the RH has been found to be significantly thicker than that in the LH in the male rat; in females, the reverse pattern (i.e., thicker cortex in the LH than in the RH) has been found to exist as a function of age (Diamond, cited in Kimura, 1985). Also, the cuneus, an occipital structure, is larger in the LH than in the RH in males, but larger in the RH than in the LH in females (Wada, 1976, cited in McGlone, 1980).

Next, in a regional volumetric analysis of 14 male and female adult human brains (Horvath et al., 1986), although no gender differences were found in overall magnitude of asymmetry, such differences did emerge in pattern of asymmetry. Males showed cerebral asymmetries in the prerolandic regions, whereas females showed asymmetries in the postrolandic regions. The researchers concluded:

> "We interpret the lack of sex differences in the overall degree of regional volumetric asymmetries as evidence that from an anatomical perspective, at least, global statements on the degree of lateralization in males and females are premature. Sex differences, however, in the

> patterns of asymmetry may have some functional significance." (p. 719)

A finding that did suggest sexual dimorphism in magnitude of asymmetry was that the splenium (posterior corpus callosum) in 9 male and 5 female human postmortem brains was larger and more broadly shaped in the female than male specimens (de Lacoste-Utamsing & Holloway, 1982). These data implied, according to the investigators, that an increased number of peristriate and temporal fiber connections, resulting in relatively greater interhemispheric signal transmission and functional integration, exists in female brains.

Two subsequent studies did not replicate the de Lacoste-Utamsing and Holloway findings. First, as mentioned above, Witelson (1985b) measured the corpus callosum in 42 postmortem brains of patients who had died of non-neurological diseases. She found this structure to be larger in left-handers than in right-handers, but did not find any significant gender effects.

Second, Byne, Beier, and Houston (1986) imaged (with nuclear magnetic resonance [NMR]) the midsagittal section of the corpus callosum in 15 male (mean age = 46.5 years) and 22 female (mean age = 35.9 years) brains. They reported no significant gender differences in splenium size, but a significant Age x Gender interaction effect: The cross-sectional area of the anterior sections of the corpus callosum was smaller in the brains of males over 40 than in females. These researchers also stressed the high degree of individual variability in this data set.

The different results among the above three studies are not surprising in that the samples differed with respect to number, age, health status, and state (in vivo vs. postmortem) of the brains examined.

The functional significance of many of the above-cited gender differences in cerebral anatomy have been implied, not actually demonstrated. Nonetheless, these data provide a framework that facilitates the understanding of the behavioral data presented below.

Gender Differences in Proficiency During Visuospatial Tasks

Normative behavioral data have revealed that male performance (measured by speed or accuracy) exceeds that of females in a wide variety of visuospatial tasks: the alignment of a rod to a vertical line, figure disembedding, mental rotation, point localization (Stafford, 1961; Thurstone, 1938; Witkin, 1949, all cited in McGlone, 1980), left-right discrimination, map reading, visual maze solving, position recall (see Nichelli, Manni, & Faglioni, 1983), picture assembly, and block design (McGee, 1979, cited in Springer & Deutsch, 1985, chap. 7).

Other data concerning gender differences in proficiency were yielded by divided visual field studies. Hence, they are discussed in the Asymmetry subsection immediately below.

Gender Differences in Pattern and Magnitude of Asymmetry

This subsection contains: (a) definitions of the terms pattern of asymmetry and magnitude of asymmetry, (b) a delineation of the implications of the hypothesis that magnitude of asymmetry in males exceeds that in females, (c) a critique of the methods used to test this hypothesis, and (d) presentation of the relevant data.

Definitions of Terms

When a given pattern of asymmetry vis-à-vis visuospatial and verbal processing is described, it typically gives the following information: (a) whether both hemispheres or only one is involved in the behavior(s) being examined, that is, whether a bilateral or unilateral pattern of control exists; and (b) in the case of a unilateral pattern, whether the RH is specialized for visuospatial, and the LH for verbal, processing or vice versa (the direction of specialization).

The term magnitude (degree or size) of asymmetry again refers to the case of a unilateral pattern: It specifies the amount of involvement of the specialized hemisphere during a given task. A large amount of unilateral involvement indicates a large magnitude of asymmetry; a small amount of such involvement denotes a small magnitude of asymmetry.

The measures of hemispheric involvement range from physiological indices of activation (e.g., EEG, EPs, ERPs, and rCBF) to behavioral measures of proficiency (absolute or relative). The behavioral visual field advantage index, a relative accuracy measure used in the current study, is defined in subsection 1.5 below.

Implications of the Hypothesis

The most effective way to understand the implications of the hypothesis that magnitude of asymmetry in males exceeds that in females is to state it conversely: The amount of interhemispheric interaction in females exceeds that in males.

Hence, this hypothesis suggests: (a) The incidence and magnitude of the typical dextral pattern of unilateral processing (RH processing of visuospatial, and LH processing of verbal, stimuli) is greater in males than in females, (b) the magnitude of the unilateral pattern just described is smaller in females than in males, and (c) both the trend toward and incidence of bilateral processing (RH and LH representations of visuospatial and verbal stimuli) are greater in females than in males.

Critique of Methods

The research concerning gender differences in cerebral asymmetry has been criticized on three grounds. First, sample sizes are often too small to detect what may be a small effect (Butler, 1984; Hines & Gorski, 1985; Springer & Deutsch, 1985, chap. 7). Second, hand preference is often not carefully controlled (Butler, Ibid.), and asymmetry patterns significantly vary with handedness (see subsection 1.1/3 above).

Third, negative results are treated in a skewed fashion in two respects: (a) Many such results are often not published (Springer & Deutsch, Ibid.). Such omissions give a biased view of the truth value of the hypothesis as well as withhold information that could be used to localize sources of the effect and to design further studies; (b) those that are published are often deemphasized in discussions of this topic. Fairweather (1982, cited in Heister, 1984) noted that 103 out of 129 divided visual field studies reported no significant gender differences in cerebral asymmetry; many of them are not considered in the interpretation of positive results.

Data Concerning Gender Differences in Magnitude and Pattern of Asymmetry

Most data concerning this topic have been yielded primarily by normative and clinical anatomical and behavioral (divided visual field, dichotic, and dichaptic) methods. It is beyond the scope of this dissertation to review all aspects of this literature. (For reviews, the reader is referred to Bryden, 1979, and Buffery & Gray, 1972, both cited in McGlone, 1980; for supportive behavioral data, the reader is referred to Levy, 1974, cited in Bryden, 1982, and Witelson, 1976, cited in McGlone, Ibid.).

As was seen in the discussion above concerning implications of the magnitude of asymmetry hypothesis, magnitude and pattern of asymmetry are closely interwoven; they are rarely differentiated in data analyses and discussions in the literature. Consequently, the data herein are not presented for each of these hypotheses separately.

As shown below, gender differences in pattern and magnitude of asymmetry vary with type of population, dependent variable, and visuospatial task used to investigate these effects: (a) Greater bilateral processing in females than in males, (b) greater bilateral processing in males than in females, (c) greater RH involvement in visuospatial processing in males than in females, (d) greater RH involvement in visuospatial processing in females than in males, and (e) no differences between males and females in cerebral asymmetry have been demonstrated by clinical and normative behavioral and physiological studies.

Greater bilateral processing in females than in males. The main finding in clinical behavioral studies was that in RH-damaged patients, males showed greater visuospatial deficits than females; in LH-damaged patients, males demonstrated greater verbal impairments than females (see Kimura & Harshman, 1984, for discussion; Landsell, 1962; McGlone, 1978, cited in Springer & Deutsch, 1985, chap. 7; Snow, Freedman, & Ford; 1984). The measures used in many of these studies were intelligence test scores (WAIS; Wechsler-Bellevue).

These data were interpreted to indicate that the RH mediates visuospatial, and the LH mediates verbal, processing in males, whereas both hemispheres mediate these two types of processing in females (Butler, 1984; Springer & Deutsch, Ibid.). McGlone (1980) concluded from her examination of the adult clinical literature concerning asymmetry for nonverbal and verbal functions that it supports the hypothesis that functional cerebral asymmetry in males is more marked than that in females.

Greater bilateral processing in males than in females. The opposite asymmetry pattern, which is contrary to that predicted by the greater magnitude of asymmetry in males hypothesis, was also suggested by other clinical data as well as by normative data. Landsell (1968b, cited in McGlone, Ibid.) found this result in a study in which unilaterally damaged subjects were administered the Mooney Closure Task. Annett (1970, cited in Kimura & Harshman, 1984) found that the incidence of sinistrality in normal males exceeded that in normal females.

Greater RH involvement in visuospatial processing in males than in females. Within the unilateral pattern of cerebral asymmetry, the following gender differences in direction of asymmetry have been noted. Some normative tachistoscopic divided visual field data have suggested that RH mediation of visuospatial processing in males was more proficient than that in females. Different types of nonverbal stimuli yielded stronger LVF advantages (speed or accuracy) in males than in females. For example, LVF performance in males exceeded that in females in (a) the localization or enumeration of scattered dot stimuli (Kimura, 1969; Levy et al., 1976; McGlone & Davidson, 1973, the latter two studies cited in McGlone, 1980) and in (b) the identification of line orientation (Sasanuma &

Kobayashi, 1978, cited in McGlone, Ibid.).

A clinical behavioral study corroborated these findings. Landsell (1962) found, on a design preference task (Graves Test), that dextral males with RH resections yielded lower mean scores than dextral males with LH resections; dextral females showed the reverse pattern (those with LH resections yielded lower scores than those with RH resections). Hence, these findings suggest that males are more RH dependent than females, and females more LH dependent than males, when forming judgements concerning visuospatial stimuli (McGlone, Ibid.).

Greater RH involvement in visuospatial processing in females than in males. A normative physiological study revealed the pattern opposite to that just described. Gur et al. (1982, cited in Springer & Deutsch, 1985, chap. 7) found that females showed a greater amount of rCBF activity in the RH than males during a line orientation task.

No intergender differences in asymmetry. Finally, some normative and clinical data have demonstrated that no significant gender differences exist in pattern and/or magnitude of asymmetry. Some normative divided visual field studies using nonverbal stimuli found no significant Visual Field x Gender interactions (Bryden, 1976; Kail & Segal, 1978, both cited in McGlone, Ibid.). Finally, McGlone (Ibid.) concluded from her review of the clinical data on visual recognition processing that

"it appears that perceptual tasks involving form or

> pattern recognition show no systematic or lasting interactions between sex and side of brain damage." (p. 216)

Possible Origins of Gender Differences in Proficiency and Cerebral Functional Asymmetry During Visuospatial Processing

At the proximate level of causation, between-gender differences in genetic and cerebral anatomical characteristics have been suggested as causes of greater magnitude (and hence, the unilateral pattern) of asymmetry in male brains. This unilateral male pattern (and conversely, bilateral female pattern) of asymmetry have, in turn, been cited as sources of gender differences in proficiency in verbal and nonverbal processing.

In addition, intergender differences in the use of the verbal type of processing strategy, hormonal systems, and maturation rates have been cited as sources of male superiority in visuospatial processing.

At the ultimate level of causation, evolutionary pressures have been suggested as a cause of gender differences in patterns of cerebral asymmetry and male superiority in visuospatial skills. Brief descriptions of the above-listed factors are presented below.

Ontogenetic Causes

Genetic factors. Netley and Rovet (1983) found, using the dichotic listening procedure, that genetic abnormality correlated with degree of lateralization. Subjects lacking a Y-chromosome (the XO genetic composition characterisitic of Turner's Syndrome) showed relatively small right ear advantages to verbal stimulation, whereas subjects with an extra Y-chromosome (the XXY composition characteristic of the Supermale Syndrome) demonstrated relatively large advantages. These results suggest that X-chromosomes (the genetic marker of females) correlate with a bilateral pattern of cerebral organization, whereas Y-chromosomes (the genetic marker of males) correlate with a unilateral one.

Anatomical factors. Next, Kimura (1985) postulated that stronger interhemispheric connections in the female than male brain might be one cause of the female bilateral pattern of cerebral organization. The putatively larger and more broadly shaped splenium (resulting in increased interhemispheric communication in posterior cortex) in the female than male brain (de Lacoste-Utamsing & Holloway, 1982; see above subsection concerning cerebral structural differences) could serve as the mechanism hypothesized by Kimura.

If and how (a) the female bilateral pattern facilitates verbal processing in which that gender putatively excels (see Bryden, 1982; Kimura & Harshman, 1984; McGlone, 1980, for reviews) and (b) the male unilateral pattern facilitates visuospatial processing in which that gender putatively excels are complex questions also addressed by Kimura (Ibid.). She proposed that gender differences in cerebral asymmetry vary with the particular aspect ("sub-behavior") of visuospatial or linguistic processing tapped by a given task.

For example, Kimura cited electrical stimulation and dichotic listening data that suggested that the female brain was more focally organized than the male's with respect to some language functions (e.g., speech), but more diffusely organized than the male's with respect to other language functions (e.g., the defining of words).

Hence, Kimura showed that whether bilateral organization improves or hinders verbal processing (and implied that whether unilateral organization improves or hinders visuospatial processing) depends, not on these complex behaviors per se, but rather on the particular aspect(s) of these behaviors being processed during a given task. She stressed that the existence, direction, and magnitude of functional asymmetry vary with intellectual function. Springer and Deutsch (1985), after reviewing the literature, drew a similar conclusion: "There may be a relationship between lateralization and ability that is different for different tasks" (p. 185).

Processing factors. Kimura (Ibid.) also hypothesized that gender differences in functional asymmetry may be due to a factor other than the above-cited differences in structural asymmetry. She suggested that the magnitude of lateralization in the male brain may be equal to that in the female brain, but that females may utilize verbal strategies more effectively than males (Bryden, 1978, 1979, both cited in McGlone, 1980).

Hormonal factors. McGlone (1980) cited indirect behavioral evidence for the influence of hormones on intergender differences in visuospatial skills. First, she noted that these between-gender differences become especially marked in normal postpubescent subjects, a change she attributed to the genetically controlled release of hormones during adolescence.

Second, regarding the specific hormones responsible for these gender differences, the female hormone estrogen and the male hormone testosterone have respectively been associated with poor and good visuospatial performance. Concerning estrogen, when females of all ages were tested on their visuospatial abilities, maximal performance correlated with minimal estrogen levels. These results suggest that normal premenopausal females with high estrogen levels have relatively poor visuospatial capacities (Kimura, 1985).

Concerning testosterone, Diamond et al. (cited in Garmon, 1985) showed that this hormone accelerates the growth of RH regions in the developing rat brain (also see Diamond as well as Nordeen & Yahr, both cited in Kimura, 1985, for discussion of specific effects of sex hormones on cortical growth, cerebral asymmetry, and sex-typical behaviors, as demonstrated by ovarectomy and castration in neonatal rat).

Geschwind (cited in Garman, 1985; Konner, 1985) reasoned from these data that RH-mediated functions (a) develop prior to LH-mediated ones and (b) become more developed than the latter due to practice effects. Hence, according to Geschwind, males' superiority in RH-mediated visuospatial processing is due to their prenatal exposure to high testosterone levels. Levy (cited in Kimura, 1985) pointed out that, conversely, the LH in females may develop relatively faster and thereby predispose that gender to a high level of verbal proficiency.

Maturation factors. Waber (1976, 1977, both cited in Netley & Rovet, 1983) provided data that also concern the relationship between rate of development, cerebral functional asymmetry, and gender, but vis-à-vis postnatal behavior rather than prenatal anatomy. Waber adminsistered standardized tests of spatial and verbal abilities to young adults and correlated their scores with the rate of maturation information they had provided.

The early [fast] maturers performed significantly better on the verbal than spatial questions, whereas the late [slow] maturers yielded the opposite pattern (better spatial than verbal performance). Waber concluded that because females mature more quickly than males, the putative female superiority in verbal processing correlates with a rapid rate of maturation; conversely, because males mature more slowly than females, the putative male visuospatial superiority correlates with a slow maturation rate.

Netley and Rovet concluded:

> "Variations in growth rate, beginning in prenatal life, may, through their impact on neural maturation and hemispheric organization, be responsible for some part of the cognitive distinctiveness of the two sexes." (pp. 263-264)

It is important to note that although gender differences in perceptual and cognitive capacities exist early in life (the neonatal human brain is already sexually dimorphic [Reinisch et al., 1979, cited in Netley & Rovet, 1983]), these behaviors are dynamic: They are continually modified by postnatal experience. Hence, they are determined not solely by the genetically controlled factors mentioned above, but rather by the interaction of genetic and environmental factors throughout the human lifespan (Kimura, 1985).

Phylogenetic Causes

Regarding the phylogenetic origin of gender differences in structural and functional cerebral asymmetries, Horvath, Woodward, and de Lacoste (1985) found regional volumetric asymmetries in two pongid species: (a) In chimpanzee, the LH regional volume was greater than that in the RH in parietal association cortex, and (b) in gorilla, the RH regional volume was greater than that in the LH in prerolandic cortex; the LH volume was greater than that in the RH in postrolandic cortex.

Further, minor gender differences were found in the gorilla pattern. These researchers contrasted these minor sexual dimorphisms in pongid cerebral asymmetry with the significant gender differences revealed in regional RH and LH volumes in the hominid asymmetry pattern (see structural differences subsection above); they concluded: "In evolution, there may have been selective pressures on the hominid line for sex differences in cerebral asymmetry" (p.

868).

Levy, 1978 (cited in Springer & Deutsch, 1985, chap. 7) suggested that some of these pressures may have derived from the socioeconomic structure characteristic of early human societies. In those societies, labor was divided between the sexes: Males engaged in hunting, and females, in child-rearing activities. The former activity required excellent visuospatial capacities; the latter, in contrast, entailed verbal interactions.

Finally, A. Brown, Woodward, and de Lacoste (1986) found "a sex-related reversal in patterns of regional volumetric asymmetries in primate cerebra" (p. 1537). In some New World monkey species (ceboids and cercopithecoids), asymmetrical patterns similar to those in Old World monkeys as well as in subhuman and human hominids (viz., maximal asymmetry in retrocalcarine [striate and peristriate] cortex ([de Lacoste, Horvath, & Woodward, 1986]) were found. Some of the male New World monkey brains showed a RH bias across regions; conversely, some of the female brains showed a LH bias across regions.

These investigators noted, however, that because their sample size was small, examination of a greater number of primate brains is required before conclusions concerning a systematic pattern of gender differences in primate cerebral asymmetry can be drawn.

5/ Interhemispheric Interaction

"The principle of cerebral duality began with the idea

> that a single hemisphere is enough for a mind. You may be familiar with the story of Arthur Ladbroke Wigan, an English physician who had an acquaintance who died rather suddenly. At the man's postmortem, when the skull was opened, one hemisphere was completely missing. This not only astounded Wigan, but he had the wits to realize that it was meaningful . . . . In 1844 . . . he claimed that one hemisphere is clearly enough for . . . the emotions, sentiments and faculties which we call . . . mind." (Bogen, 1985, p. 28)

One brain or two?

One of the consequences of split-brain research has been a model of the human mind as two separate brains, each generating its own sphere of consciousness (capacities for awareness, self-awareness, and language). It should be noted that language is considered a component of consciousness because split-brain data suggest that some affective capacities emerge in conjunction with linguistic ones: Some commissurotomized patients developed the abilities (a) to process language with their RH and (b) to make different subjective judgements with their right and left hemispheres:

> "When this system [i.e., language] is absent, as in the right hemisphere of most split brain patients, . . . the organism functions mainly at the perceptual motor level. Though certain cognitive skills can be demonstrated in such instances, the richness and characteristic flexibility of human behavior seems to be lacking in the absence of linguistic sophistication . . . . Add a rich linguistic system to an isolated mass of non-verbal tissue as in the RH of P. S., and a human being with the capacity to value, aspire, and reflect on life emerges." (Le Doux et al., 1977, cited in Springer & Deutsch, 1985, p. 258)

Each cerebral hemisphere of the split-brain patient demonstrated the capacities to experience sensations, perceptions, and memories; to generate thoughts; and to learn new information, that is, each hemisphere possessed the properties of an independent mind: "When you divide the brain surgically by midline section of the cerebral commissures, the mind also is correspondingly divided" (Sperry, 1985, p. 11); "If one hemisphere is enough for one mind, then with two hemispheres we can have two minds" (Wigan, 1844, paraphrased in Bogen, 1985, p. 28). The same conclusion was drawn from hemispherectomy data: "A single cerebral hemisphere, either the right or left, is capable of carrying out a mental life" (Benson, 1985b, p. 3).

Hence, split-brain research has resulted in viewing the normal brain as if it were a split brain (Bogen, 1977; Galin, 1977; Levy, 1977, all cited in Le Doux, 1983), that is, in seeing the self as if it were "two co-conscious selves sharing one cranium" (Sperry, 1985, p. 12). Instead of thinking that a surgical technique has resulted in an abnormal condition (viz., the existence of two disconnected masses of living brain tissue), some researchers view the split brain as a mirror that reveals the underlying physiology of the normal brain (Bogen, 1985).

One consequence of this viewpoint is the overlooking of the fact that a two-brain structure with intact callosal fibers is a single system (Le Doux, 1983). Behavior, or cerebral output, in such a system results not only from intrahemispheric activity, but also from interhemispheric activity.

Whether lateralization in the human brain results in the duplication, division, or integration of functions and, hence, in our having two brains (Bogen, 1985) or one brain consisting of two halves (Le Doux, 1983; Sperry, 1985) is not necessarily an all-or-none issue. For example, it may depend on stage and level of processing: Early, lower level (sensory) processing may involve duplication of function, and later, higher level (cognitive) processing, its division and integration (Luria, 1966, cited in Le Doux, 1983).

The mechanism controlling these three types of interhemispheric operations is the cerebral commissure system. This system consists of four sets of fibers, the first three of which are cortical and the fourth of which is subcortical: (a) corpus callosum, (b) anterior commissures, (c) hippocampal commissures, and (d) massa intermedia.

These fibers have both inhibitory and facilitative effects: The former controls the functional division, and the latter, the functional integration, operations mentioned above. Inhibition prevents interhemispheric competition, and facilitation permits integration and information exchange (Levy, 1985).

Callosal and Specialization Dysfunctions

When (a) the callosal fibers are damaged or entirely lacking, and/or (b) a given behavior is mediated by the hemisphere not typically specialized for that behavior, behavioral dysfunctions emerge.

Callosal Dysfunctions

Concerning the first point, (a) split-brain patients and callosal agenics, both of whom lack an intact commissure system, and (b) chronic schizophrenics, who, according to postmortem data, have abnormally large corpus callosa (Beaumont & Dimond, 1973, cited in Springer & Deutsch, 1985, chap. 10), display disorders related to the imbalance of interhemispheric activity.

The "hypo-commissure" types demonstrated unsustained attention, rapid shifts between typical RH and LH processing modes, and a rapidly attained state of fatigue during perceptual tasks (Dimond, 1977; Levy, 1985; Netley, 1977, cited in Gladstone & Best, 1985; Sperry, 1969, cited in Kinsbourne & Smith, 1974; Zangwill, 1974, cited in Dimond, 1977). They were also less efficient than normal controls in a bimanual perceptual-motor coordination task (Jeeves, 1969). The "hyper-commissure" types displayed a disunified sense of self.

Hence, when improperly connected, the hemispheres seem to be serially wired; they interact in a time-sharing fashion (Friedman & Polson, 1981, cited in Tucker & Williamson, 1984; Wingfield & Byrnes, 1981) that results in sequential hemispheric activity, inefficient performance, and a fragmented or multiple consciousness state.

When properly connected, on the other hand, the hemispheres seem to be wired in parallel; they interact in a space (capacity)-sharing fashion (Ibid.), resulting in simultaneous, laterally specialized activity; efficient performance; and an integrated state of awareness. The presence of the callosal system appears to permit the spatial integration of resources allocated to each of the hemispheres.

Specialization Dysfunctions

Concerning the second point listed above (viz., abnormalities correlated with a given behavior's mediation by the hemisphere not typically specialized for that behavior), dyslexics, stutterers, and autistic patients exemplify this situation. These three abnormalities entail either bilateral involvement or reversed lateral dominance patterns in language behavior. For example, in 42% of the dyslexics given CAT scans, the RH parieto-occipital region was wider than that in the left. Thirty-nine percent of that group were dextral and displayed RH control of linguistic, and LH control of visuospatial, processing (Springer & Deutsch, 1985, chap. 10).

Among stutterers, both physiological (Wada Test) and behavioral (pursuit auditory tracking) measures indicated bilateral mediation of language. Among autistic patients, 65% of those tested were either ambidextrous or sinistral at 5 years of age, and 70% displayed RH mediation of language (as measured electrophysiologically [alpha activity]) (Springer & Deutsch, 1985, Ibid.).

Another example of a hemispheric dysfunction due to a behavior's mediation by the hemisphere opposite to the one specialized for that behavior was provided by Teuber (1975, cited in Goodman & Whitaker, 1985). He observed visuospatial deficits in individuals who had sustained LH damage during infancy. Teuber hypothesized that, in these cases, the RH had tried to take on LH functions and "to do more than it was orginally meant to do" (p. 135). He described this pattern as a "crowding effect" (Ibid.) because the RH became too crowded to function normally.

Models of Hemispheric Interaction

Hence, it appears that normal cerebral functioning requires two properly connected hemispheres each of which is specialized for a particular behavior (or aspect of behavior). The mechanism of interaction between these properly connected, appropriately specialized hemispheres is not definitively known.

The dual inhibitory and excitatory nature of the callosal system described above has resulted in the formulation of five models concerning the mechanism of interhemispheric communication and, hence, the definition of hemispheric specialization (see Allen, 1983): (a) unilateral specialization, (b) negative interaction, (c) cooperative interaction, (d) parallelism, and (e) allocation. Brief descriptions of these models follow.

Unilateral Specialization

This model (suggested by Semmes, 1968) fosters the absolute competence connotation of hemispheric specialization (see subsection 1.1/1). According to this model, a given behavior is exclusively mediated by one hemisphere. For example, only the RH is capable of (specialized for) visuospatial behaviors and synthetic processing; only the LH is capable of (specialized for) linguistic and analytic processing. A given behavior is 100% lateralized to one hemisphere or the other, but is never partially controlled by each hemisphere.

The other four models are all relativist models of hemispheric specialization (again, refer to subsection 1.1/1). They propose that both hemispheres are involved in the mediation of a given behavior, but that each hemisphere may be active at a different processing stage. Although these models appear to contradict one another, they, in fact, complement one another: The mechanisms they propose may each be true for a different processing stage.

Both the second and third models entail bilateral interaction. In the negative interaction case, however, the hemispheres inhibit one another, whereas in the cooperative interaction case, they excite one another. In contrast, both the fourth and fifth models propose bilateral noninteraction.

Negative Interaction

This model (Moscovitch, 1973, cited in Allen, 1983; Moscovitch, 1977, cited in Kolb & Whishaw, 1985, chap. 24) asserts that, depending on processing stage, either (a) the activity of one hemisphere inhibits that of the other (unidirectional inhibition) or (b) the activity of both hemispheres inhibits that of one another (mutual or reciprocal inhibition).

This model suggests, for example, that both the RH and

LH are capable of language, but that the LH inhibits RH linguistic activity. The facts that (a) RH mediation of language has been observed in split-brain patients, and (b) an abnormally high degree of bihemispheric activity has been noted in callosal agenics (Netley, 1977, cited in Kolb & Whishaw, Ibid.) demonstrate the inhibitory function of the callosal fibers, that is, negative interaction between the hemispheres.

Cooperative Interaction

This model is based on the division of labor principle. It proposes that (a) early in processing, each hemisphere mediates the particular aspect of a given behavior for which it is specialized, and (b) later in processing, the neural activity of each hemisphere is coordinated and integrated with that of the other (Dimond, 1972). In this way, each hemisphere contributes its specialized function to a given complex behavior.

For example, in oscine vocalization, each hemisphere appears to be preferentially sensitive to different frequency ranges. Any given note seems to result from the cooperative coupling between the relatively high and low frequencies respectively processed in the different hemispheres (Nowicki & Capranica, 1986).

Parallelism

This model proposes that both hemispheres are simultaneously and independently active during a given task (Dimond & Beaumont, 1974, cited in Allen, 1983). Whether that activity is the same or different in both hemispheres varies with processing stage: Early in processing, when simpler functions tend to be mediated, the activity in one hemisphere duplicates that in the other; in contrast, late in processing, when more complex functions are usually mediated, the activity in one hemisphere complements that in the other. "Parallel duplication," putatively characteristic of early processing, is synonomous with the split-brain (cerebral duality) model (Bogen, 1985; see "One Brain or Two?" above in the current subsection).

Allocation

This model purports that either hemisphere has the capacity to undertake a given task, but that one or more factors unrelated to stimulus material (e.g., attention, task instructions [Harris & Haber, 1963; Seamon & Gazzaniga, 1973], and a subject's preferred strategy) determine which hemisphere will mediate that task.

For example, attention (i.e., a state of physiological arousal and correlative mental alertness in which one's sensitivity to incoming events is heightened [Wingfield & Byrnes, 1981, chap. 6]) toward a given area in the visual field (due to either an external orienting factor or an internal expectancy factor) may direct, or prime, the hemisphere contralateral to that area to initiate processing (Kinsbourne, 1970; Klein, Moscovitch, & Vigna, 1976).

Second, a given subject may have a preferred processing mode (cognitive style) that selectively engages the hemisphere mediating that mode independent of stimulus type. For example, a subject may use an analytic processing mode whether the stimulus material is visuospatial or verbal (Zenhausern, 1978, cited in Allen, 1983).

Third, the hemisphere that is directly stimulated may process input more efficiently than the indirectly stimulated one (the direct access hypothesis, Kimura, 1966; supported by the electrophysiological and psychophysical data of Andreassi, Okamura, & Stern, 1975; Eason & C. T. White, 1967; Rizzolatti et al., 1971).

Finally, this allocation effect is dynamic: It may occur at any time and any number of times during processing. As a result, switching (the alternation of processing between hemispheres) may occur as a result of non-stimulus-related factors.

Conclusion

Concerning the current status of these five models, Allen (1983) puports that any model supporting the competence or relative proficiency notion of hemispheric specialization within the functional localization framework (i.e., one entire hemisphere exclusively mediates a given behavior because either (a) it has the capacity to do so and the other hemisphere does not or (b) both hemispheres have the capacity, but the active one is more competent vis-à-vis this particular behavior than the inactive one) is considered weak.

Such evidence as the electrophysiological data of Gevins et al. (1981, 1983, 1985; see subsection 1.1/2) undermines these positions. They support, instead, the concept of hemispheric specialization more closely aligned with the aggregate field model of cerebral organization: Hemispheric specialization is a time-dependent function between "neural processing units" (Allen, 1983, p. 93) (i.e., cerebral loci in both hemispheres that mediate aspects of a given behavior during particular processing stages [Allen, 1983; Le Doux, 1983]).

6/ The Advantages of Hemispheric Specialization

> "Cerebral localization is determined by the separation of incompatible mechanisms which cannot occur in the same place at the same time." (Lashley, cited in Bever, 1975, p. 251)

Thus far, Teuber's first two questions concerning hemispheric specialization (what it is and how it works) have been addressed. His third question (whence it came) remains. Implicit in this question is why this type of cerebral organization developed and what advantages it has.

Advantages

Parallel Processing

Functional asymmetry requires that some loci in each of the two hemispheres operate in parallel at some point during a given processing sequence. Parallel processing is a highly efficient mode of operation because it (a) is rapid and (b) "divides the labor" (Waldrop, 1984). Concerning the first point, parallel processing is significantly faster than serial because in the former, events occur simultaneously (hence requiring no interevent time), whereas in the latter, events occur successively (thus requiring time to proceed from one event to another).

Concerning the second point, the division of labor principle states that rather than one unit's mediating all aspects of a given function, several subunits mediate those aspects for which they intrinsically possess or develop expertise. The output thus represents the work of a combination of specialized processors rather than that of a single general processor.

The overall fatigue level of the "machinery" in this type of system is relatively low. Sharing (or distributing) the "load" among several parts, rather than allocating the total load to one part, helps sustain the overall energy level of the entire system.

Hence, both the quality of the output and the range of inputs which can be processed are maximized in this type of system. The net effect of this complementary specialization type of organization is that the output of the whole is greater than that of the respective parts. Stated with respect to the functional asymmetry type of cerebral organization, the combined activity of both hemispheres is more powerful than the activity of either hemisphere alone (Dimond, 1972; Teuber, 1974).

Dimond and Beaumont (1973, cited in Dimond, 1977) provided an example of this principle. These investigators found that when they presented signals (a 200-ms brightening of one of four red lights) in either the LVF or RVF to split-brain subjects in a detection task, LVF presentations yielded a steady level of relatively poor detection performance, whereas RVF presentations resulted in initially superior performance followed by a decrement:

> "The right hemisphere, apparently incapable of such high levels of performance unless sustained by the left, keeps a steady level of low-level vigilance action which could . . . maintain a low level of performance long after the left hemisphere has exhausted its capacity." (p. 346)

These data hence suggest that (a) the RH is relatively more proficient than the LH in the sustained type of vigilance, and the LH, more proficient than the RH in transient vigilance; and (b) over time, the operation of both hemispheres together increase the probability that a given signal will be detected.

Redundancy

Another advantage of functional asymmetry is redundancy: If one hemisphere is damaged, another one remains. Although the intact hemisphere may be specialized for different stimulus types, processing modes, and response types than the damaged hemisphere, due to the plasticity property of the nervous system, the intact hemisphere may act as a back up system to the damaged one. The former can resume the latter's functions by combining the processing characteristics of both hemispheres. The degree to which the intact hemisphere incorporates the specialized functions of the damaged one depends on such factors as age at which damage occurred (see Witelson, 1985a, for discussion).

Separation of Incompatible Modes

Another advantage of hemispheric specialization is the separation of two incompatible modes that, if combined in the same region, would mutually antagonize one another (Bever, 1975; Lashley, cited in Bever, Ibid.; Levy, 1969; Tucker, 1976).

Levy (1969) found, for example, that left-handers, with a greater likelihood of bilateral mediation of language than right-handers, yielded (a) relatively low scores on performance IQ tests and (b) relatively large differences between their performance and verbal IQ scores. In contrast, right-handers, with a greater probability of unilateral mediation of language than left-handers, yielded (a) relatively high performance IQ scores and (b) similar performance and verbal IQ scores.

Levy concluded that the lack of hemispheric specialization for "vocal apparatus" and "Gestalt perception" (p. 615) hindered visuospatial and linguistic processing, whereas the presence of such specialization improved such processing.

Relationship Between Asymmetry and Proficiency

Whether hemispheric specialization does, in fact, hinder or improve performance during visuospatial and linguistic tasks is a complex problem. Several researchers have stressed that the facilitative effect of functional asymmetry on cognitive processing is not a general effect, but rather a task-specific one (Kimura, 1985; Netley & Rovet, 1983).

Trotter (1985) suggested that, because size of corpus callosum indicates degree of functional asymmetry (i.e., a relatively large structure indicates greater interhemispheric communication [less asymmetry], whereas a relatively small structure indicates less interhemispheric communication [greater asymmetry]), "we have to . . . correlate certain measures of intelligence . . . with the size of the corpus callosum to see if there is a link between anatomy and cognitive skills" (p. 24).

Asymmetry and intelligence. Electrophysiological data have indicated that degree of asymmetry covaries with IQ. Both alpha activity (Lairy et al., 1969, cited in Callaway, 1973) and visual EPs recorded over central sites in 10- to 11-year-olds (Rhodes, Dustman, & Beck, 1969) and adults (Callaway, 1973) showed greater interhemispheric amplitude differences in relatively bright than in relatively dull subjects.

Asymmetry and task: Facial recognition. Behavioral data have shown that degree of asymmetry covaries with performance during (a) perceptual processing (e.g., forming line orientation judgements [Sasanuma & Kobashi, 1978, cited in Nichelli et al., 1983]) and (b) cognitive processing (e.g., recognizing random shapes [Birkett, 1978, cited in Ross & Turkewitz, 1982] and faces [Ross & Turkewitz, Ibid.; Turkewitz & Ross-Kossak, 1984; Ross-Kossak & Turkewitz, 1984]).

With regard to these facial recognition data, Turkewitz and Ross-Kossak (Ibid.) presented four black-and-white photographs of faces in a divided visual field paradigm (3.2 degrees between the central fixation point and the center of a given stimulus in the RVF or LVF) to 8-, 11- and 13-year-old dextral males and females (of above average intelligence). Stimulus duration was 140 ms for the 8-year-olds and 110 ms for the two older age groups. (These different exposure times yielded equivalent accuracy levels.)

Each subject's task was to point to the face (on a sheet containing photographs of the four faces) that had just been projected. Forty experimental trials, a 3-minute familiarization period, and two practice trials were given. Results showed that the correlation between magnitude of asymmetry and performance varied with subject characteristics: The older females showed the highest correlation between visual field advantage and recognition accuracy.

The facial recognition studies (Ross & Turkewitz, 1982; Ross-Kossak & Turkewitz, 1984) also showed that, although magnitude of visual field advantage positively correlated with accuracy (i.e., the larger the advantage, the better the performance), the correlation between direction of advantage and performance was dynamic: It varied with degree of subject's familiarization with stimulus set.

(*Note*. Stimulus parameters, except for the 100-ms exposure time used here, and task requirements were identical in these two studies to those used in the Turkewitz and Ross-Kossak [1984] study. The sample, length of session, and degree of familiarization did differ in the current two experiments from those in the previously described experiment: Here, 39 dextral female undergraduates constituted the samples; 96 experimental trials [1982] and 192 such trials [1984] without stimulus familiarization prior to testing were used.)

These researchers found that the two types of RH strategies which they identified (primitive holistic [#1] and advanced holistic [#2]), correlated with high accuracy during the earliest and latest parts of the session, respectively; the LH analytic strategy correlated with high accuracy during the middle part.

Hence, (a) RH Strategy 1 that entailed the processing of undifferentiated percepts formed by external facial characteristics (e.g., overall shape) was used to recognize unfamiliar stimuli, (b) the LH strategy that based recognition judgements on distinctive features (internal facial features, e.g., the nose or mouth) was used for moderately familiar stimuli, and (c) RH Strategy 2 that encoded integrated percepts of both external and internal facial characteristics was used to recognize the familiar stimuli.

Both normal and clinical data corroborated this finding that a RH strategy was not unconditionally superior to a LH strategy, and vice versa. Concerning the normal data, Nichelli et al. (1983) showed that during a dot pattern discimination task, male and female dextral adults, each of whom displayed significantly different hemisphere advantage patterns from one another, performed equally well (RT and accuracy measures).

Concerning the clinical data, subjects with isolated hemispheres, due to either right or left hemispherectomies (Damasio et al., 1975, cited in A. Damasio & H. Damasio, 1983), or commissurotomies (Levy et al., 1972, cited in A. Damasio & H. Damasio, Ibid.), were capable of facial recognition. A. Damasio and H. Damasio (Ibid.) proposed that facial recognition is a bilateral cerebral function in which each hemisphere contributes a unique strategy at particular times during processing.

Hence, a human brain consisting of only a RH or a LH is not disadvantaged relative to a brain containing both hemispheres with respect to the fact that the cognitive strategies mediated by both hemispheres are equally capable (according to some studies) and equally proficient (according to others) during the above-cited tasks. However, a "single strategy" brain is disadvantaged relative to a "dual strategy" brain because at different processing and learning stages, one strategy is more effective than the other.

"Optimal shifters." Thus, the covariance between direction of asymmetry and proficiency may depend, not on direction per se, but rather on a given subject's selecting an initially effective strategy and his/her shifting to another effective strategy at appropriate times during processing (Ross-Kossak & Turkewitz, 1986). The performance of a given individual in the above-cited tasks who tended to use a RH strategy or LH strategy under all circumstances was worse than that of one who selected appropriate processing strategies at particular times.

1. _Asymmetry and creativity_. In addition to being more proficient than "nonoptimal shifters," the "optimal shifter" types of individuals (i.e., those who demonstrate the greatest level of cognitive flexibility and the maximally efficient utilization of both hemisphere-based strategies) may be more creative (Bogen & Bogen, 1969, cited in Katz, 1978; Katz, Ibid., 1986; Ross-Kossak & Turkewitz, Ibid.)

For example, Katz (1986) found that, although the direction of hemisphericity (the tendency to use either the RH-synthetic or LH-analytic cognitive style) differed among architects, scientists, and mathematicians (the first group was more RH dependent, and the latter two, more LH dependent), the most highly creative individuals in all three professions demonstrated efficient use of the cognitive modes mediated by both hemispheres.

(_Note_. Katz measured hemisphericity by the appositional/propositional ratio [Bogen et al., 1972, cited in Katz, 1986]. In this ratio, the numerator [index of RH activity] is determined by a subject's score on the Street Gestalt Completion Test; the denominator [index of LH activity], by his/her score on the WAIS Similarities subtest. Katz measured creativity [a] objectively, by profession-specific productivity [e.g., number of patents for scientists]; [b] subjectively, by peer evaluations; and [c] psychometrically, by the Barron-Welsh Art Scale and TAT cards.)

Finally, Bogen and Bogen (1969, cited in Katz, 1978) also advocated the association between use of both hemispheres and creativity: They suggested that relatively uncreative individuals have poor transcallosal neural transmission.

Conclusion

The functionally asymmetric type of cerebral organization is advantageous because it entails (a) rapid processing, (b) a high fatigue threshold, (c) the processing of a wide range of stimuli, (d) redundancy, and (e) the production of behaviors mediated by specialized processing strategies that avoid mutual interference because they are localized in spatially distinct regions.

Magnitude of asymmetry positively correlates with (a) IQ score and (b) response accuracy during the perception of line orientation and the recognition of random shapes and faces. Well-timed shifts in direction of asymmetry positively correlate with response accuracy; such efficient use of both hemispheres may be associated with creativity.

In sum, it seems that (a) the availability of two different types of processing strategies permits greater proficiency than that of one type, and (b) the location of the neural ensembles mediating these strategies in nonoverlapping regions likewise permits greater proficiency than their location in overlapping regions. Hence, either a unilateral brain mediating one type of processing mode or a nonlaterally specialized brain with two types of processing modes would be less efficient than the laterally specialized brain that has evolved in the human species.

7/ The Evolution of Hemispheric Specialization

> "Evolution leads to stricter defintion of the parts and thus to a lack of symmetry and greater differentiation. Asymmetry was thus viewed as a sign of evolutionary progress that distinguished the simple from the complex and the primitive from the advanced." (Goethe, Metamorphosis, paraphrased in LeMay, 1985, p. 40)

The Comparative Framework

The reasons that (a) functional asymmetry evolved, and (b) the direction of this asymmetry evolved in humans such that the LH is specialized for language, and the RH, for visuospatial processing (in right-handers) are not definitively known. One approach used to investigate this question is comparative psychology: By identifying (a) those species that demonstrate structural and/or functional asymmetries and (b) the behaviors associated with those asymmetries, the purpose of this type of cerebral organization may be better understood.

For example, one hypothesis states that hemispheric specialization emerged due to language; if such specialization were found in nonlinguistic species, then this view would be undermined (Springer & Deutsch, 1985, chap. 9).

Viewed within the comparative framework, cerebral asymmetry is a class-specific characteristic common to several mammalian species, such as rats, birds, and primates (e.g., pongids [including chimpanzees and gorillas]; prosimians; Rhesus monkeys; macaques; and humans).

A trend from a less to more complex central nervous system, including: (a) increasing cephalization (a dominant head relative to trunk and limbs), (b) contralateral control (RH control of functions in the left half of the body and LH control of functions in the right half of the body), and (c) cerebral asymmetry, characterizes the progression from lower to higher animals on the phylogenetic scale (Dimond, 1972).

Contralateral Control

The anatomical basis of contralateral control in the primate visual system is vertical hemidecussation (see Figures 1-3): Fibers projecting from the right hemiretina of the left eye toward the RH cross (decussate) those projecting from the left hemiretina of the right eye toward the LH. Efferent fibers from the left hemiretina of the left eye project to the LH; efferent fibers from the right hemiretina of the right eye project to the RH.

Hence, the nasal retinal fibers decussate and thereby project to the respective contralateral cerebral hemispheres; the temporal retinal fibers do not decussate and thereby project to the respective ipsilateral cerebral hemispheres.

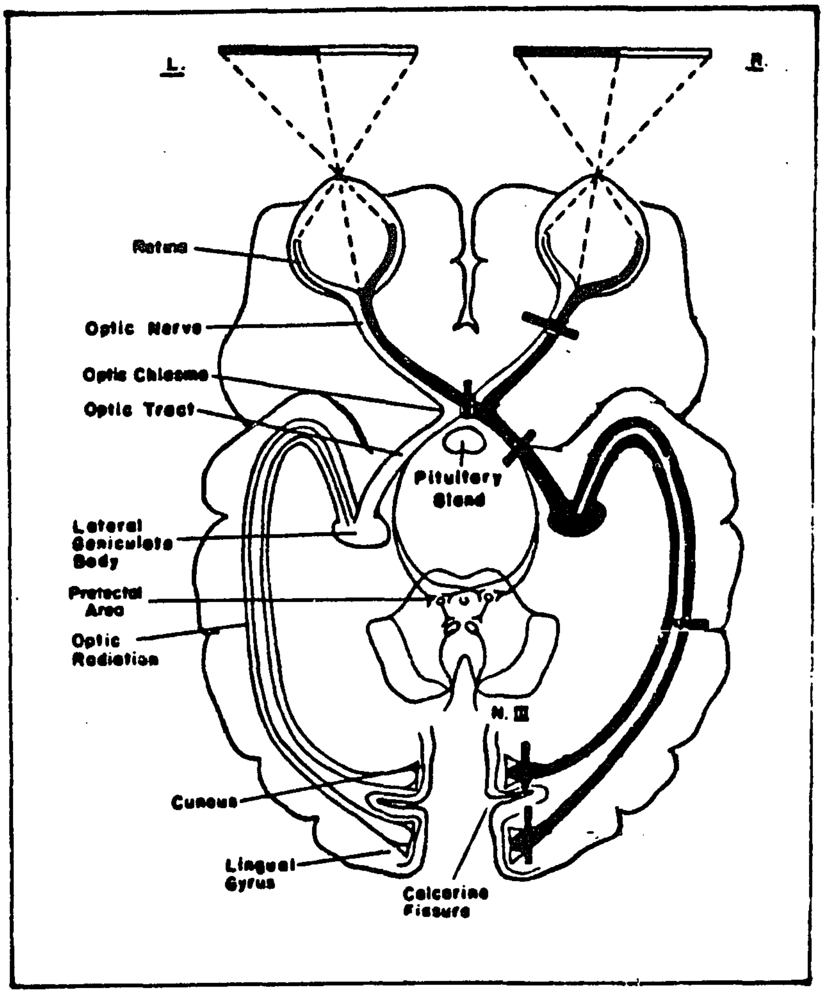


__Figure 1__. Hemidecussation in the primate visual system.

__Note__. From __Manter and Gatz's Essentials of Clinical Neuroanatomy and Neurophysiology__ (p. 113) by R. G. Clark, 1975, Philadelphia: F. A. Davis Co.

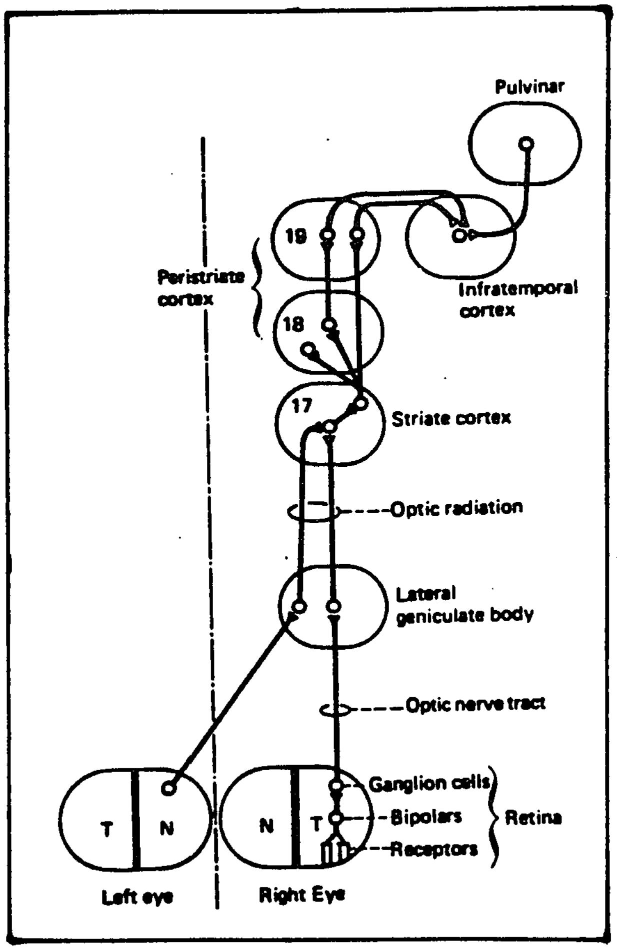


Figure 2. Highly schematic diagram of the visual projections to the cortex in primates.

Note. From "Visual System III: Physiology of the Central Visual Pathways" by E. R. Kandel. In Principles of Neural Science (p. 237) by E. R. Kandel and J. H Schwartz (Eds.), 1981, New York: Elsevier/North-Holland (chap. 21).

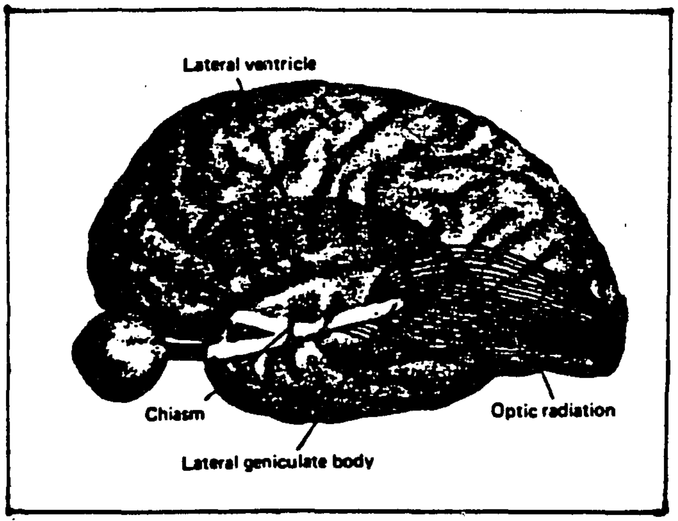


Figure 3. Lateral view of retinocortical projections in primate cortex.

Note. From "Visual System II: Anatomy of the Central Visual Pathways" by J. P. Kelly. In Principles of Neural Science (p. 233) by E. R. Kandel and J. H. Schwartz (Eds.), 1981, New York: Elsevier/North-Holland (chap. 20).

Why this structural arrangement evolved is unknown. Pettigrew (1986) proposed one hypothesis. He showed (by single-unit recording and horseradish peroxidase [HRP] staining) that, in bats, decussation exists when highly refined visual detection and discrimination skills (e.g., high contrast sensitivity and well-developed pattern and motion vision) are required for survival.

Pettigrew found that vegetarian bats (megachiropterans) that require a highly developed visual system for foraging and obstacle avoidance possess a decussated type of organization. In contrast, insectiverous bats (microchiropeterans) that require a highly developed auditory system for echolocation, the means by which they capture their prey, lack decussation.

Hemispheric Specialization

Concerning hemispheric specialization (the third characteristic listed above regarding cerebral organization in higher animals), Springer and Deutsch (1985, chap. 12) suggested that this type of organization permits a greater number of and greater proficiency in cognitive skills (see prceceding subsection for discussion).

Dimond (1972) similarly proposed that the availability of specialized functions within a nervous system with a well-developed capacity to integrate those functions (see division of labor discussion in preceding subsection) contributes to the increased cognitive capacities of higher primates.

Springer and Deutsch's and Dimond's hypotheses pose the question: Which cognitive capacities are related to cerebral asymmetry? The following evidence exists for asymmetries associated with visual and linguistic processing in the mammalian species listed above.

Mammalian Cerebral Asymmetries

Visual and Communication-Related Asymmetries

Asymmetries have been found in visual cortex in several primate species. In lemuridae (a nonanthropoid primate), asymmetries were found in (a) sensory (visual and auditory) and motor association cortex and (b) primary visual cortex (de Lacoste & Woodward, 1985).

More specifically, regional volumetric analysis revealed asymmetries (up to 13%) in peristriate (visual association areas) and striate (visuosensory area) cortex as well as in Brodman's areas 6 and 8 (motor association cortex). Sylvian fissure (auditory association cortex) asymmetries (this structure was higher in the RH than LH 75% of the time) were also found. In contrast, primary somatosensory, motor, and auditory cortex were found to be symmetrical when measured in terms of regional volume.

De Lacoste and Woodward concluded that "evidence of hemispheric differences in prosimians with sparse association cortex suggests that anatomical asymmetries play a role early in primate brain evolution" (p. 868).

In a subsequent study, de Lacoste et al. (1986) extended these findings concerning visual cortex to other primate species. They found a high degree of volumetric asymmetry in retrocalcarine cortex (striate and peristriate areas). Amount of asymmetry increased with increasing status on the phylogenetic scale: Pongids and prosimians displayed a 9% interhemispheric difference in regional volume in these regions; lemuridae and New World monkeys, a 14% difference; Rhesus monkeys, a 17% difference; and humans (adults), a 20% difference.

These investigators concluded:

> "Primary and associational visual areas are characterized by significant left/right regional volumetric asymmetries in species at all phylogenetic levels within the primate order. The degree of striate and peristriate asymmetry significantly exceeds that found for the neighboring parieto-temporo-occipital (PTO) association areas." (p. 719)

De Lacoste et al. also noted that because these various primate species were arboreal, a highly developed capacity for spatial relation recognition was adaptive for them: The asymmetrical type of cerebral organization may have contributed to the elaboration of the visual system necessary for these species' survival.

<u>Communication-related asymmetries</u>. In addition to the asymmetries related to communication already cited, the following ones have been found. First, Japanese macaques demonstrated a right ear advantage for vocal stimuli in a dichotic listening task (Petersen et al., 1978, cited in Springer & Deutsch, 1985, chap. 9).

Second, as mentioned in subsection 1.1/5, asymmetries have been demonstrated in songbird species' auditory sensitivity to temporal frequency ranges, resulting in bilateral mediation of vocalization (Nottebohm, 1977, cited in Springer & Deutsch, Ibid.; Nowicki & Capranica, 1986).

Third, such interhemispheric differences in sensitivity to temporal frequency information have also been behaviorally demonstrated in humans. Studdert-Kennedy and Shankweiler (1970, cited in Springer & Deutsch, 1985. chap. 12) found (with dichotic listening) a right ear advantage for decoding speech sounds consisting of extremely rapid frequency transitions (e.g., such consonant-vowel syllables as ba, da and ga).

Next, as mentioned above, the planum temporale (part of auditory association cortex) was found to be significantly larger in the LH than RH in humans (Geschwind & Levitsky, 1968) and, to a lesser extent, in chimpanzees (Yeni-Komshian & Benson, 1976). This structure, however, was equal in size in both hemispheres in Rhesus monkeys (Yeni-Komshian & Benson, Ibid.).

These latter researchers concluded that "anatomical asymmetries may be part of an evolutionary development that is reflected by the trend toward asymmetry among some of the living members of the order primates" (p.389). This notion corroborates the de Lacoste et al. (1986) findings cited above.

Summary

The following comparative data suggesting that asymmetries evolved in relation to complex visuospatial processing and communication have been found in the above-cited mammalian species:

1. Structural asymmetries have been identified in (a) visuosensory cortex and (b) visual and motor association cortex.

2. Structural and functional asymmetries have been shown in auditory association cortex.

3. Significant asymmetries were found in association, but not in sensory, cortex, except for the visual system: In that case, asymmetries were found in both regions.

4. The degree of asymmetry in intramodal (secondary) association cortex exceeded that in cross-modal (tertiary) association cortex.

The Evolution of Hemispheric Specialization for Linguistic and Visuospatial Processing

Asymmetries for these two functions evolved as a result of environmental pressures interacting with intrinsic neural changes. Because the timing of these external pressures on, and internal changes in, the visual system relative to that in the "communication" system is unknown, the order in which the hemispheres became specialized is likewise unknown.

Spatial Preadaptations for Language in the LH

Le Doux (1983) proposed that hemispheric specialization developed progressively as a function of interhemispheric feedback effects. He noted that the PTO region in both hemispheres in monkey controls spatial behaviors, but only the RH-PTO region in humans serves this function.

Le Doux argued that, in protohominids, the same cerebral region that bilaterally mediates nonlinguistic spatial behaviors in nonhominid primates came to unilaterally (LH) mediate linguistic spatial behaviors (viz., gestural communication, the earliest form of human language):

> "The emergence of human language involved a reorganisation of the primate brain such that language development involved adaptations in the spatial mechanisms of the left [PTO] . . . [because] the neural mechanisms underlying spatial behavior in early humans were preadaptive to language development." (p. 207)

Le Doux further argued that, after the above-described development, modifications occurred in RH neural actitivty to accomodate the LH language-related changes (i.e., RH functions resulted from neural adaptations to LH control of language).

Finally, Le Doux pointed out that "this formulation is non-committal as to why the leftward bias in language lateralization exists, as well as to why language should be lateralized at all" (p. 208).

Motor Preadaptations for Language Production in the LH

Hence, Le Doux focused on the spatial component of gestural communication: He proposed that the neural substrates of spatial behaviors were preadaptive to language. In contrast, Kimura and Archibald (1974) focused on the motor component of gestural communication: They proposed that the neural substrates of fine motor behavior were preadaptive to language.

This latter hypothesis is committal with respect to direction of lateralization: It suggests that LH specialization for fine motor behavior, which existed prior to that for formal language per se, predisposed that hemisphere to mediate language production (gestural communication in rudimentary language and speech in more developed language systems).

Cognitive Processing in the LH

Whereas the above two hypotheses emphasize the production component of gestural communication (its spatial nature in the former case and its motor nature in the latter), sign aphasiac data highlight the cognitive component of gestural communication (Bellugi, Poizner, & Klima, 1983; Curtiss, 1985). These data indicate that the LH controls "what linguists refer to as `the grammar' [of language], regardless of performance modality" (Curtiss, 1985, p. 110).

For example, Bellugi et al. showed that when deaf humans with LH damage were comprehensively behaviorally tested on their mastery of sign language, they performed significantly better on the visuospatial tests (e.g., line orientation and dot localization) than on the linguistic ones. (Their types of linguistic impairments included those of grammar, fluency, and lexicon.) Such data suggest that the LH mediates linguisitic processing per se, not linguistic production.

Motor Involvement in Language Production and Perception

Like Curtiss and Bellugi et al., Studdert-Kennedy and

Shankweiler (1970, cited in Springer & Deutsch, 1985, chap. 12) focused on a non-production-related aspect of language. They pointed out that motor involvement in language extends beyond speech production into the domain of speech perception.

Their motor theory of speech perception claims that certain sounds are perceived as similar because they are produced in a similar fashion. They investigated the fact that although consonants in different consonant-vowel combinations sound slightly different from one another, they are accurately recognized as the same consonant (e.g., the signal _b_ in the syllable _be_ slightly differs from _b_ in the syllable _ba_, yet _b_ in both syllables is correctly identified as the same sound).

These investigators concluded, from behavioral data, that listeners mentally calculate how they would produce the sounds that they are trying to decode and comprehend.

Summary

The intimate relationships between (a) fine motor behavior, gestural communication, and speech production and perception, and (b) LH control of fine motor behavior and LH mediation of linguistic processing imply that the hemispheres became functionally specialized in the following order: (a) The LH was specialized for a rudimentary form of language (gesture) prior to RH specialization for complex visuospatial processing, and (b) further LH specializations for more advanced aspects of linguistic processing (speech) succeeded the RH visuospatial specialization.

The above-cited hypotheses and data outline a progression concerning the neural control of communication in primates: What began as LH control of nonlinguistic spatial and fine motor behaviors evolved into, first, LH control of manipulospatial aspects of human protolanguage, and, second, LH control of cognitive and fine motor aspects of more advanced forms of human language. Whereas the LH may have been predisposed to linguistic processing due to its superiority in those sensorimotor behaviors constituting the production-related components of language, the LH may have come to be involved in comprehension-related aspects as well.

Conclusion

The discussion herein partially answers the questions posed at the outset of this subsection (viz., [a] why asymmetry evolved at all and [b] why the direction of asymmetry evolved as it has). The evolution of increasingly complex cognitive capacities in higher mammals was probably due to feedback effects between intrinsic species-specific neural properties and environmental pressures.

For example, when increasingly elaborate visual and communicative systems were required for survival, modifications in cerebral organization may have occurred. First, foraging requirements, offensive and defensive postures in predator-prey interactions, and other environmental pressures for highly developed visual capacities may have influenced the evolution of decussation and structural cortical asymmetries in the visual system.

Second, as social structures became increasingly complex, pressures for improved forms of communication likewise increased; they may have influenced the evolution of hemispheric specialization in motor, auditory, and cross-modal association cortex. Furthermore, the direction of this specialization may have been biased toward the LH due to its superiority in fine motor processing, a critical component of the rudimentary forms of human language.

In sum, several hypotheses have been advanced concerning the evolution and adaptive advantages of cerebral asymmetry. (Note. To review, the advantages mentioned in the preceding subsection include: (a) the processing of a wide range of visuospatial and verbal stimuli, (b) the spatial separation of incompatible processing modes (synthetic and analytic), (c) increased speed of visuospatial and verbal processing, and (d) increased accuracy in certain types of visuospatial recognition.)

However, until the precise subunits of visuospatial and verbal behaviors for which each hemisphere is specialized are specified, a complete account of the evolution of cerebral asymmetry in mammals cannot be formulated. Continued comparisons among experimental, clinical, and comparative data need be made to better understand the interrelated "what" and "whence" aspects of hemispheric specialization.

It is important to note that the above discussion concerning the advantages and evolution of lateral asymmetry has assumed that this type of cerebral functional organization (a) is adaptive and (b) currently serves functions directly related to those served at earlier stages of evolution.

Gould and Lewontin (1979) challenge this assumption: They argue that, consistent with Darwin's statement that "natural selection has been the main, but not exclusive means of modification" (Darwin, cited in Ibid., p. 589), a given organismic form, function, or behavior did not necessarily evolve due to its being the best suited to survive under a particular set of enviromental pressures.

These researchers propose, instead, that, in certain cases, alternatives to the "adaptationist programme" (p. 584) operate; some of their suggested alternatives include the following:

1. Random factors (e.g. genetic drift), rather than adaptation to selective pressures, underlie evolutionary development.

2. The form of one part of an organism may not be due to natural selection, but may be correlated with another part that is due to selection. This situation includes the "`mysterious' laws of the `correlation of growth'" (Darwin, cited in Ibid., p. 591) or allometry: Whereas body size may be determined by selection, the size of a given part of that body may be determined by its relation to overall body size,

not by selection per se.

3. The current function of a given organismic part may differ from its original function; the former may be viewed as a secondary function, perhaps due to architectural or developmental constraints on the organism, whereas the latter may be viewed as its primary function.

Stated in the words of Gould and Lewontin, "One must not confuse the fact that a structure is used in some way . . . with the primary evolutionary reason for its existence and conformation" (p. 587) . . . . "The immediate utility of an organic structure often says nothing at all about the reason for its being" (p. 593). These authors provide both biological (e.g., the divaricate form common among mollusks and brachiopods) and nonbiological (architectural and anthropological) examples of this point.

Concerning one of their architectural examples, they note that (a) the initial function of the spandrels (i.e., the tapering triangular spaces formed by the intersection of two rounded arches at right angles) in the Cathedral of San Marco in Venice was not an adaptation; rather, their original "reason for being" was that they were necessary structural by-products of mounting a dome on rounded arches, that is, they were architectural constraints; and (b) their current function, namely, the provision of the ceiling space in which frescoes are painted, contrasts their intial one.

Hence, according to the reasoning of Gould and Lewontin, cerebral lateral asymmetry (a) was not necessarily initially due to natural selection and (b) does not necessarily serve functions similar to those it originally served. Sergent's suggestion (see subsection 1.4/2) that hemispheric specialization for processing mode (holistic vs. analytic) and stimulus type (nonverbal vs. verbal) is epiphenomenal, that is, a secondary effect of greater RH proficiency in processing low spatial frequencies (the neural substrates of holistic and nonverbal processing) and greater LH proficiency in processing high spatial frequencies (the neural substrates of analytic and verbal processing) is consistent with at least the second point illustrated by the spandrel argument.

8/ The Development of Hemispheric Specialization

> "In our newborns, the appearance of driving activity in the RH to rhythmic visual stimuli suggests that this may be an early index of cerebral dominance." (Crowell, Jones, Kapuniai, & Nakagawa, 1973, p. 207)

"Whence hemispheric specialization" concerns not only the phylogenetic development of this type of cerebral organization, but also its ontogenetic development. Concerning the latter, three issues need be addressed: (a) the stages of life during which asymmetry begins and ends, (b) the direction in which magnitude of asymmetry changes throughout the lifespan (i.e., whether it increases or decreases with increasing age), and (c) the relative rates of development of the callosal fibers and the individual hemispheres.

Concerning the first two issues, the following four positions have been formulated:

1. Asymmetry does not exist in the neonate. Rather, both hemispheres are equipotential from birth until 2 years of age at which time asymmetry begins. It then gradually increases with increasing age (the progressive maturation hypothesis [Orton, 1937, cited in Kershner, 1985]). Krashen (1973, cited in Searleman, 1983) proposed that this process stabilizes at roughly 5 years of age; Lenneberg (1967), in contrast, argued that such stabilization occurs during puberty.

2. Asymmetry does exist in the neonate and does not significantly change in magnitude throughout the lifespan (the developmental invariance hypothesis [Kinsbourne, 1975, cited in Kershner, 1985]).

3. Asymmetry exists in the neonate and increases in magnitude with increasing age (Hécaen, 1976, cited in Witelson, 1985a).

4. Asymmetry exists in the neonate and decreases in magnitude with increasing age (the developmental balance, or inverted progressive maturation, hypothesis [Kershner, 1978, cited in Kershner, 1985]).

Regarding the third issue (viz., rate of development of the callosal fibers relative to that of the cerebral hemispheres), the following four positions have been proposed:

1. The corpus callosum gradually matures throughout childhood (Salamy, 1978, cited in Kershner, 1985; Yakolev & LeCours, 1967, cited in Desmedt, 1977).

2. The RH develops more rapidly than the LH (Chi et al., 1977, cited in Witelson, 1985a).

3. The LH develops more rapidly than the RH (the maturational gradient hypothesis [Corballis & Morgan, 1978] and the LH for language hypothesis [Ellis, 1983; Le Doux, 1983; Lenneberg, 1967]).

4. Some RH functions develop prior to LH functions that, in turn, develop prior to other RH functions (Turkewitz & Ross-Kossak, 1984).

Evidence regarding some of the above-listed hypotheses follow.

The Status of Cerebral Asymmetry During Early Life and Its Variation in Magnitude Throughout Life

The Onset of Hemispheric Specialization

Asymmetry during infancy has been shown by neuroanatomical, behavioral, and electrophysiological data. First, the relatively larger LH than RH planum temporale (a language-mediating structure) found in adult human brains (Geschwind & Levitsky, 1968) was also observed in fetuses (Wada, cited in Kinsbourne, 1978) and neonates (Witelson & Pallie, 1973). Second, head position and body posture asymmetries were found in young infants (Turkewitz, 1976). Third, auditory EP activity to speech stimuli was shown to be greater over the LH than RH in infants (Molfese et al., 1975, cited in W. S. Brown, Marsh, & Ponsford, 1985).

One electrophysiological study can be interpreted to support both the "asymmetry in infancy" and "no asymmetry in infancy" positions. Crowell et al. (1973) measured photic driving (synchronization between the temporal frequency of light stimulation and that of the EEG) in 36 neonates. They recorded EEG over laterally homologous occipital sites (O1 and O2) to light flashes bilaterally and repetitively presented at a fundamental frequency of 3 Hz.

Sixteen subjects showed unilateral photic driving favoring the RH; 2 subjects demonstrated unilateral driving favoring the LH; the remaining 18 showed bilateral driving. These data demonstrate that (a) both asymmetrical and symmetrical patterns exist in neonates, and (b) when the former pattern does occur, the direction of that asymmetry shows the typical adult dextral pattern (RH specialization for visual stimulation).

The existence of hemispheric specialization early in life has been supported, not only by most of the above-cited data, but also by an argument formulated by Witelson (1985a). This argument explains why some behavioral evidence, actually supportive of this position, is often misinterpreted as countersupportive.

Witelson noted that specialization is often confounded with complex cognitive capacities. Because such capacities, which are markers of specialization, do not develop until late childhood or adolescence, it falsely appears that specialization does not develop until that time either.

Witelson argues that functional cerebral asymmetry exists prior to complex cognitive behaviors in a latent form and becomes manifest when such behaviors develop. She cautions against misreading the apparent situation (lack of specialization in early life and specialization in later life) to be the real situation (latent specialization in early life and manifest specialization in later life).

Development of Magnitude of Asymmetry

Increase in magnitude. If asymmetry does exist throughout the lifespan, the question arises: Does its magnitude increase or decrease? Hécaen (1976, cited in Witelson, 1985a) proposed that magnitude increases, at least throughout childhood. He supported his position by citing clinical data showing decreasing equipotentiality for language during this period: More cases of aphasia are found in children than in adults with RH lesions. (Note. Witelson [Ibid., p. 76] suggests that these data are incorrect due to methodological error.)

Decrease in magnitude. Kershner (1978, cited in Kershner, 1985), on the other hand, advocated that hemispheric specialization decreases (or conversely, that interhemispheric integration and collaboration increase) with increasing age. Behavioral, electrophysiological, and neuroanatomical data support his position.

For example, the magnitude of the right ear advantage found to digit stimuli (during a dichotic listening task) decreased with increasing age in 360 first to sixth grade subjects (Kershner, Ibid.). Hiscock and Kinsbourne (1977, cited in Kershner, 1985) corroborated these results. They demonstrated that size of right ear advantage in preschoolers exceeded that in adults. Although these data may reflect real effects, they may also reflect a ceiling effect due to the task's being easier for the older than younger subjects (Kershner, 1985).

Further behavioral evidence was provided by Kirk (1985) who analyzed the development of graphomotor production in normal children. She found that relatively younger children used either LH (internal features and serial processing) or RH (external features and parallel processing) strategies, whereas older children used bihemispheric strategies.

Molfese et al. (1975, cited in Kershner, 1985) provided auditory EP evidence for Kershner's hypothesis. They found that magnitude of asymmetry in infant EPs to music and speech stimuli exceeded that in adult EPs.

Finally, de Lacoste et al. (1986) found that the magnitude of the regional volumetric asymmetries in retrocalcarine cortex in human adult brains (20%) was smaller than that in human fetus brains (30%). These data show that a decrease in asymmetry with increasing age may be due, not to developmental changes in interhemispheric interaction, but rather to such changes in the hemispheres themselves.

Relative Rates of Development of the Interhemispheric Connections and the Cerebral Hemispheres

The Corpus Callosum

As the above data demonstrate, the development of each component of the neural system underlying cerebral asymmetry (viz., [a] the interhemispheric neural connections and [b] each of the hemispheres) must be examined to understand the development of this type of cerebral organization.

Concerning the first component, the corpus callosum is "disproportionately small" in the neonatal brain (Springer & Deutsch, 1985, p. 195) and, according to neuroanatomical data, gradually matures throughout childhood (Salamy, 1978, cited in Kershner, 1985; Yakolev & LeCours, 1967, cited in Desmedt, 1977).

The Cerebral Hemispheres

Earlier RH than LH development. Concerning the second component, one neuroanatomical study provided evidence for the earlier development of the RH relative to that of the LH. Chi et al. (1977, cited in Witelson, 1985a) found that the convolutions in the RH superior temporal gyrus developed significantly earlier than those in the LH in 67% of the human brains they examined.

Earlier LH than RH development. Also concerning the second component, some behavioral data suggest the opposite of Chi et al.'s results. Carey and Diamond (1977) found that recognition accuracy was equal to upright and inverted unfamiliar faces in children younger than 10 years of age, but was significantly worse to inverted faces in children older than 10.

The investigators interpreted these results to indicate that younger children use separate facial features as the basis for recognition, whereas older ones use an integrated percept of the separate features to recognize the facial stimuli. Carey and Diamond, as well as Young (1983) (in a review chapter), attributed this shift from a LH-mediated piecemeal to a RH-mediated configurational strategy to the earlier maturation of the LH relative to the RH.

S. C. Levine (1985) suggested that use of the LH-based piecemeal strategy prior to the RH-based configurational one during facial recognition may be due to an experiential, rather than maturational, factor. She proposed that children younger than 10 may not have had the amount of experience with faces required for them to form the neural representations of these stimuli (called schemata) used during configurational processing.

In contrast to Levine, several advocates of the LH prior to RH hypothesis have focused on maturational (intrinsic) factors. They have suggested that the major reason for this developmental course is that normal language development requires that the LH be prepared for language processing at birth.

Some of the neuroanatomical and electrophysiological data cited above provide evidence for this LH prepotency for language: (a) Witelson and Pallie (1973) found that the "language-mediating" planum temporale was larger in the LH than in the RH in 14 postmorten neonatal brains, and (b) Molfese et al. (1975, cited in Springer & Deutsch, 1985, chap. 8) showed that the amplitudes of auditory EPs recorded during speech stimulation were greater in the LH than RH in 9 out of 10 infants.

A corollary to the notion that normal language development requires extremely early LH development is that functions are allocated to the LH prior to the RH: RH functions are effectively "leftovers" of LH language-related functions (Ellis, 1983; Le Doux, 1983; Lenneberg, 1967), and the RH is the "default" hemisphere that develops after the LH (Corballis & Morgan, 1978; Netley & Rovet, 1983). Whether or not this order effect is true, the fact remains that the association between language and lateral asymmetry is strong.

The relationship between asymmetry and language. The strength of this correlation is demonstrated by the data showing that when language is not acquired during the critical period for this behavior, cerebral asymmetry does not develop. For example, RH control of both language and nonlanguage functions (dichotic listening and ERP measures) was found in a dextral individual (Genie) who did not learn her first language until adolescence. (Note. Even then, she learned only "primarily lexical and propositional semantics, with little acquisition of structural or computational linguistic knowledge" [Curtiss, 1985, p. 108].)

Data from deaf individuals also demonstrate the intimate relationship between language and hemispheric specialization. Congenitally deaf children and adults who lacked mastery of language (including sign) showed no evidence of lateral asymmetries for processing linguistic or nonlinguistic information. In contrast, deaf individuals who had acquired a formal language (sign) during the critical period did show asymmetries for these two types of processing (ERP measures) (Neville, 1977, cited in Curtiss, 1985).

Hence, "without language, signed or spoken, individuals show an absence of functional asymmetry" (Curtiss, 1985, p. 110). How this close relationship between language and asymmetry affects the allocation of functions to, and rates of development of, each cerebral hemisphere requires further investigation.

Function-specific determinants of rate of hemispheric development. Some behavioral data exist that reconcile the apparently contradictory positions of (a) RH development prior to that of the LH and (b) LH development prior to that of the RH. As mentioned above, the facial recognition data of Turkewitz and Ross-Kossak (1984) suggest that two types of RH-based processing strategies may develop at different times: RH Strategy 1 (primitive holistic; uses external facial characteristics as cues for recognition) develops prior to the LH strategy; the latter, in turn, develops prior to RH Strategy 2 (advanced holistic; uses an integrated percept of external and internal facial characteristics as recognition cues).

Further, error score analysis revealed that 8- and 11-year-old males and females used only the first two types of strategies, whereas 13-year-old females used all three types. (See subsection 1.1/6 for description of experimental procedure and broader definition of these strategies.)

Hence, these results suggest that, in females, some aspects of RH function develop earlier than those of the LH that, in turn, develop earlier than other aspects of the RH. If this entire pattern is also true for males, the age at which the RH functions underlying the advanced holistic strategy develop is older than that for females.

Conclusion

The above data suggest that the development of human cerebral asymmetry can be viewed as having two components that mature at different rates: One component, unilateral specialization, develops prenatally; the other, the callosal system, completes development postnatally (during adolescence at the latest).

Regarding the first component, the distinction between competence and performance (Chomsky, 1965) must be made: At birth, the hemispheres are specialized for the potential to acquire, produce, and comprehend cognitive functions (competence) rather than for the developed functions themselves (performance). Hemispheric specialization for cognitive performance develops postnatally, and the rate of development for each cognitive skill is specific to that particular skill.

In sum, it appears that hemispheric specialization per se exists in the neonate, but the development of the cognitive functions for which the hemispheres are specialized and the interhemispheric integration of those functions remain incomplete until late childhood or early adolescence.

9/ Hemispheric Specialization as a Function of Stimulus Familiarization

Whether an individual uses a RH-based holistic, or a LH-based analytic, strategy during recognition depends on several factors including time. Different time scales have been used to measure shifts in these putatively hemisphere-mediated cognitive strategies.

For example, in the preceding subsection, such shifts were shown to vary with chronological age (i.e., learning throughout the lifespan) (Carey & Diamond, 1977; Turkewitz & Ross-Kossak, 1984). In contrast, in the current subsection, such shifts are shown to vary with stimulus familiarization (i.e., learning during a single experimental session). Ross-Kossak and Turkewitz (1986) call the former time scale the macro level and the latter, the micro level.

Some clinical data highlight the fact that the processes used to recognize certain classes of familiar and unfamiliar stimuli are dissociated. For example, prosopagnosiacs cannot recognize familiar faces, but can recognize unfamiliar ones (Benton, 1980; Warrington & James, 1967).

Normative data indicate that the strategy and associated hemisphere used during recognition depend on relative degree of stimulus familiarization. (_Note_. In experiments, this latter variable is controlled by numbers of practice and experimental trials.) Examples of different shift patterns in hemispheric advantage during recognition as a function of familiarization follow.

RH to LH Shift with Increasing Familiarization

First, in an auditory recognition task in which sequential musical notes were the stimuli, musically naive subjects displayed a left ear advantage, and musically experienced ones, a right ear advantage (Bever & Chiarello, 1974, cited in Bever, 1975).

Second, in facial recognition tasks, an initial RH advantage was found to unfamiliar stimuli when no practice trials had been administered in both clinical (Levy, Trevarthan, & Sperry, 1972; Milner, 1968; Yin, 1970) and normative (Geffen, Bradshaw, & Wallace, 1971) samples. In contrast, Umilta et al. (1982, cited in Ross-Kossak & Turkewitz, manuscript) found an initial LH advantage when practice trials had been administered, that is, when subjects were somewhat familiar with the stimuli.

Goldberg and Costa (1981) postulated that this RH to LH shift accompanying increasing experience with a given stimulus is due to the use of different codes to recognize novel and familiar stimuli: _Nondescriptive systems_ (i.e., nonanalytic and nonverbal representations typical of RH processing) are used to recognize novel stimuli; _descriptive systems_ (i.e., analytic and verbal representations typical of LH processing) are used to recognize familiar ones.

LH to RH Shift with Increasing Familiarization

In another auditory recognition task in which simultaneously presented musical notes (musical chords) were the stimuli, Kellar and Bever (1980, cited in Bever, 1975) found the opposite pattern to that of Bever and Chiarello. In this second study, musically naive subjects displayed a right ear advantage, and musically experienced ones, a left ear advantage.

Tripartite (RH to LH to RH) Shift with Increasing Familiarization

In divided visual field recognition tasks with dextral female undergraduate subjects (and accuracy as the dependent variable), Ross-Kossak and Turkewitz sometimes found the same LH to RH pattern as Kellar and Bever. Other times (as mentioned in subsections 1.1/6 and 1.1/8), they found a tripartite shift in hemispheric advantage (from the RH to the LH and back to the RH) with increasing familiarization with initially unfamiliar facial stimuli (Ross & Turkewitz, 1982; Ross-Kossak & Turkewitz, 1984; Ross-Kossak & Turkewitz, 1986).

Differences in initial hemispheric advantage may have reflected individual differences in hemisphericity (one's tendency to be a RH type or LH type). Ross-Kossak and Turkewitz postulated that those who demonstrated the tripartite pattern had available two kinds of RH-mediated strategies each of which they used as a function of degree of stimulus familiarization. (See subsection 1.1/6 for descriptions of experimental procedures and these cognitive strategies.)

The robustness of this finding was demonstrated by (a) its replication in a number of studies and (b) the fact that subjects demonstrated this same pattern when the initial set of facial stimuli was replaced by a second set of facial stimuli in the same study (Turkewitz & Ross, 1983). This second finding suggests that subjects had learned more than how to recognize a particular set of facial stimuli: They learned, instead, a general approach to solving recognition problems characterized by shifting between holistic and analytic strategies at approriate times (Ibid.).

As mentioned in subsection 1.1/8, this tripartite pattern is age- and gender-specific: 13-year-old females used both primitive and advanced holistic RH-mediated strategies, in addition to the LH analytic strategy. In contrast, 8- and 11-year-old males and females used only the primitive holistic RH strategy, in addition to the LH analytic strategy (Turkewitz & Ross-Kossak, 1984).

S. C. Levine, Banich, & Koch-Weser (manuscript) replicated Ross-Kossak and Turkewitz' finding of a RH advantage to highly familiar facial stimuli during recognition. Levine et al., however, provided a different account of their results. They suggested that (a) stimulus familiarization permitted the formation of strong schemata of those stimuli, and (b) such schemata are used only by the

RH as the basis for recognition judgements. (See S. C. Levine, 1985, in subsection 1.1/8 regarding the consequences of this effect on type of strategy used by children younger and older than 10.)

The work of Ross-Kossak and Turkewitz suggests that the apparently incompatible results yielded by the two auditory studies cited above may, in fact, be compatible. If the recognition strategies described by Ross-Kossak and Turkewitz are used in the auditory as well as visual domain, then (a) the RH to LH shift in advantage found in the Bever and Chiarello study may have represented the RH Strategy 1 to LH strategy shift, and (b) the LH to RH shift in superiority revealed in the Kellar and Bever study may have represented the LH strategy to RH Strategy 2 shift.

Further, in the latter study, the initial LH advantage may have reflected LH types in the sample. Also, the gestalt nature of the stimuli (musical chords) may have elicited the strategy (RH 2) that uses integrated percepts as the basis for recognition.

Conclusion

It seems that moderately familiar musical and facial stimuli elicit LH-mediated processing strategies, and highly familiar musical and facial stimuli elicit RH-based strategies. Variations in this pattern may be due to (a) subject characteristics (e.g., gender, age, and hemisphericity) and (b) subjects' degree of familiarization with the stimuli. Finally, the generality of this pattern to other stimulus classes requires further investigation.

10/ Critique of Two Aspects of Lateralization Research: The Dichotomania Position and Stimulus Control

First, caution must be taken to avoid <u>dichotomania</u>, that is, the absolute allocation of visuospatial, holistic, and gross motor processing to the RH and that of linguistic, analytic, and fine motor processing to the LH. This view is reductionistic and yields an incorrect description of cerebral functional organization (McKeever, 1981, cited in Corballis, 1983).

Although a given hemisphere may be relatively more involved and/or proficient than the opposite one vis-à-vis a particular behavior at a particular time, it does not necessarily follow that the same hemisphere controls all aspects of that behavior under all circumstances. Experiments have shown that such factors as subject characteristics, subjects' degree of stimulus familiarization, processing stage, and task demand affect differential hemispheric engagement.

Second, one must also be cautious when one interprets data concerning the behaviors for which the hemispheres are putatively specialized. Certain stimulus duration values and the inadequate control of stimulus composition result in testing the hemispheric mediation of a different behavior from that which the study was intended to test: What is interpreted to be the hemispheric control of one behavior may, in fact, be the hemispheric control of another, unidentified behavior. Examples from the literature concerning dichotomania and stimulus control follow.

Dichotomania

Subject Characteristics

As discussed in subsection 1.5 below, subject characteristics (e.g., gender, age, hand preference, incidence of familial sinistrality, ethnic background, number of languages spoken, visual acuity, ocular dominance, and intelligence) affect an individual's lateralization pattern.

Stimulus familiarization on the macro and micro levels. The age variable, in particular, highlights the fact that functional asymmetry is dynamic: Whether the RH or LH is relatively more involved in a given behavior is a function of time. As one ages, his/her amount of experience with a given stimulus increases, and hemispheric involvement in the processing of that stimulus varies with degree of stimulus familiarization. This relationship holds with respect to learning (a) across the lifespan (macro level) and (b) during a single experimental session (micro level) (Ross-Kossak & Turkewitz, 1986; see subsection 1.1/9).

Task Characteristics

Processing stage. Hemispheric engagement varies not only with stage of learning, but also with stage of processing during a particular task. No matter how simple tasks may appear, on the underlying level, they are complex, multiple-stage processes. Electrophysiological data concerning visuospatial processing (Gevins et al., 1981, 1983, 1985) and behavioral data concerning linguistic processing (Benson, 1985a; Broadbent, 1974; Lenneberg, 1967; Searleman, 1983; Thatcher, 1980; and E. Zaidel, 1985a; see subsection 1.1/2) support this notion.

The dynamic mosaic model. In concordance with the above data, many researchers currently advocate the dynamic mosaic model of cerebral function (Gevins et al., 1981). This model views a given behavior as a network of constituent sub-behaviors processed in different cerebral loci in both hemispheres at different times (Allen, 1983; Le Doux, 1983).

Data such as those of Gevins and his colleagues suggest that a model of hemispheric specialization more closely aligned with the aggregate field than functional localization view more accurately describes the functional organization of the human brain, at least with respect to higher functions. A static, highly localized model involving unilateral control of a given behavior cannot account for cerebral mediation of human cognitive behaviors because these "abstract mental functions involve the complex interaction of many brain areas" (Luria, 1973, 1977, cited in Gevins, 1983, p. 337).

Task demand. Hence, task-related variables affect selective hemispheric activation. The latter varies not only with processing stage and/or sub-behavior during a given task, but also with task demand (Berent, 1977; Klein et al., 1976; Sergent & Bindra, 1981). Posner (1978) showed, for example, that a RH advantage was found under physical match instructions to letter stimuli, and a LH advantage, under name match instructions to the identical stimuli.

Stimulus Control

Stimulus and Interstimulus Interval (ISI) Duration.

Certain stimulus and ISI duration values can result in the testing of hemispheric specialization for a different behavior than the one apparently tested. For example, in facial discrimination tasks, when brief test stimulus durations and long intervals between the two faces being compared are used, the capacities to process partially encoded information and poor-quality stimulus representations (due to trace decay during the ISIs), not the capacity to recognize faces, are the actual behaviors tested.

Conversely, the use of long test stimulus durations and short ISIs really tests the abilities to process completely encoded information and high-quality stimulus representations. The former conditions generally result in a RH advantage, and the latter, in LH superiority (Nebes, 1971; Nebes, 1972, 1973, cited in Kinsbourne, 1978; Sergent, 1982a, 1982b, 1982d, 1983a, 1983b, manuscript; Sergent & Bindra, 1981; Warrington & James, 1967).

Hence, whereas the data putatively show RH or LH involvement during facial processing, they actually demonstrate hemispheric activation vis-à-vis low- and high-quality stimulus representations (Sergent, Ibid.).

Stimulus Composition. Finally, although differential hemispheric engagement may be observed to a given stimulus dimension, the response pattern may be partially due to uncontrolled stimulus variables. For example, differential hemispheric sensitivity to visuospatial and verbal stimuli found in many divided visual field studies may not have been entirely due to the nonlinguistic/linguistic dimension of the stimuli. Rather, another stimulus dimension, such as the spatial frequency composition of the pictorial and alphabetic stimuli, may have contributed to these results.

Hemispheric specialization for spatial frequency. Sergent (1982a) proposed that hemispheric specialization for different spatial frequency ranges may be more fundamental than that for nonverbal and verbal stimuli. It is this spatial frequency model of hemispheric specialization that the current study was designed to test. Hence, the term spatial frequency, and evidence for and against this model, are discussed in the subsequent subsections of this Introduction.

1.2] SPATIAL FREQUENCY CONSTITUENTS OF PATTERNED STIMULI

1/ Definition of Spatial Frequency

To understand the spatial frequency dimension of light, some fundamental characteristics of light itself need be described. First, light, the stimulus for vision, is the 400-750 nanometer (nm) band of the electromagnetic radiant energy spectrum. (Note. One nm is a unit of wavelength equal to 10^{-9} meters.)

Second, light energy is specified in either absolute physical units called radiometric units or units weighted according to the sensitivity of the human visual system called photometric units. The current study used photometric units to specify the stimuli. Because an extended light source was used, namely, a rear-illuminated screen, these units were foot-Lamberts (ft-L).

The simplest spatial pattern of light used in vision research is a grating, that is, a series of light and dark bars. In this pattern, luminance level varies in one direction: The light distribution across the stripes is characterized by a sine wave (sinusoidal) luminance profile. (Note. A sine wave, or periodic oscillation above and below a mean intensity value in which one such oscillation constitutes one cycle, is the simplest natural form of a pattern of light.)

The number of pairs of light and dark bars, that is, the number of sinusoidal cycles around a constant mean luminance, in a given unit of space (typically measured in cycles per degree [cpd] of visual angle) is the spatial frequency of the pattern.

Another pattern typically used in vision research, and used in the current study, is the checkerboard. This pattern consists of vertical and horizontal square-wave gratings placed orthogonally with respect to one another and, hence, is a two-dimensional spatial stimulus. In this stimulus, the number of pairs of light and dark checks in the horizontal direction is used to calculate the spatial frequency of the pattern. Few cycles per degree (low spatial frequency) appear as large checks; many cycles (high spatial frequency), as small ones (Campbell & Maffei, 1976) (see Figure 4).

Because low-frequency stimuli contain relatively few, large components, and high-frequency stimuli, relatively many, small ones, some researchers categorize the former as simple stimuli and the latter as complex (Attneave, 1957, cited in Karmel, 1969) (see Figure 4). This characterization, however, is by no means unequivocal: Stimulus complexity may also be determined by structural criteria (geometric relationships between stimulus components), rather than by component size.

2/ The Spatial Frequency Model of Visual Processing

> "We may suppose that the visual system behaves . . . as a number of independent detector mechanisms each preceded by a relatively narrow-band filter tuned to a different frequency. Each filter and detector would constitute a separate `channel.'" (Campbell & Robson, 1968, p. 564)

Campbell and Robson (1968) proposed that the mammalian visual system contains neurons which function as Fourier analyzers: They extract information from inputs at particular spatial frequencies.

These neurons are grouped into parallel <u>channels</u> which function as bandpass filters: Each channel is tuned to, and only transmits sinusoidal signals of, a particular frequency range. The value of that range varies with processing level

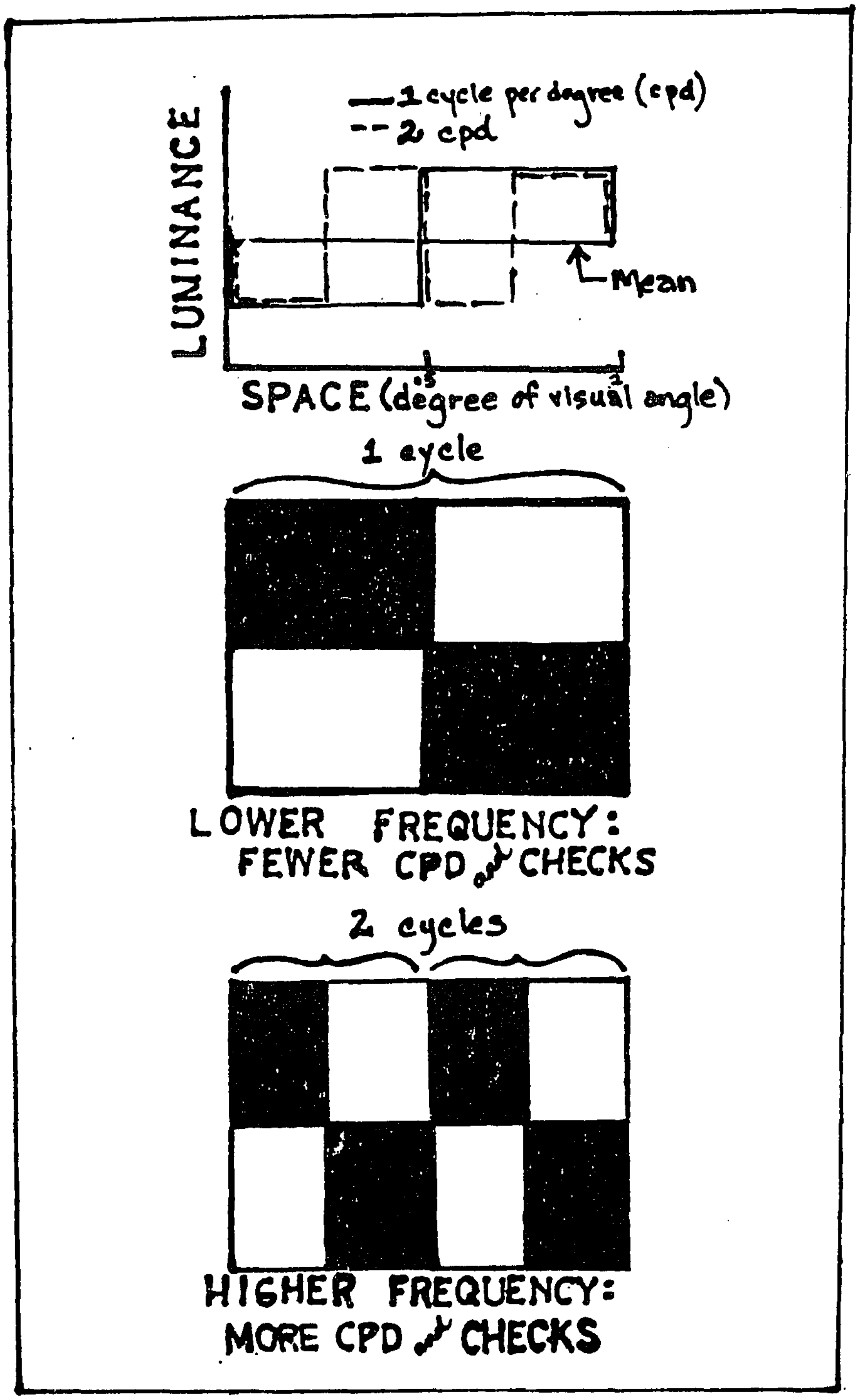


Figure 4. Spatial frequency: The fundamental component of checkerboard patterns.

(the lower the level, the broader the tuning, e.g., cortical channels are more narrowly tuned than retinal ones [Robson, 1975; Shapley & Lennie, 1985]). The summation (or envelope) of these individual frequency channels represents stimulus processing by the entire visual system.

As shown in Figure 5, the "channel envelope" in the human visual system is optimally sensitive to middle-range frequencies (3-6 cpd), and its sensitivity falls off at lower and higher frequencies. Figure 5 (referred to as either the spatial frequency or contrast sensitivity function) graphs the reciprocal of the amount of contrast required by a given subject to detect a grating stimulus; the spatial frequency of that stimulus is varied according to the values labelled on the abscissa.

At each level of the visual system (the retina, lateral geniculate nucleus [LGN] of thalamus, and areas 17-19 of cortex), spatial frequency channels form neural representations of the visual field as follows:

1. A given neuron, and its associated channel, selectively respond to a particular frequency band constituting part of the total visual field.

2. A given neural array (consisting of several different channels) selectively responds to several different frequency bands constituting a given part of the total visual field.

3. The above steps are repeated for each part of the total visual field, resulting in the patch-by-patch encoding

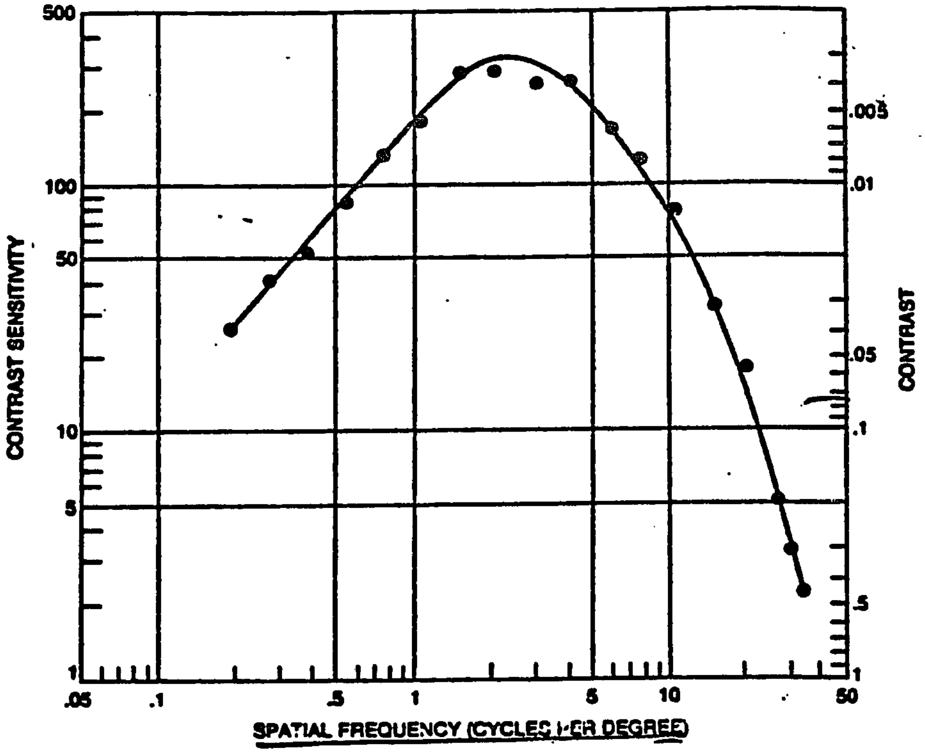


Figure 5. Human contrast sensitivity function to grating stimuli of different spatial frequencies.

Note. From "Contrast and Spatial Frequency" by F. W. Campbell and L. Maffei. In Recent Progress in Perception (p. 35) by R. Held and W. Richards (Eds.), 1976, San Francisco: W. H. Freeman.

of the total field (K. K. De Valois, R. L. De Valois, & Yund, 1979; Robson, 1975).

3/ Putative Neural Mechanisms of Spatial Frequency Processing

Anatomical, physiological, and psychophysical data from cat, monkey, and human have suggested possible neural mechanisms of spatial frequency processing and, hence, have provided strong evidence for this model.

Two types of visual neurons, (a) the parvocellular (small) X-cell (that presumably constitutes the <u>sustained</u> visual subsystem) and (b) the magnocellular (large) X-cell (that partially constitutes the <u>transient</u> subsystem), have been identified as the putative mediators of high and low spatial frequency processing, respectively. A third type of visual neuron, the Y-cell (the other constituent of the transient subsystem), has been identified as the putative modulator of X-cell activity (Lennie, 1980; Spitzer & Hochstein, 1985).

Lennie (Ibid.) pointed out a major advantage of the mammalian visual system's being composed of these complementary cellular subtypes: Each subtype's being specialized to process a particular frequency range permits the entire system to be sensitive to a wide range of illuminance modulation.

Table 2 and the remainder of this subsection (a) describe the major characteristics of, and evidence for, these visual susbsystems and (b) highlight the ways in which

Table 2

Characteristics of X- and Y-cells

	Cell Type	
Characteristics	X-cell	Y-cell
Function	mediates pattern discrimination (small cells process high spatial frequencies; large cells process low ones)	1. mediates contrast and movement detection 2. modulates X-cell activity in relation to input salience
Anatomy		
Size of overall cell, receptive field, and axon	small large	large
Location (wiring)	1. central retina 2. LGNd (thalamus) 3. area 17; simple and complex cells (cortex)	1. peripheral retina 2. LGNd (thalamus); superior colliculus (brainstem) 3. areas 17, 18, 19; simple and complex cells (cortex)

(table continues)

	Cell type	
Characteristics	Sustained system (small X-cells)	Transient system (large X-cells and Y-cells)
Response:		
1. Temporal		
Axon conduction	slower	faster
Response (decay) time	longer (slower)	shorter (faster)
Optimal stimulus	low temporal frequency (sustained stimulation)	high temporal frequency (brief stimulation)
2. Spatial		
Optimal stimulus	high spatial frequency (small)	low spatial frequency (large)
Summation mode	linear (both small and large X-cells)	nonlinear (Y-cells only)

these characteristics are consistent with the spatial frequency model.

Anatomical Characteristics of X- and Y-cells and Evidence for Parallel Channels

Size of Individual X- and Y-Cells and Cellular Components

The overall cell, receptive field, and axon of X-cells are smaller than those of Y-cells (Enroth-Cugell & Robson, 1966; Cleland et al., 1971, cited in Di Lollo & Woods, 1981; Fukuda, 1971, cited in Lennie, 1980; Gouras, 1969, cited in Di Lollo & Woods, Ibid.).

Location of X- and Y-cells Both Within and Between Ascending Processing Levels

Retinal level. Among ganglion cells, increasing receptive field size covaries with eccentricity (Mansfield, 1982). As a rule, the probability of an X-cell's being found in the fovea exceeds that of a Y-cell's being found there (Enroth-Cugell & Robson, Ibid.). In cat, X-cells were found in the area centralis, and Y-cells, in the periphery (Fukuda & Stone, 1974, cited in Lennie, Ibid.). In monkey, most X-cells were found in the fovea and decreased in frequency with increasing eccentricity, whereas no Y-cells were found closer than 10-20 degrees away from the fovea (de Monasterio, 1978a, cited in Lennie, Ibid.).

Receptive field size correlates with spatial frequency sensitivity such that cells with smaller fields respond to higher frequencies, and cells with larger fields respond to lower frequencies. Hence, retinal eccentricity also covaries with sensitivity to lower frequencies (Shapley & Lennie, 1985).

Robson (1975) pointed out that retinal cells of many sizes may have evolved to maximize retinal image information content. In this case, each of the different-sized cells contributes information concerning the spatial frequency range to which it is sensitive; their combined responses represent the total spatial frequency content of a given input.

Retinogeniculate projections. The efferent retinal X- and Y-cell pathways were found to project independently of one another (in parallel) to the next higher processing level, the dorsal LGN (LGNd) (Hoffman, Stone, & Sherman, 1972). Further, whereas all retinal ganglion X-cells project only to the LGNd, the efferent retinal Y-cell pathway bifurcates: One pathway, like that of the X-cells, projects to the LGNd; the other, unlike that of the X-cells, projects to superior colliculus (in the brain stem) (Lennie, 1980; Robson, 1975; Spitzer & Hochstein, 1985).

Geniculocortical projections. Like the efferent retinal pathways, the efferent geniculate X- and Y-cell pathways were shown to project independently of one another to cortex (Cleland et al., 1971, cited in Robson, 1975; Shapley & Lennie, 1985). Also, in cat, Stone (cited in Robson, Ibid.) found that Y-pathways project directly from LGN to area 18 without traversing 17. In monkey, the LGNd X-cells were found to project to striate cortex (17) in contrast to the

Y- cells' projecting to both striate and extrastriate cortex (17, 18, and 19).

With respect to the geniculocortical cellular interactions, rather than the pathways, both X- and Y-cells were found to drive both simple and complex cortical cells (Lennie, Ibid.; Shapley & Lennie, Ibid.).

Intracortical level. Finally, within cortex itself, spatial frequency-sensitive neurons in cat have been shown to be anatomically organized as follows:

> "High spatial frequency columns are confined to the central striate cortex, and low spatial frequency columns extend peripherally, as one would predict from the well-known fall-off in acuity with eccentricity." (Tootell, 1981, p. 815)

(Note. [a] A spatial frequency range of 0.25-2 cpd and [b] the 2-deoxyglucose [2-DG] labelling technique were used in this study.)

Comparison of the Spatial Frequency and Feature Detection Models

The data suggesting that (a) the respective X- and Y-retinogeniculate and geniculocortical pathways project independently of one another, (b) geniculocortical Y-pathways project directly to 18 (in cat), and (c) geniculate X- and Y-cells drive both cortical simple and complex cells (rather than geniculate output's driving simple cells that, in turn, drive complex cells) support the notion of parallel channels postulated by the spatial frequency model.

These data are important because not only do they provide evidence for this model; they also provide counterevidence for serial wiring, a major aspect of a competing model, that is, feature detection (Lettvin, Maturana, McCulloch, & Pitts, 1959; Hubel & Wiesel, 1962, 1968).

Feature detection proposes that visual neurons are sensitive to certain stimulus features (e.g., edges), rather than to the underlying spatial frequency constitutents of those stimuli. These "feature-detecting" neurons are wired in a convergent hierarchy such that, at each level of the visual system, (a) the ratio of relatively lower to higher level neurons is many to few, or the same number of lower and higher level neurons exist such that their projections contain many interconnections and overlaps, and (b) increasingly higher level neurons are sensitive to increasingly more specific and complex stimuli.

For example, extrastriate complex cells selectively respond to an edge of a particular orientation moving in a particular direction, whereas striate simple cells are not direction-specific.

When the logic of this model is pursued to its extreme, it requires that an individual cell exist for every type of naturalistic stimulus and, hence, that the visual system contain infinite storage capacity. A strong argument in favor of spatial frequency, and against feature detection, is that the former does not require an infinite number of these "hyper-hypercomplex" or "grandmother cell" types of neurons. (Note. Data supporting feature detection are not presented herein; it is possible that both parallel and serial processing exist in the visual system.)

Electrophysiological Evidence for the Spatial Frequency Model

In addition to the "grandmother cell" argument and the anatomical (parallel pathways) evidence cited above, electrophysiological evidence for spatial frequency and against feature detection exists. For example, Albrecht, R. L. De Valois, & Thorell (1980) demonstrated that, in cat and monkey, area 17 single-unit sensitivity to spatial frequency was twice that to a stimulus feature (bar width). Further, response magnitude to optimal frequencies in grating stimuli exceeded that to optimal width in bar stimuli. (Note. Grating stimuli are patterns of alternating light and dark horizontal or vertical bands typically used in spatial frequency experiments.)

K. K. De Valois et al. (1979) corroborated this finding that single-units in cat and monkey visual cortex optimally respond to stimulus frequency rather than to stimulus features (in this case, intercheck edge distance). These investigators found that response magnitude was greater to grating and check stimuli of the same bar and check width (i.e., the same fundamental frequency) than to intercheck edge distance.

Finally, the single-unit data recorded from cat retinal ganglion X- and Y-cells (Enroth-Cugell & Robson, 1966) also provided evidence for the spatial frequency model. These data demonstrated "the existence within the visual system of separate channels having bandpass characteristics with different optimal spatial frequencies" (Campbell & Robson, 1968, p. 565).

Response Characteristics of the Transient and Sustained Systems, and Psychophysical and Electrophysiological Evidence for the Spatial Frequency Model

> "The stimulus could be detected . . . by the fast transient Y cell system, particularly when all that is required is the registration of a stimulus regardless of its character. Where the stimulus must be further analysed, probably both transient and sustained systems contribute to the processing of a stimulus and to its perceptual characteristics." (Kulikowski, 1975, cited in Parker & Salzen, 1977, p. 1204)

Spatiotemporal Complementarity Within Each Subsystem

A substantial body of psychophysical and electrophysiological data concerning spatial frequency processing has revealed (a) superior temporal analysis by the transient system and (b) superior spatial analysis by the sustained system. These findings are so consistent and fundamental to the nature of these systems that they are reflected in their names: Transient refers to its typical phasic [faster] responses; sustained, to its typical tonic [slower] responses (see Cleland et al., 1971, 1973, cited in Lennie, 1980, regarding differential response types and correlated decay times in X- and Y-cells).

These data further demonstrated the existence of spatiotemporal complementarity within each subsystem

(Breitmeyer & Julesz, 1975):

1. The transient channels displayed poor spatial and good temporal resolution: They responded to low spatial frequencies (large sizes) and high temporal frequencies (briefly presented stimuli, e.g., abrupt on/off, fast flicker, or fast pattern reversal).

2. The sustained channels demonstrated good spatial and poor temporal resolution: They responded to high spatial frequencies (small sizes) and low temporal frequencies (sustained stimulation, e.g., gradual on/off, slow flicker or slow pattern reversal) (Breitmeyer, 1975). (Note. See Cleland et al., 1973; Enroth-Cugell & Robson, 1966; Fukuda & Saito, 1971, all cited in Breitmeyer, 1975, for single-unit evidence of this principle. See Breitmeyer & Julesz, 1975; Kulikowski & Tolhurst, 1973; Tolhurst, 1973, all cited in Breitmeyer, 1975; Tolhurst, 1975, for psychophysical evidence).

Accounts of response characteristics of each subsystem.

1. Cellular anatomy. First, as mentioned earlier in this subsection, receptive field size covaries with stimulus pattern size. Cells with large receptive fields (the Y and large X transient cells) optimally respond to large patterns (low spatial frequencies); conversely, cells with small receptive fields (the small X sustained cells) optimally respond to small patterns (high spatial frequencies).

Second, (a) the relatively larger and, hence, faster conducting axons typical of transient cells and (b) the relatively smaller, slower conducting axons typical of sustained cells are major determinants of the differential temporal integration capacities of these two visual subsystems. (Note. A Y-cell retinocortical action potential requires 4 ms, whereas an X-cell action potential travelling the same distance requires 6-7 ms; Fukuda, 1971, cited in Lennie, 1980.)

2. Temporal integration effects. (Note. See Sergent, 1983a, for discussion.) First, the transient system's capacity for rapid temporal integration results in its (a) sensitivity to briefly presented stimuli and (b) relatively rapid response time. Conversely, the sustained system's inability for such rapid integration results in its (a) requirement for longer stimulus durations and (b) slower response time.

Second, temporal integration time is inversely proportional to stimulus luminance: A larger field of light requires less integration time; a smaller light field requires more time (Breitmeyer & Ganz, 1977). Hence, lower spatial frequency patterns (with wider bands of light) require less temporal integration time than higher ones (with narrower bands of light) (Ibid.). Lower spatial frequencies are thus processed by rapid temporal integrators (transient cells), and higher spatial frequencies, by slow temporal integrators (sustained cells).

Third, consistent with the principle just mentioned, Sergent (1983b) and Breitmeyer and Ganz (1977) showed psychophysically that higher spatial frequency processing requires longer stimulus durations. For example, the latter investigators found that, during detection, critical duration increased (from 60 to 200 ms) with increasing spatial frequency (from 0.5 to 16 cpd): Larger patterns were detected when briefly presented, but smaller patterns required sustained presentations to be detected.

Breitmeyer and Ganz also noted that, concomitant with their results, critical duration for pattern discrimination (200-400 ms; Kahneman, 1964, cited in Breitmeyer & Ganz, Ibid.) exceeded that for brightness discrimination (100 ms; Bloch, cited in Brietmeyer & Ganz, Ibid.).

Fourth, additional psychophysical evidence for more rapid temporal integration of low spatial frequencies was provided by Meyer and Maguire (1977) and Di Lollo and Woods (1981). They both showed, with different procedures and with respect to different frequency ranges, that duration of visible persistence (stimulus representation in iconic memory) covaries with spatial frequency.

Meyer and Maguire alternately presented vertical square wave gratings (50 ms) and blank-field stimuli to subjects instructed to adjust the duration of the blank field until they saw the grating as continuous (method of adjustment). The duration of the blank field at threshold provided a measure of iconic duration. Results showed that as spatial frequency increased from 0.9 to 15 cpd, iconic duration likewise increased from 300 to 500 ms.

Di Lollo and Woods sequentially displayed pattern parts and instructed subjects to perform a task that necessitated their perceptual integration of those separate parts (they had to locate a pattern component missing from the entire pattern). The longest ISI at which pattern parts could be integrated was considered to reflect iconic duration. Again, iconic duration increased with increasing spatial frequency, but, in this case, the frequency range was 1.41 to 6 cpd.

Finally, both psychophysical (Breitmeyer, 1975) and electrophysiological (Parker & Salzen, 1977) data have demonstrated another characteristic of spatial frequency processing suggested above: RT lengthens with increasing spatial frequency. Hence, coarser patterns (low spatial frequencies) elicit relatively fast responses (short latencies), whereas finer patterns (high spatial frequencies) elicit relatively slow responses (long latencies).

3. Spatial integration effects. Thus far, the effect of temporal summation on the responses of the visual subsystems has been discussed; the effect of spatial summation on their responses must also be addressed. X-cells spatially summate their inputs in a linear fashion, that is, their outputs represent a spatially weighted arithmetic sum of their inputs.

Y-cells, in contrast, summate nonlinearly, that is, their output waveforms significantly differ from those of their input. These cells modify their inputs by such operations as rectification, which may eliminate part of an incoming wave, and multiplication, which may introduce gain to a given input.

The net effect of the Y-cells' response characteristics is a significant transformation of the input spatial frequency range: Neural representations of stimuli are shifted to higher or lower frequencies than the stimuli themselves.

Pharmacological Characteristics of the Spatial Frequency Processors

The cholinergic system has been implicated by anatomical and psychophysical studies in mammalian spatial frequency processing. The data, however, are sparse and unclear with respect to the range(s) of spatial frequencies with which this system is involved.

Dense concentrations of the enzyme acetylcholinesterase (AChE), a marker for the neurotransmitter acetylcholine (ACh), were found by histochemical methods in those laminae of adult cat LGN (*N* = 8) composed primarily of X-cells (A. F. Dean, Bunch, Tolhurst, & Lewis, 1982). In contrast, in adult monkey LGN (*N* = 3, *Macaca fascicularis*), greater AChE concentrations were found in the magnocellular than parvocellular layers of LGN (Ibid.). The magnocellular layers putatively contain neurons driven predominantly by retinal Y-cells; they also contain a subtype of X-cells with particularly high contrast sensitivity (Shapley et al., 1981, cited in A. F. Dean et al., Ibid.).

Other monkey species (Galago senegalensis and Aotus trivirgatus) showed the reverse pattern, that is, concentrations of LGN AChE activity in the parvocellular laminae (Fitzpatrick & Diamond, 1980, cited in A. F. Dean et al., Ibid.). Dean et al. interpreted this apparent contradiction to indicate that ACh is selectively involved in high-sensitivity X-cell activity, and that the LGN laminae in which this cell type is located is species-specific.

Cholinergic involvement in low spatial frequency processing was demonstrated by pattern EP data in adult cat (N = 2) (Harding, Wiley, & Kirby, 1983). Occipital and parietal potentials were recorded during the presentation of counterphased gratings ranging from 0.10 to 1.5 cpd. After the carbamate physostigmine, a source of abundant cholinergic stimulation (physostigmine binds AChE and thereby prevents ACh hydrolysis at synaptic sites) was administered, a significant amplitude reduction to low frequencies, but no amplitude change to high frequencies, occurred.

Atropine sulphate, a muscarinic antagonist (atropine sulphate competes with ACh for postsynaptic cholinergic receptor sites, thereby reducing the influence of an abundance of ACh), reversed this effect. In so doing, it provided further evidence that "excessive cholinergic stimulation within a pathway must mediate the effect" (p.

1077).

The Functions of the X- and Y-cells

The Localization and Discrimination Functions of the Visual System

To understand the functions of the X- and Y-cells, some properties of the entire visual system must be discussed. The function of this system is to provide information about the three-dimensional world to a given organism (Robson, 1975). Two of the most fundamental bits of information it provides are (a) the location and (b) the identity of objects (Kolb & Whishaw, 1985, chap. 9).

Beginning with Holmes in the early twentieth century (1918, cited in Kolb & Whishaw, 1985, p. 209), different researchers have viewed the visual system as consisting of two functional subsystems: One indicates where objects are; the other, what objects are (Harter, Aine, & Schroeder, 1982; Held, 1967-1968, cited in Julesz, 1985; Held, 1970; Julesz, 1985; Ungerleider & Mishkin, 1982).

The former entails a faster and more gross type of processing, and concerns interstimulus perception (e.g., figure-ground differentiation, contrast and movement detection, and spatial [positional] processing). The latter, on the other hand, involves a slower and finer type of processing, and concerns intrastimulus perception (e.g., feature differentiation and pattern discrimination).

Treisman (1982) pointed out that localization occurs prior to discrimination: First, a given organism groups components of the visual field into perceptual units (separates figure from ground); second, the resultant units influence where that organism directs its visual attention and, hence, which stimuli it further analyzes (i.e., discriminates).

The preattentive and focal attentive modes of visual attention. The visual system mediates these detection and discrimination functions in conjunction with the attentional system. This latter system, according to Julesz and his colleagues (Bergen & Julesz, 1983; Julesz, 1985; Julesz & Bergen, 1983; Sagi & Julesz, 1985), may be functionally divided in a similar fashion: (a) The rapid preattentive mode, entailing global scanning and parallel processing, is used to detect stimuli; (b) the slower focal attentive (or attentive) mode, involving local scanning and serial processing, is used to discriminate among stimuli.

Like Treisman, these investigators stressed that preattention and detection occur prior to focal attention and discrimination: The function of the earlier processes is to rapidly scan the entire visual field to locate salient information; the function of the later ones, to slowly scan and analyze that selected portion.

Sagi and Julesz (Ibid.) provided evidence for the different processing rates of the two modes. They found that, in a localization task (line detection), processing time was independent of target number, hence indicating relatively rapid parallel processing; in contrast, in an identification task (line recognition), processing time varied with target number, thereby suggesting relatively slow serial processing.

Interlocution and intralocution. Harter et al. (1982) provided other names for these two types of attentional processes. These researchers stressed that localization entails between-object differentiation, whereas discrimination involves within-object differentiation. They, therefore, labelled the former interlocutional and the latter intralocutional. Their data (VEP) concerning these two modes of visual attention are discussed below.

Regional Mechanisms of Localization and Discrimination

Superior colliculus and visual cortex. Some researchers have suggested neural mechanisms at the regional and cellular levels that may mediate these two functions. First, concerning the regional level, Rosinski (1977) concluded from a literature review that (a) superior colliculus processes ambient information in the visual field and, hence, mediates spatial processing; and (b) visual cortex processes focal information and, thus, mediates pattern processing.

The tectopulvinar and geniculostriate systems. Holmes (1918, cited in Kolb & Whishaw, 1985, p. 209) provided clinical evidence suggesting that the tectopulvinar system ("the secondary visual system"; Harter et al., 1982) mediates the detection of, location of, attendance to, and following of objects. In contrast, the geniculostriate system ("the primary visual system"; Harter et al., Ibid.) controls object discrimination by providing information concerning stimulus size, color, texture, and so forth.

Anterior and posterior cortex. Electrophysiological data have shown that neural activity in the anterior human brain, putatively related to stimulus location, occurs prior to that in the posterior, putatively related to stimulus identification. Harter et al. (Ibid.) found that, in 4 male and 2 female adults (with mixed handedness), the central (sites C3 and C4) VEP waveform component, correlated with stimulus position information, occurred earlier than the occipital (sites O1 and O2) VEP waveform component, correlated with stimulus type information.

1. Lateralization effects. Harter et al. (Ibid.) further found significant lateralization effects: (a) The location-correlated component was consistently larger in the hemisphere contralateral to the stimulus, and (b) the type-correlated component was consistently larger in the posterior LH. (Note. The stimuli in their study were briefly flashed colored circles containing dots. Also, see Filscov & Boll, 1981, and Kolb & Whishaw, 1980, pp. 245-246, both cited in Harter et al., Ibid., for data showing RH mediation of stimulus location and LH mediation of stimulus type.)

Occipitoparietal and occipitotemporal cortex. Two other cerebral regions have been implicated in the "where" and "what" aspects of vision. Electrophysiological (single-unit), anatomical (2-DG labelling of pathways), and ablation data from monkey cortex have suggested (a) occipitoparietal involvement in spatial perception and visuomotor processing and (b) occipitotemporal involvement in object recognition (Ungerleider & Mishkin, 1982).

For example, these investigators found that (a) parietal neurons responded to stimulus motion, and their firing patterns correlated with tracking eye movements; and (b) temporal neurons demonstrated shape and color specificity.

Ungerleider and Mishkin (1982, cited in Gattas, Sousa, & Covey, 1985) interpreted their data to indicate that the visual system consists of "two functional streams" (p. 16): One, located in parietal cortex, mediates spatial perception and memory; the other, located in inferotemporal (IT) cortex, controls pattern vision, object recognition, and visual memory.

Iwai (1985) provided further support for parietal and temporal involvement in the respective localization and identification functions of the visual system. He showed electrophysiologically (single-units) and behaviorally that, during pattern discrimination acquisition by macaques, (a) parietal cortex mediated spatial and selective attention functions, and (b) IT cortex (the posterior area _TEO_ and anterior area _TE_) controlled pattern perception (detail discrimination) and cognition (learning, categorization, and memorization).

Ungerleider, Desimone, and Moran (1986) showed similar results using anterograde and retrograde tracing techniques (tritiated amino acids, WGA-HRP, and flourescent dyes) in monkey cortex. These investigators found parietal involvement in peripheral visual field stimulation, TEO involvement in central visual field (central 10 degrees) stimulation, and TE involvement in stimulation from 2-30 degrees of the visual field. They concluded that parietal cortex mediates spatial vision, and TEO, object vision.

1. Lateralization effects. Clinical data also exist that not only corroborate those of Mishkin and his colleagues, but also show lateralized control within parietal and temporal cortex of these detection and discrimination functions. For example, humans with RH parietal damage demonstrated deficits in a spatial task (maze-learning), whereas those with RH PTO damage displayed recognition dysfunctions (Newcombe & Russell, 1969, cited in Young, 1983).

Further, subjects with RH lesions in parietal association cortex performed poorly on stimulus location tasks (Kolb & Whishaw, 1980, cited in Harter et al., 1982), whereas those with RH lesions in IT cortex showed impairments in attending to stimulus features (dots) (Ibid.).

Cellular Mechanisms of Localization and Discrimination

Concerning the cellular neural substrates of the localization and identification functions of the human visual system, as mentioned above, Y-cells may mediate the former function, and X-cells, the latter. To briefly review, Y-cells probably mediate contrast and movement detection, and modulate X-cell activity; X-cells probably mediate pattern discrimination. (Those with small receptive fields optimally respond to small patterns [high spatial frequencies]; those with large receptive fields, to large patterns [low spatial frequencies].)

First, the facts that Y-cells (a) have large receptive fields and (b) are located predominantly in the peripheral retina suggest their involvement in detection under scotopic (low luminance) conditions. The facts that X-cells (a) have variably sized receptive fields required for the analysis of different-sized patterns and (b) are found primarily in the central retina suggest their role in discrimination (Lennie, 1980).

Second, the Y-cells' capacity for rapid temporal integration (partially due to their large, fast-conducting axons) implies that these cells mediate localization, a faster process than discrimination. Conversely, the parvocellular X-cells' sustained type of processing (partially due to their small, slow-conducting axons) and their capacity for superior spatial resolution suggest the involvement of these cells in discrimination.

Third, the fact that one of the two efferent retinal Y-cell pathways projects to superior colliculus, a region that controls motor-related vision functions (e.g., eye movements), implicates this type of neuron in localization.

The fact that the final target of the other efferent retinal Y-cell pathway is visual cortex suggests Y-cell involvement in pattern vision as well; this "involvement" is hypothesized to be Y-cells' control of X-cell activity.

Although the precise mechanism of this cellular interaction is unknown, Y-cells may relate to X-cells as the preattentive mode relates to the focal attentive mode: Just as (a) the function of preattentive vision is to scan the entire visual field for salient information, and (b) the function of the focal attentive mode is to analyze those selected parts of the visual field, so may (a) "the function of a Y-cell [be to] regulate the sensitivity of a group of cortical cells . . . that sample a restricted region of visual space" (Lennie, 1980, p. 589), and (b) the function of an X-cell be to analyze the features within that space.

Spitzer and Hochstein (1985) similarly postulated that "early Y-cell activity could bring cortical cells to attention for imminently arriving functionally important detailed X-cell input" (p. 1264).

In sum, current theory maintains that spatial frequency processing is directly mediated by X-cell activity that, in turn, is modulated by Y-cell activity.

4/ Relationship Between Spatial Frequency Range and Processing Speed

Some psychophysical data have shown that low spatial frequency components of a given visual stimulus are processed prior to higher ones (the global precedence model

[Navon, 1977]). Other psychophysical data have demonstrated some of the limiting conditions of this model.

For example, Kinchla and Wolfe (1979) proposed that global precedence is true if and only if stimuli subtend a particular retinal angle. J. Hoffman (1980) and Paquet and Merikle (1984) suggested that stimulus quality (controlled by stimulus distortion in the former study and stimulus duration in the latter) affects whether the global or local components of a given stimulus are processed relatively faster. The current subsection briefly describes each of these studies.

Global Precedence

The global precedence model is consistent with the notion discussed in the preceding subsection: Localization precedes discrimination during visual processing. This model views the visual system as "a multipass system in which fine-grained processing is guided by prior cursory processing" (Navon, 1977, p. 354) and in which the function of the "first pass" (Ibid.) stage of processing is to locate stimuli:

> "The perceptual system treats every scene as if it were in a process of being focused or zoomed in on, where at first it is relatively indistinct and then it gets clearer and sharper (p. 354) . . . . When no specific demands are made to the viewer with regard to what should be recognized, his visual system is tuned to pick just the identity of the global pattern." (p. 368)

Navon's (1977) Experiments

Navon supported his model with data from four experiments. Three used an interference paradigm with "visual Stroop" letter stimuli (a large letter [a global H or S] composed of a group of small letters [local Hs or Ss] such that either [a] the global letter was the same as the local letters [consistent condition] or [b] the global letter was different from the local letters [conflict condition]). The fourth experiment used a discrimination paradigm with visual Stroop geometric stimuli (global triangles [24'] composed of local squares [8']).

In one version of the interference paradigm (Experiments 1 and 2), subjects were required to indicate (by a keypress) whether they had heard the letter H or S which had been aurally presented in conjunction with the 80-ms visual presentation of the global-local H or S. Independent of global stimulus size (whether the stimulus subtended 3 minutes (') 12 degrees or 4 degrees 48'), the global stimuli influenced subjects' responses.

In another interference paradigm (Experiment 3), the letter stimuli were visually presented for 40 ms, and the subjects' task was to identify the global and local letters. RTs to the global letters were significantly shorter than those to the local ones.

Further, subjects responded equally fast to the global stimuli independent of condition (i.e., they were able to attend to the global level without interference from the local one), but they responded faster to the local level only during the consistent condition (i.e., they could not attend to the local level without interference from the global one).

In the fourth experiment, Navon presented the geometric global-local stimuli in a same/different paradigm. He found that subjects more accurately detected interstimulus differences at the global than local level.

Navon's Conclusions

Navon concluded that because (a) local components did not interfere with global ones, and global components did interfere with local ones; and (b) speed and accuracy of processing global components exceeded those of processing local ones, these results supported the global precedence model. Navon further stressed that this effect applies to global and local stimuli defined in relation to one another, not in terms of absolute size. In sum, "one may conclude from the results that in a given scene, the larger features have priority in attracting attention" (p. 380).

Optimal Angular Size

Kinchla and Wolfe (1979) used a target search paradigm (a modified version of Navon's auditory-visual interference paradigm) to investigate global precedence. These investigators (a) aurally presented the letter E, H, or S; then (b) visually presented a global-local letter (these stimuli were varied with respect to size: Height of global components ranged from 4.8 to 22.1 degrees of visual angle); and (c) required subjects to report whether the aurally presented letter was the same as either the global or local visually presented one (a "yes" keypress indicated that the same letter was both aurally and visually presented; a "no" keypress, that it was not).

Results showed that RT varied with stimulus size: When stimuli were small (subtended less than 6-9 degrees), subjects responded "yes" more quickly to global than to local stimuli. Conversely, when stimuli were large (subtended greater than 6-9 degrees), subjects responded "yes" more quickly to local than to global stimuli.

Kinchla and Wolfe concluded that a given stimulus component must be of an optimal angular size to be rapidly recognized: Local components that are "too small" are processed more slowly than global components; conversely, global components that are "too large" are processed more slowly than local ones.

Stimulus Quality

Stimulus Distortion

J. Hoffman (1980) provided further evidence that the "global level of a form is not invariably processed prior to local levels" (p. 227). Hoffman asked 4 females and 2 males to report whether a letter designated as relevant had been one of the letters in a previously presented memory set. (In one condition, the global letter was relevant; in another, the local was relevant; and in a third, both were relevant). Results showed that RTs to global and local letters were equal.

Next, Hoffman selectively manipulated stimulus quality by distorting the global or local letter. He found, under these conditions, that RTs to global letters were faster than to local when the latter had been distorted; conversely, RTs to local letters were faster than to global when the latter had been distorted.

In addition to showing that stimulus quality determines global or local precedence, Hoffman pointed out the relevance of global and local visual processing to top-down and bottom-up cognitive processing.

Hoffman noted that because (a) the global components of a given stimulus constitute the higher structural levels of that stimulus, and (b) the local components, the lower levels (in the level of structure model), (a) global precedence is the visual analog of the top-down strategy of cognitive processing (higher levels predict lower ones), and (b) local precedence, that of the bottom-up strategy (lower levels imply higher ones).

Stimulus Duration

Paquet and Merikle (1984) tested Hoffman's hypothesis that stimulus quality (discriminability) determines global or local precedence. They controlled quality by varying stimulus duration. Their rationale was that (a) shorter durations result in poorer stimulus quality and a greater probability that only global stimulus components will be extracted (partial encoding); and (b) longer durations result in better stimulus quality and a greater likelihood of the local components' also being extracted (complete encoding).

Both verbal (the letters H and E) and nonverbal (a square) global-local stimuli (as described above) were presented at three different durations (10, 40, and 100 ms) to 26 female college students instructed to identify the large and small stimuli. As expected, the global level was processed faster than the local one at the short duration, but the global and local levels were processed at about the same rate at the longer stimulus durations.

These investigators concluded that global precedence should be considered "as a special case, not as a processing rule" (p. 52). They further pointed out that, in the global-local literature, stimulus duration varies from experiment to experiment; such variation probably partially accounts for discrepancies concerning relative speed of processing of the global and local levels of visual stimuli.

Summary

Thus, relatively low spatial frequencies (the global level) of a given visual stimulus are processed faster than higher frequencies (the local level) only under certain conditions, namely, if the latter are too high, distorted, and/or not extracted from the stimulus due to brief presentation.

5/ Relationship Between Spatial Frequency Range and Recognition Performance

One hypothesis being tested in the current study proposes that low spatial frequencies are sufficient for accurate pattern recognition (Harmon, 1973). This subsection presents the evidence and counterevidence for this hypothesis.

Most studies that have tested the effect of spatial frequency range on recognition (and similar cognitive processes) have used either geometric or facial stimuli. Although (a) many of the "geometric" studies found that low frequencies provided sufficient information for accurate classification (Carl & Hall, 1972; Ginsburg, 1971; Ginsburg, in press; Kabrisky, 1970, all cited in Ginsburg, 1975), and (b) some of the facial studies (Ginsburg, 1978, cited in Sergent, manuscript; Harmon, 1973; Tieger & Ganz, 1979) showed that low frequencies were sufficient for accurate recognition, these latter results were not clearcut.

For example, Ginsburg (1978, cited in Sergent, Ibid.) found that high frequencies in addition to low ones sufficed for accurate recognition. Fiorentini et al. (1983, cited in Sergent, Ibid.) corroborated his result. Finally, Tieger and Ganz (1979) showed that low-to-intermediate frequencies (2.2 cpd in a 0.54-3.9 cpd range), rather than low frequencies per se, were sufficient for accurate facial recognition.

These variant results are not surprising in that (a) widely different procedures were used by the various investigators, and (b) spatial frequency was not always carefully controlled.

Concerning the first point, (a) such stimulus parameters as novelty (famous vs. unknown faces), luminance, frequency range, and filtering technique; (b) such task parameters as type (classification, identification and recognition) and difficulty; and (c) dependent variables (motor vs. verbal) varied from experiment to experiment.

Concerning the second point, Sergent (manuscript) noted that Fiorentini et al. (Ibid.) increased the mean luminance values of the high-frequency facial stimuli to assure visibility of the facial features. Hence, luminance and frequency were confounded in this study; the high accuracy rate to high-frequency faces may have been related to luminance.

Harmon's (1973) Study

Because Harmons's hypothesis is being tested in the current study, some aspects of his study are described herein. Unfortunately, he did not specify his stimulus range, so this parameter cannot be included herein. Harmon used two techniques ([a] block portraiture and [b] continuous smearing) to filter out the high spatial frequency components of facial stimuli (to create degraded images). Then, he tested normal adults' recognition capacities vis-à-vis the resultant low-frequency stimuli. Both stimulus generation procedures are described below prior to the experimental procedures and results.

Stimulus Generation

Block portraiture. A block portrait, a 16 x 16 square image in which each square has been assigned 1 out of 16 levels of gray, is produced from a naturalistic photograph as follows:

1. The photograph is scanned in a raster containing 1,024 lines, each of which contains 1,024 points.

2. An analog-to-digital (A-to-D) converter assigns 1 out of 1,024 values to the brightness level of each point of each line.

3. A central processing unit (CPU) divides that image into a 16 x 16 square image; each square equals the average brightness of all the values constituting that square.

Continuous smearing. A "continuously smeared" portrait, a 256 x 256 element image in which each element has been assigned a brightness value equal to the mean brightness value of its adjacent points, is produced from the original facial image in the following manner:

1. The analog image is digitized, and each point is assigned a brightness value.

2. The averaging window technique is used: The mean of the set of points which forms a square around a given point is calculated, and that point is reassigned that mean value.

3. Step 2 is repeated until a new value has been assigned for each of the 256 x 256 elements constituting the resultant blurred image.

The Experiments

In the "block portrait" experiment, 14 such stimuli were shown to 28 subjects. Each subject was given a list of 28 names including those of the 14 people depicted in the stimuli. The subjects' task was to name a given block portrait when presented. Results showed that (a) high frequencies were not necessary for facial recognition, and (b) the precise rate of recognition accuracy varied as a function of grid placement over original images during stimulus generation.

Regarding the second point, a given grid was arbitrarily positioned over a given face during the scanning process; in some cases, it landed "unluckily for adequate representation" (p. 74), that is, it landed halfway off an internal feature. In other cases, in contrast, it was "fortuitously placed" (Ibid.) over the face. A 48% accuracy rate resulted when the grids had been "unluckily" placed over the original images, whereas accuracy reached 95% when the grids had been "fortuitously" placed.

The procedure in the second ("continuous smearing") experiment was identical to that described for the first one. Further, one finding in the second study was likewise identical to that in the first: Low frequency information was sufficient for accurate facial recogntion.

This second study also showed that degree of blurring varied inversely with recognition accuracy as follows: (a) The maximal blurring condition (a 51 x 51 point averaging window that eliminated all facial features) yielded a 60% recognition accuracy rate; (b) the moderate blurring condition (a 43 x 43 point window), a 65% accuracy rate; and (c) the minimal blurring condition (a 27 x 27 point window), an 84% accuracy rate.

Harmon concluded from his second study that

> "[when] the low-frequency information that relates to head shape, neck-and-shoulder geometry and gross hairline is all that remains unimpaired, . . . this alone seems to be adequate for rather good recognition among individuals in a restricted population." (p. 78)

Conclusion

Two aspects of this literature require attention. First, although low-frequency components of facial and geometric stimuli have been shown to suffice for both minimally accurate and good performance during recognition, identification, and classification, they probably are insufficient for maximal performance.

(a) Harmon's finding that a minimally degraded facial image correlated with maximal recognition accuracy and (b) Sergent and Switkes' (1984, cited in Sergent, manuscript) demonstration that facial stimuli containing their full ranges of spatial frequencies yielded better recognition performance than those containing relatively narrower ranges support this position.

Second, the particular spatial frequency range that permits simulus recognition varies not only with stimulus category, but also with individual stimuli within those categories. For example, Harmon noted that recognition accuracy varied with (a) feature arrangement and (b) distinctive features in the different faces: Some facial patterns and some distinguishing external features (e.g., a bald head) were easily recognized in their coarsely represented forms by most subjects, whereas other facial patterns and features were rarely recognized.

Similarly, Moore (1985) found that the frequencies that permit the perception of stimulus unity varied with individual stimuli within a given category. This investigator manipulated the spatial frequency content of fragmented (e.g., Cubist) and unified (e.g., Photorealist) paintings and recorded the ratings of college students concerning the apparent unity of these two art styles under four viewing conditions (viz., one normal and three degrees of blurring).

Moore found that low frequencies were critical to the perception of unity within the fragmented paintings, that is, they seemed unified when their details were filtered out. In contrast, high frequencies were critical to unity perception within the unified paintings, that is, they seemed unified when their details were not extracted.

6/ The Development of Spatial Frequency Sensitivity

Both electrophysiological (pattern EP) and psychophysical data exist showing that human spatial frequency sensitivity varies with age. The current subsection (a) presents these data for the entire lifespan and (b) discusses the implications of these data for the developmental changes in cognitive strategies found by Carey and Diamond (1977) and Turkewitz and Ross-Kossak (1984) described above.

Human Developmental Changes in Spatial Frequency Sensitivity: Lifespan Data

Infancy

Acuity: Psychophysical data. When do humans first demonstrate sensitivity to visual patterns and to what types of patterns do they respond? Fantz' (1962; 1972) psychophysical data showed that (a) neonates can discriminate patterns (as measured by fixation time), and (b) their capacity to do so significantly improves within the first six months of life. Fantz presented black-and-white gratings of different spatial frequencies to infants and found that those younger than 1 month could resolve 60' of arc at a 10 " distance; 1-2-month-olds could resolve 40'; 4-month-olds, 10'; and 6-month-olds, 5'. (Note. Adults can resolve 1' at a 10 " distance). Fantz (1962) concluded that

> "pattern vision becomes progressively more acute, starting with the ability of the neonate to see stripes as narrow as 1/8" at a 10" distance. By six months, 1/64" stripes can be resolved at 10 or 15." (p. 916)

Acuity: Physiological data. The maturation of both perceptual and motor components of the visual system during the first six months of life underlies this substantial improvement in pattern vision at this time. These components include: (a) increased macular receptor density, (b) improved abilities for foveal fixation and lens accomodation, (c) decreased corneal sphericality, (d) increased myelination of optic nerve fibers, (e) improved binocular coordination, and (f) maturation of visual cortex (Abramov et al., 1982; Fantz, 1962; Gross, 1985, chap. 4; Harter & Suitt, 1970).

Concerning macular development, for example, Abramov et al. provided neuroanatomical evidence for macular immaturity (characterized by a thin receptor layer, short receptor segments, and relatively few cones) in the 8-day-old human retina. These investigators concluded that vision, at this age, was predominantly controlled by extrafoveal mechanisms.

Hence, the anatomical and psychophysical data corroborate one another. The latter showed that relatively young infants have poor visual acuity (they cannot resolve patterns consisting of narrow stripes); the former provided one reason for this behavior: The foveal (central retinal) region that mediates pattern vision is in large part nonfunctional at this stage of development.

Configurational processing. Psychophysical data also exist which show that not only does the infants' capacity to resolve details improve with age, but also their capacity to process details simultaneously (engage in parallel processing) improves. Ruff (1976) found that when patterned stimuli (composed of angles and lines) were presented to infants aged 2 to 6 months, the relatively younger ones fixated on (a) fewer details and (b) fewer details at once; the older ones, in contrast, attended to (a) a greater number of details and (b) more details simultaneously. Ruff interpreted these data to indicate that

> "with perceptual experience, the infant learns to focus on the distinctive features, and can later perceive the structure or configuration of a stimulus by processing several distinctive features simultaneously." (p. 357)

Fantz (1965b, cited in Rosinski, 1977, chap. 7) also showed that the ability to perceive stimulus configuration covaries with age during early infancy. He found that infants younger than 1-month-old demonstrated no preference (as measured by fixation time) for scrambled versus unscrambled faces, whereas those between 1 and 4 months preferred the unscrambled faces. Fantz concluded that the younger infants were attending to stimulus features, and the older ones, to stimulus configuration (see Bower, 1972; Kagan et al., 1966, cited in Rosinski, Ibid., for further evidence of configurational processing at 4 months of age).

Shift in preference from stimulus features to configuration. Hence, during infancy, the abilities to process both pattern components and the structure formed by those components develop, that is, both quantitative and qualitative changes in visual perceptual processing occur at this time. Fantz, Fagan, and Miranda (1975) proposed that the following tripartite trend exists:

1. The youngest infants (0-2 months) attend to the large, high-contrast components of patterned stimuli (the pattern definition stage).

2. Two- to 6-month-olds prefer patterns with many small elements (the pattern quantity stage).

3. Infants older than 4 months select organized, rather than disorganized, patterns (the pattern configuration stage).

Consistent with this trend, Ruff and Turkewitz (manuscript) found that infants 10 weeks of age and younger preferred (as measured by fixation time) larger sized stimuli independent of pattern type (bull's eye or stripe); conversely, those older than 10 weeks preferred pattern type (the bull's eye) independent of size.

Childhood

The trend described above in sensitivity to higher spatial frequencies with increasing age continues from infancy into early childhood. Dobson, Salem, Mayer, Moss, and Sebris (1985) found, with the preferential looking procedure, that the highest resolvable frequency progressively increased from 4.6 cpd in 6-month-olds to 11.1 cpd in 3-year-olds. At what age does this trend terminate, that is, when does the mature spatial frequency function emerge?

Sokol and Jones (1979) demonstrated electrophysiologically (pattern reversal visual EPs [VEPs]) that VEPS to checks larger than 30' attained adult-like P1 latency values by 16-20 weeks of age, whereas the P1 VEP latencies to checks smaller than 30' progressively decreased from infancy until about 6 years of age. (Note. [a] P1 refers to the first positive component of a VEP occurring at about 100 ms and correlated with sensory processing. [b] *N* = 7 preterm and 12 fullterm infants, 24 children [mean age = 4 years 10 months], and 20 adults [mean age = 30 years].)

Moskowitz and Sokol (1983) found a similar trend: Pattern reversal VEPs to large checks (60 or 48') attained adult-like P1 latency values by roughly 1 year of age, whereas the P1 VEP latencies to small checks (15 or 12') had still not reached adult levels in 5-year-olds. These findings are reliable in that they reflect a large sample (N = 439).

Finally, Spekreijse (1978) showed that check size yielding maximal pattern onset VEP responses gradually decreased with age. The values of these check sizes at the ages tested were: (a) 72' at 1 month, (b) 36' at 3 months, (c) 18' at 6 months, and (d) 9' (adult values) from age 6 years on. He further noted that the peak latencies of the first two components (a positive-going peak at 75-90 ms and a negative-going peak at 100-120 ms) were longer than those in the adult potentials until roughly 10 years of age.

Summary. The VEP data indicate that sensitivity to low spatial frequencies matures significantly earlier than that to high: (a) Whereas the infant response to low frequencies ressembles that of the adult, only the response of children older than roughly 10 years of age approximates the adults'; and (b) relatively large checks elicit maximal responses earlier than relatively small checks.

Moskowitz and Sokol (Ibid.) suggested that different activity levels of the transient and sustained visual subsystems at different ages may partially account for the differential rate of development of latency to large and small checks. (They did not specify the cause[s] of these different activity levels.)

Adulthood

Changes in human spatial frequency processing continue throughout adulthood. Sokol, Moskowitz, and Towle (1981) found that among 125 normal subjects ranging from 13 to 82 years of age (mean age = 43 years), (a) from 20 years of age onward, the P1 latency to pattern reversed checkerboard stimuli increased with increasing age, and (b) the rate of increase in latency to small checks (12') was roughly twice as fast as that to large (48').

These researchers attributed the first result to both optical and neural-biochemical factors, namely, with increasing age, the following changes occur within the visual system: (a) Pupil size and, hence, retinal illuminance decrease; (b) retinal ganglion cells degenerate; (c) the number of optic nerve fibers diminishes; and (d) biochemical and cytoarchitectonic changes occur in LGN and visual cortex. They did not specify a mechanism accounting for the differential rate of change in P1 latency to high and low spatial frequencies.

Implications of Developmental Changes in Spatial Frequency Processing for Developmental Shifts in Recognition Processing Strategies

The (a) age-related changes in pattern processing discussed above and (b) developmental changes in cognitive processing discussed below may contribute to the findings of Carey and Diamond (1977) and Turkewitz and Ross-Kossak (1984) discussed in subsection 1.1/8. To review, the former reported that prior to age 10, children use a piecemeal strategy to recognize faces, whereas after 10, they use a configurational one.

The latter found that in late childhood, children use primitive holistic and analytic strategies during facial recognition, whereas in early adolescence, females use an advanced holistic strategy in addition to the other two. (Note. Piecemeal and analytic are synonomous, and configurational and advanced holistic are synonomous.)

Possible Causes of Childrens' Shifting from Analytic to Holistic Processing

What are these perceptual and cognitive changes that occur during childhood that make younger children more likely to use stimulus features, and older ones, stimulus structure, as cues for pattern recognition? According to Gibson (1969), with increasing age, children demonstrate improved capacities to (a) discriminate, (b) attend, and (c) efficiently extract information.

Regarding the first capacity, as shown above, childrens' RT accelerates, the patterns that they are able to resolve become finer (Gibson, Ibid.), and their spatial frequency sensitivity reaches adult levels at about 10 years of age. Hence, those older than 10 can process many distinctive features extremely rapidly, that is, they can process holistically.

Concerning the second capacity, childrens' patterns of examining a given stimulus (as measured by eye scanning patterns) change from one of random exploration and nondiscrimination between relevant and irrelevant details to one of systematic exploration and selectivity of relevant stimulus features (Gibson, Ibid.). Also, their focus of scanning changes from that of internal to external features: Younger children (3- to 5-year-olds) scan predominantly within contours; older children (6- to 7-year-olds) scan the contours themselves more than younger children do (Zaporozhets, 1965, cited in Rosinski, 1977, chap. 7).

Regarding the third capacity, childrens' detection of the higher order structure of a given stimulus increases due to: (a) their utilization of new processing strategies, such as chunking (combining inputs into logical units so that the stimuli are in a manageable and memorable form); (b) their improved ability to see embedded relationships; (c) the emergence of the ability to conserve (to see the underlying, invariant aspects of a given stimulus despite surface transformations, e.g., state); (d) the emergence of the capacity to parallel process; and (e) the increased length of their span of perception (Gibson, Ibid.).

Summary. Thus, with increasing age, children become capable of (a) detecting more individual features due to the emergence of sensitivity to higher spatial frequencies, (b) systematically comparing those features due to the maturity of eye scanning patterns, and (c) detecting the invariant relationship between those features due to the development of perceptual and cognitive skills (Rosinski, 1977, chap.

7).

This progression combined with the (a) shift in eye scanning patterns from internal to external features and (b) mechanisms of higher order structure perception listed above probably contribute to the shift from analytic to holistic processing in late childhood.

The Qualitative and Quantitative Developmental Processing Changes Which Contribute to the Developmental Shift in Recognition Strategy

Changes in cognitive processing. The question has been raised in the literature as to whether this age-related strategy shift is due to qualitative or quantitative changes in perceptual and cognitive development. Carey and Diamond's (Ibid.) findings suggest qualitative changes: Children younger than 10 yielded equally accurate recognition judgements to upright and inverted unfamiliar faces (and, hence, may have used distinctive features as their basis for recognition); those older than 10 recognized upright faces more accurately than inverted ones (and, therefore, may have used an integrated percept to recognize the faces).

In contrast, the data of Pedelty, S. C. Levine, and Shevell (1985) suggest quantitative changes: Children younger than 10 used fewer stimulus dimensions than those older than 10 to recognize upright faces.

Changes in visual processing. Although the question-at-hand has been presented herein with respect to recognition strategy, it has also been posed in relation to visual processing in general. For example, the pattern EP data cited above suggest that the undeveloped and developed human visual systems differ qualitatively because the latter contains different channel types (high and low spatial frequency channels) from the former (low frequency channels only).

In contrast, some behavioral data suggest that the immature and mature visual systems differ quantitatively because the latter has a larger channel capacity than the former. For example, infants register the same type of information as adults, but less of it (Bower, 1972).

Gibson's (1969) and Rosinski's (1977) characterizations of perceptual and cognitive development suggest that immature and mature processing differ from one another in both qualitative and quantitative respects. The following developmental changes that take place during each of the three stages of visual processing corroborate their position:

1. Sensory register: Older children surpass younger ones in their (a) speed of processing and (b) capacity to selectively attend.

2. Short-term (working) memory: (a) Older children (like adults) can manipulate 4-9 items, whereas younger ones cannot manipulate that much information; and (b) older children use <u>control</u> (voluntary) <u>processes</u>, but younger ones do not.

3. Long-term memory: Older children (a) examine the relationships between items and (b) use effective strategies (like chunking mentioned above) to organize information for storage and later use. In contrast, younger children store information in a disorganized fashion (T. F. Gross, 1985, chaps. 6 and 7).

Summary. The following differences exist in the capacities that younger and older children bring to pattern recognition processing:

1. The former tend to process fewer, larger features relatively slowly (i.e., in series), whereas the latter process many small features relatively quickly (i.e., in parallel).

2. The former attend primarily to internal features, whereas the latter attend to both internal and external features.

3. The former attend equally to irrelevant and relevant features in contrast to the latter who selectively attend to relevant features.

4. The former cannot detect stimulus structure, whereas the latter can.

5. The former can only manipulate a small amount of information in working memory, whereas the latter can manipulate a relatively large amount.

6. The former cannot store stimulus inputs in an organized manner, and the latter can.

(*Note*. Each of these skills develops at different rates in different individuals. Hence, the dichotomous picture presented herein is true for children on the average, not for many individual children.)

In sum, most data concerning perceptual and cognitive development suggest that children younger than roughly 10 years of age do not process holistically during pattern recognition because their processing capacities differ both in type and amount from those older than 10.

1.3] RECOGNITION

1/ The Template Match Model of Recognition Memory

As mentioned at the outset of this Introduction, recognition refers to the "evocation of . . . memories that permit the experience of familiarity with a given stimulus" (A. R. Damasio, H. Damasio, & Van Hoesen, 1982, p. 337), that is, the identification of a present stimulus as having been previously encountered.

Recognition, one type of information retrieval from memory, consists of the comparison between a given input and a given memory representation (a <u>schema</u> or <u>template</u>). (<u>Note</u>. This process contrasts that of recall, the other type of retrieval, characterized by the production of past information, rather than the matching of present with past information.)

A template is defined as a neural ensemble that reflects having "learned" the characteristics of a given stimulus by several chemical and structural changes (e.g., additional glutamate at the receptor level and an increased number of synaptic connections). The more extended the learning period (i.e., the greater the amount of experience the organism has had with the stimulus-at-hand), the more permanent these neural changes and, hence, the stronger the template (Lynch, 1985).

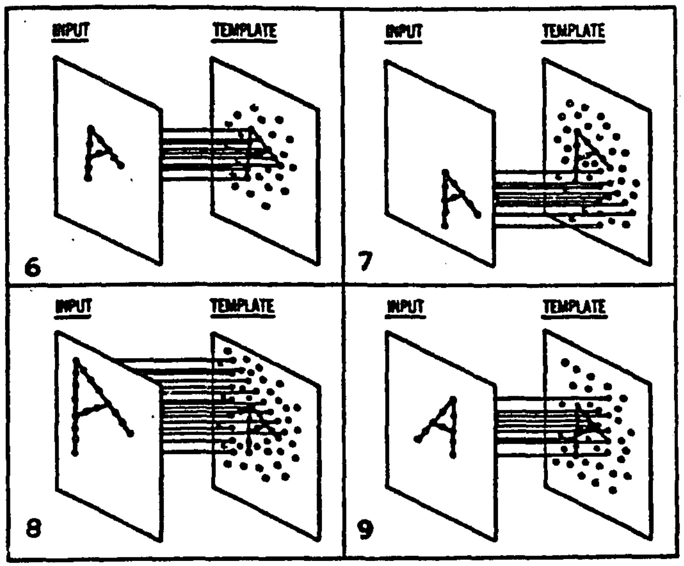
A. R. Damasio et al. (1982) describe the template match which occurs during recognition in terms of a lock-and-key analogy: The current stimulus "key" must fit the memory template "lock" for recognition to occur. They further postulate that this match may occur by either parallel or serial processing and, hence, in the RH or in the LH, respectively.

2/ Parallel Versus Serial Processing During Recognition

The parallel processing model (Selfridge & Neisser, 1972) suggests that current input is compared in a holistic fashion to a prototypical form temporarily transferred from long-term memory (deep storage) to short-term memory (working memory) (see discussion of multistore model of memory in subsection 1.3/3 for broader definitions of long- and short-term memories). If the input is identical to the prototype, then the input is recognized (see Figures 6-10).

The serial processing model (Noton & Stark, 1972), on the other hand, proposes that recognition occurs when features of the present stimulus are sequentially compared with those of the template.

This model purports that visual learning necessarily occurs prior to recognition. During learning, an eye



Figures 6-9. Definition of template matching. Figure 6 shows an input which matches the template; 7, a mismatch due to change of position; 8, a mismatch due to change of size; 9, a mismatch due to change of orientation.

Note. From Cognitive Psychology (p. 51) by U. Neisser, 1967, New York: Academic Press.

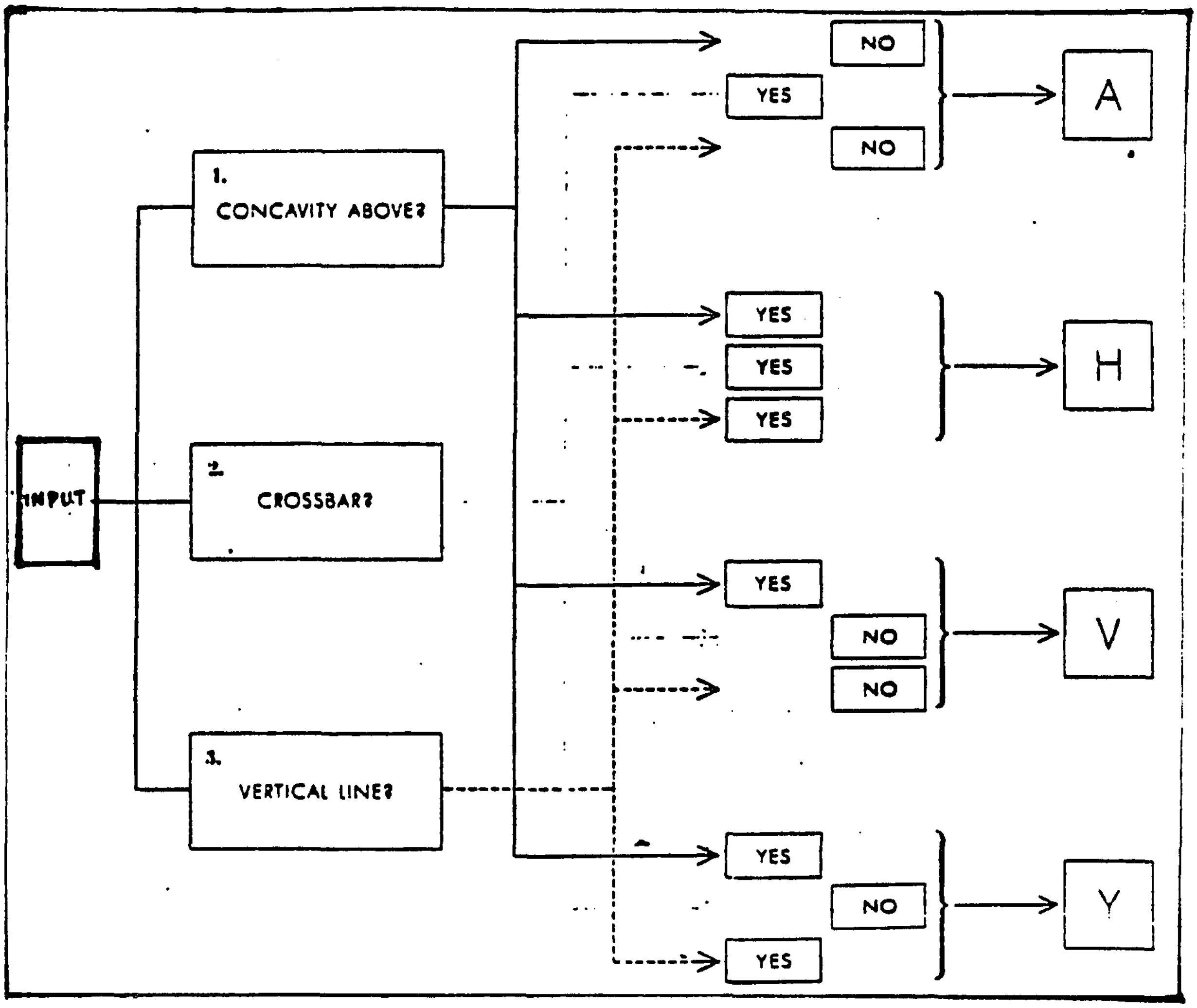


Figure 10. The parallel-processing program uses the same test features as the serial program (see Figure 11), but applies all tests simultaneously and makes decision on the basis of the combined outcomes. The input is a sample of one of the letters A, H, V, and Y.

Note. From "Pattern Recognition by Machine" by O. Selfridge and U. Neisser. In Perception: Mechanisms and Models (p. 212) by R. Held and W. Richards (Eds.), 1972, San Francisco: W. H. Freeman.

movement pattern following the distinctive features of a given stimulus recurs in a regular path and forms a sensorimotor template (feature ring). Then, during recognition, the eyes explore the current stimulus by the same scanpath as during learning; in so doing, they match the current stimulus features to the template in a serial manner (see Figure 11).

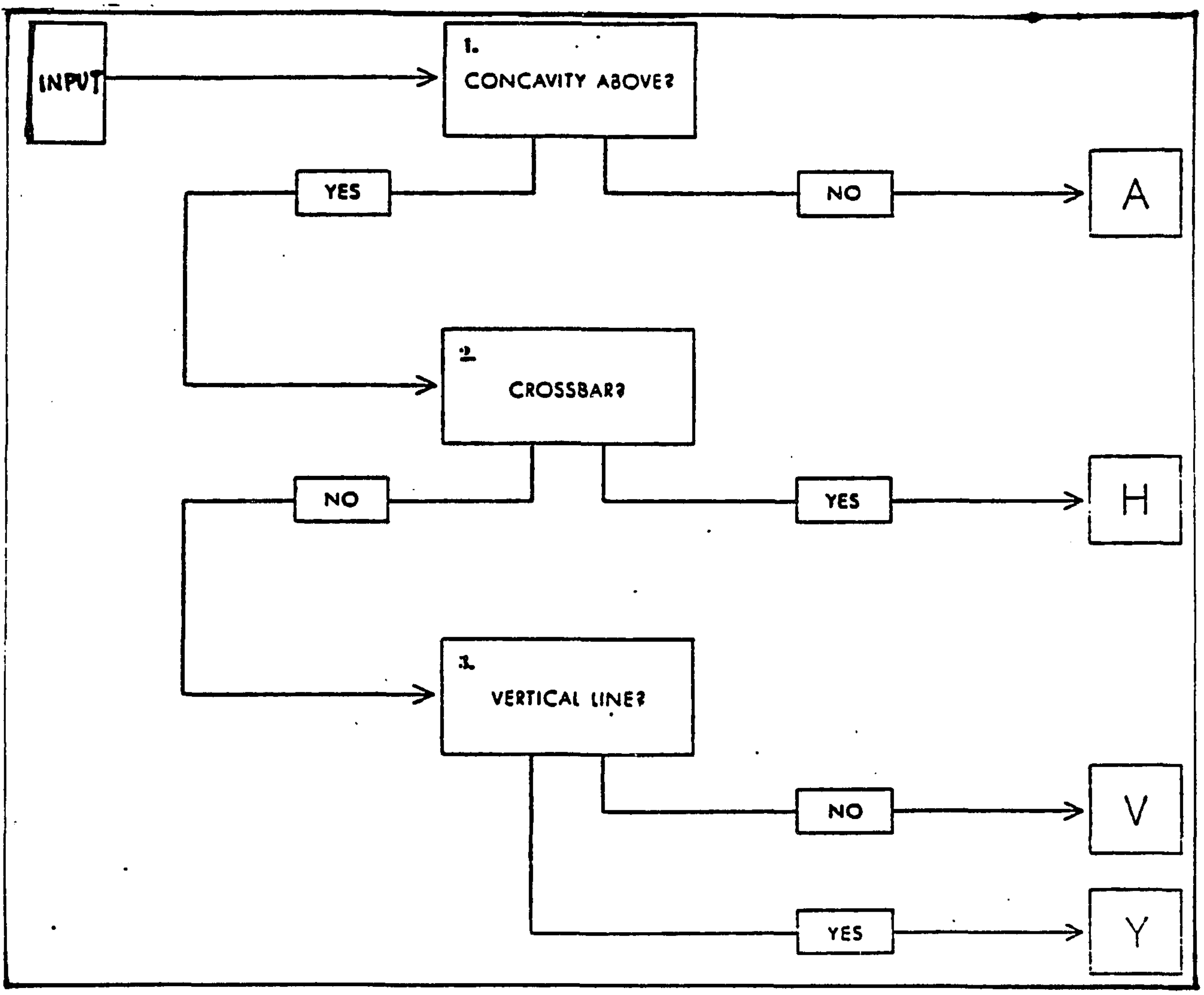
3/ Models of Memory

Because recognition is a form of memory, it cannot be understood without briefly reviewing the fundamental models of memory: (a) the structural versus procedural (Kolers, 1979) and (b) the multistore (Atkinson & Shiffrin, 1968, cited in Wingfield & Byrnes, 1981) versus levels-of-processing (Craik & Lockhart, 1972) models.

The Structural Versus Procedural Models

The structural model views any given memory (i.e., the representation of experience stored by changes within neurons and called a trace or engram) as a physical entity with mass and extent. Hence, according to this view, a given memory is physically locatable.

The procedural model, in contrast, views memory as a process, rather than as a material substance. Kolers (Ibid.), for example, defines recognition memory as the same operation performed on two separate encounters with a given stimulus. This latter view proposes that memories reside in neural connectivity (Scoville & Milner, 1957, cited in Kolb & Whishaw, 1985, chap. 20) and cannot be physically located.



<u>Figure 11</u>. The serial-processing program for distinguishing four letters, A, H, V, and Y employs three test features: (a) presence or absence of a concavity above, (b) a crossbar, and (c) a vertical line. The tests are applied in order, with each outcome determining the next step.

<u>Note</u>. From "Pattern Recognition by Machine" by O. Selfridge and U. Neisser. In <u>Perception: Mechanisms and Models</u> (p. 212) by R. Held and W. Richards (Eds.), 1972, San Francisco: W. H. Freeman.

The Multistore Versus Levels-of-Processing Models

The multistore model postulates that memory consists of a progression of three discrete stores in which information is held for increasingly longer durations: (a) short-term storage (also called iconic memory in the visual system [Neisser, 1967]), (b) short-term memory (STM), and (c) long-term memory (LTM):

1. In short-term storage, sensory representations of stimuli are formed and briefly retained (for several hundred milleseconds).

2. In STM (the "workbench" of memory, the spatial and temporal capacities of which are 4-9 items and 10-30 seconds, respectively), information is manipulated in several ways. For example, recently encoded information is further processed at a higher level: It may be (a) retained by rehearsal, (b) reorganized by chunking, and/or (c) transferred into LTM for storage.

3. In LTM (characterized by infinite spatial and temporal capacities), current input is semantically organized, that is, placed in a logical and meaningful relationship to information acquired from past experience, for the purposes of permanent storage and ease of retrieval (T. F. Gross, 1985; Wingfield & Byrnes, 1981).

(*Note*. Although this model was formulated relatively recently [1968], historically, STM and LTM were initially described by William James in 1890 [cited in Kolb & Whishaw, Ibid.]. James referred to STM as *primary memory* and LTM as

<u>secondary memory</u>.)

In contrast, the levels-of-processing model postulates that memory is not divided into discrete storage locations, each characterized by a particular channel capacity and specific functions. Rather, memory is viewed as a continuum of shallow (least abstracted) to deep (most abstracted) stimulus representations. According to this model, raw sensory inputs are (a) analyzed a particular amount, that is, to a particular depth, and then (b) stored at that level of depth.

Depth of encoding covaries with degree of elaboration (or extensiveness [spread] of processing). These latter terms refer to the number and strength of semantic associations, that is, the connections with related ideas, words, and images that the encoded bit of information contains. Hence, superficially encoded information in memory has few semantic associations, whereas deeply encoded information has many such associations.

Further, depth of encoding covaries with trace distinctiveness and ease of retention, that is, deeply encoded information has more distinctive traces and is more easily retained than superficially encoded information (Jacoby & Craik, 1979; T. F. Gross, 1985; Wingfield & Byrnes, 1981).

4/ The Experimental Investigation of Recognition: Some Methods and Results

<u>Behavioral Studies</u>

A RT paradigm (Sternberg, 1969) is typically used to test whether parallel or serial processing is used during recognition. As exemplified by the Sagi and Julesz (1985) study concerning pre- and focal attention (see subsection 1.2/3), a relatively faster RT the value of which is independent of stimulus number putatively reflects the parallel mode; a slower RT that varies linearly with stimulus number, the serial mode.

In addition to behavioral studies of the parallel versus serial modes used during recognition, behavioral studies of the recognition versus recall modes of retrieval have been performed. These latter studies have found that recognition performance is generally superior to that of recall, and that the former tends to be easier than the latter (Wingfield & Byrnes, 1981). For example, Standing et al. (1970, cited in Wingfield & Byrnes, Ibid.) demonstrated that the capacity for visual recognition in normal young adults is superlative: They correctly recognized thousands of pictures.

It is important to note that recognition performance does not attain such high levels under all circumstances: It has been shown to vary with (a) stimulus type, (b) degree of similarity between test and target stimuli, and (c) subjects' degree of familiarization with the stimuli (Glass, 1979, chap. 3).

Electrophysiological Studies

In VEP research, recognition is studied primarily by analyzing the P3 component (a positive-going wave occurring at roughly 300 ms poststimulus associated with [a] the presentation of novel and/or task-relevant stimuli, [b] stimulus evaluation, and [c] the current memory-related function). This component has demonstrated sensitivity to the reappearance of previously presented stimuli.

For example, when subjects were asked whether a given letter was the same as or different from a previously presented letter, their P3 amplitudes during same matches were significantly greater than those during different matches (Thatcher, 1977). Thatcher concluded that P3 activity reflects a match between the sensory encoding of a stimulus and an internal neural representation (i.e., a memory template).

Gomer, Spicuzza, and O'Donnell (1976) corroborated Thatcher's findings. These investigators presented a target set of letter stimuli followed by test stimuli and asked 4 males and 2 females (aged 21-37 years) whether the test stimuli had been in the target set (Sternberg paradigm, 1969a, 1969b, cited in Gomer et al., Ibid.).

They found that P3 amplitude (in VEPs recorded over vertex, viz., the Cz site) increased when the test stimuli matched the targets and, hence, provided further support for the template matching model of P3 enhancement (Donchin, Kubovy, Kutas, Johnson, & Herning, 1973). Gomer et al. further found that P3 latency varied linearly with target set size, a result suggesting that a serial mode had been used to search memory during their recognition task.

5/ The Location of Recognition Memory in the Information-Processing Hierarchy

Thus far, (a) recognition per se as well as memory-at-large have been defined, (b) a possible mechanism for this type of memory has been suggested, and (c) experimental methods and data concerning this behavior have been described. Two questions concerning recognition remain: (a) Where, both with respect to information processing and neuroanatomy, does recognition take place; and (b) what is the adpative value of recognition?

Recognition and Information Processing

First, recognition is a cognitive process and, hence, occurs during the highest stage of information processing. This latter term refers to the set of operations performed on stimulus inputs as they ascend from lower peripheral to higher central levels, that is, from sensation to perception to cognition (Forgus & Malamed, 1976). The output of each stage forms the input of the successive one: (a) Sensations are transformed by perceptual operations (e.g., figure-ground organization), and (b) percepts are transformed by cognitive operations (e.g., concept formation, categorization, language, and memory).

At each stage of information processing, the following questions (listed in ascending order) are answered:

1. Is a given stimulus present? (detection)
2. Does a unitary figure exist against background noise?

(form perception)

3. Is one stimulus different from another stimulus? (discrimination)

4. What is a given stimulus? (identification)

5. Is a given stimulus familiar (i.e., has the subject seen the stimulus before)? (recognition)

Hence, the primary function of lower level processing is to physically analyze stimulus inputs so that forms, rather than disorganized sensations, may be perceived; that of higher level, to semantically analyze those forms so that their meaning for the organism may be understood.

Recognition may be viewed as a higher level process for two reasons. First, the object of recognition is the output from a lower level, that is, a percept, and the problem of recognition entails the categorization of that percept (Neisser, 1967; Sutherland, 1969) both physically and semantically (Lindsey & Norman, 1977).

Second, recognition involves the comparison of this percept to a template, an operation of a higher and qualitatively different order than that among sensory input. The latter, called <u>perceptual integration</u>, entails an across-space intrastimulus comparison of sensations in the organism's present experience. In contrast, the former, called <u>cognitive integration</u>, involves the across-time interstimulus comparison of present and past stimuli (Tighe & Shepp, 1983).

6/ The Adaptive Value of Recognition

Cognitive integration, the distinguishing feature of recognition, is adaptive for a given organism in two ways: It provides (a) continuity to, and orientation for, an organism's subjective experience and (b) the basis for associative learning.

Another aspect of recognition contributes to its adaptive value. The capacity for pattern recognition (i.e., the recognition of highly organized, informative, and sometimes complex stimuli) is necessary for (a) concept formation and (b) language production and comprehension (Chabot, York, & Waugh, 1984). Because all of these higher cognitive functions enhance a given organism's ability to manipulate its environment, they likewise increase its probability of survival.

7/ The Location of Recognition Memory in Brain

Occipito-Temporal-Limbic Cortex Mediates Visual Memory

As mentioned in subsection 1.2/3, the occipito-parietal system may mediate spatial perception, and the occipito-temporal system, object recognition (Ungerleider, 1985). Neuroanatomical and electrophysiological data from monkey cortex suggest that this latter system in connection with the limbic system constitutes the circuit controlling visual memory processing (Mishkin, cited in Thompson, 1986) (see Figures 12-15).

As noted above, visual memory processing is a complex behavior containing sensory (or visuosensory), perceptual, and cognitive (both called visuopsychic) components. Each

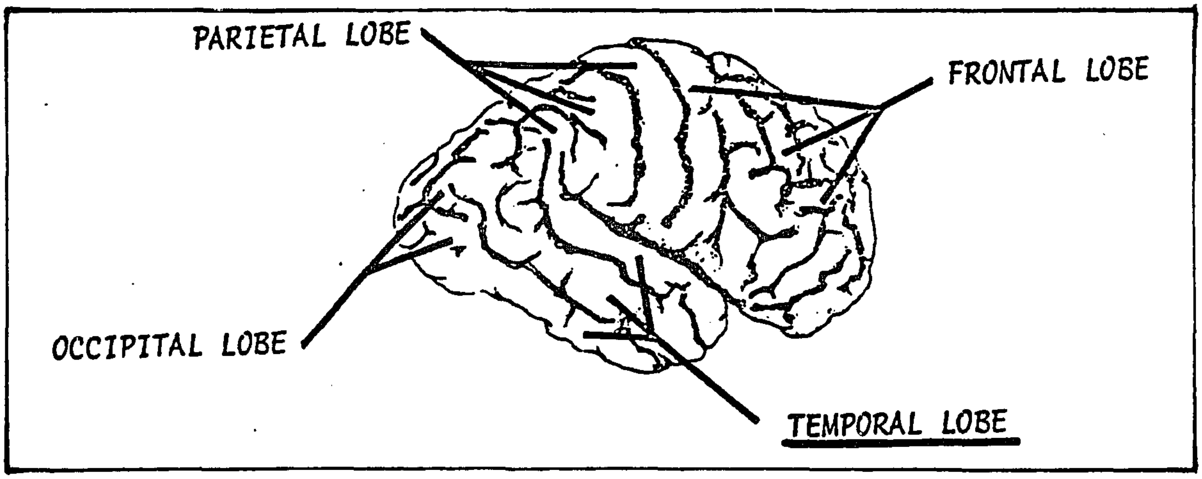


Figure 12. Right lateral view of the four cerebral lobes in the primate.

Note. From Neuroanatomy: A Programmed Text/Vol. 1 (p. 187) by R. Sidman and M. Sidman, 1965, Boston: Little, Brown.

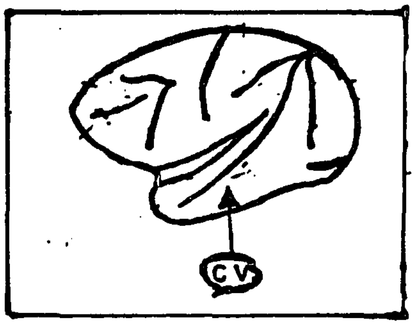
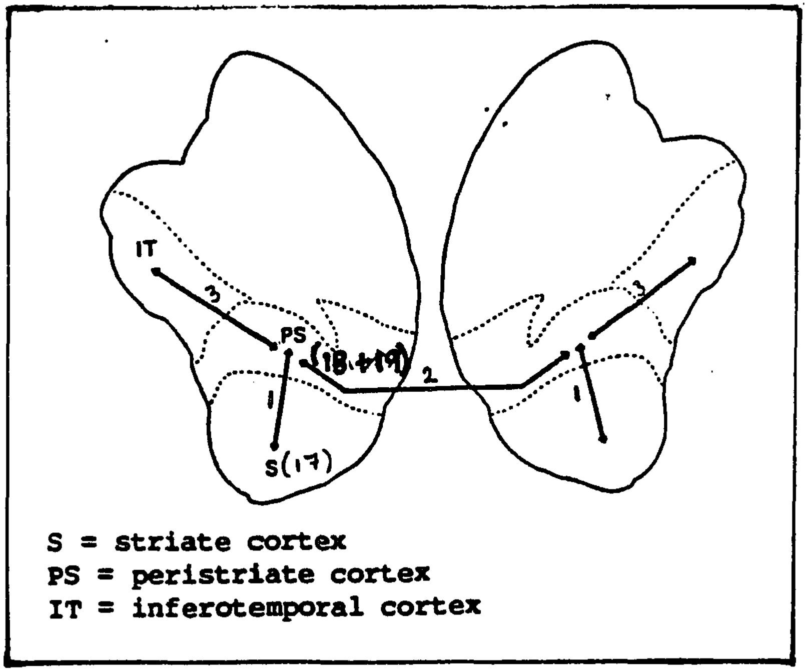


Figure 13. The functional localization of complex visual discrimination (CV) in primate cortex as suggested by lesion data.

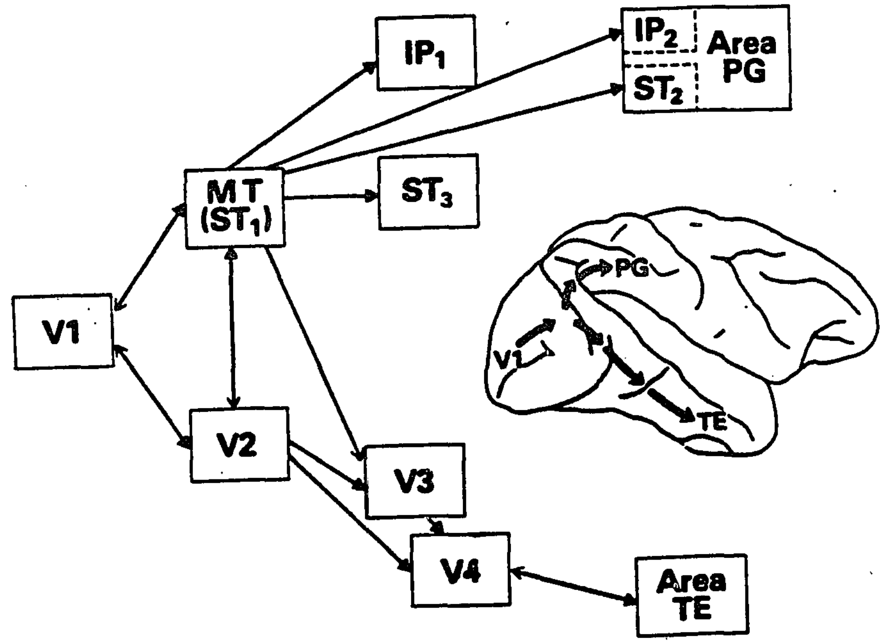
Note. From Introduction to Physiological Psychology (p. 555) by R. F. Thompson, New York: Harper & Row.



S = striate cortex
PS = peristriate cortex
IT = inferotemporal cortex

Figure 14. Pathways between visual and inferotemporal cortices of the two cerebral hemispheres. Note that the hemispheres communicate at the level of secondary (associative), not primary (sensory), visual cortex.

Note. From *Introduction to Physiological Psychology* (p. 563) by R. F. Thompson, New York: Harper & Row.



Heavy arrowheads = forward projections which terminate predominantly in layer IV and the deep part of layer III. Light arrowheads = backward projections which avoid layer IV and terminate instead in the supragranular and infragranular layers.

Figure 15. Summary of visual cortical areas and their known connections. Data suggest a divergence in the flow of visual information from striate cortex (V1), beginning with areas V2 and MT. One pathway is directed dorsally into posterior parietal cortex; the other is directed ventrally into inferior temporal cortex. These two diverging pathways may mediate spatial perception and object recognition, respectively.

Note. From "The corticocortical Pathways for Object Recognition and Spatial Perception" by L. G. Ungerleider. In Pattern Recognition Mechanisms (p. 32) by C. Chagas, R. Gattas, and C. Gross, 1985, Berlin: Springer-Verlag.

of the above-listed regions within occipito-temporal-limbic cortex putatively mediates one of these component functions.

Although the division of labor is not clearcut, that is, two different regions and inter-region pathways may perform different aspects of the same function, it seems that (a) occipital cortex predominantly controls perceptual processing, and (b) temporal cortex and the limbic system, meaning- and memory-related functions.

Concerning the latter two regions, data suggest that (a) temporal cortex is relatively more involved in the cognitive aspects of learning (e.g., the formation of semantic associations and the categorization of input) and remembering (the template match); and (b) the limbic system, in the affective aspects of learning (the mediation of emotional responses to current stimuli due to past experience, stimulus-reinforcement associations, etc.) and remembering.

Although behavioral, anatomical, and physiological data have implicated this circuit in visual memory processing, "the actual locations of the memory traces for visual patterns remain elusive" (Thompson, 1986, p. 944). Rolls (1985) postulated that such traces are difficult to locate because recognition may not occur at one point in time and space. Rather, according to Rolls, each of the five efferent pathways from IT cortex (viz., those to amygdala, hippocampus, basal forebrain and hypothalamus, orbitofrontal cortex, and the tail of caudate nucleus)

> "is used for a different function . . . so that there may be no unique `recognition' of a stimulus, but rather use of a representation of a stimulus by a number of different, subsequent, probably partly parallel and independent processing systems." (p. 211)

The current subsection specifies the relationships between cerebral region and visual recognition function. For the purpose of an overview, these relationships are listed prior to their being discussed. (Note. In both the list and discussion, cerebral regions are presented in ascending order, i.e., from lower to higher neural centers.)

Overview of Structural-Functional Relationships Within the Visual Memory Circuit

Striate and Prestriate Cortex

Striate cortex controls vision per se. Clinical data provide the most stiking evidence of area 17's function: Damage to this region results in blindness (scotoma).

Lesion data have implicated prestriate cortex (particularly in the RH) in (a) figure-ground separation, (b) discrimination of complex stimuli, (c) synthesis of picture content, (d) identification, and (e) recognition (Kolb & Whishaw, 1985, chap. 10).

Visual and Cross-Modal Association Cortex

These areas are involved in the processing of different types of complex visual stimuli. For example, neuroanatomical data from postmortem prosopagnosiac cerebra have implicated the bilateral mesial occipito-temporal cortical region ([a] inferomesial visual association cortices and [b] fusiform and lingual gyri in both cerebral hemispheres) in the recognition of familiar faces (A. R.

Damasio et al., 1982). De Renzi and Spinnler (1966) also reported posterior occipito-temporal lesions in human prosopagnosiacs.

VEP data have shown that this same general region (viz., prestriate-posterior temporal cortex), especially in the RH, processes "spatially intricate" patterned stimuli (Vella, Butler, & Glass, 1972, p. 126). These investigators found that VEP amplitudes (a) at the T6-O2 (RH) and T5-O1 (LH) sites increased to checkerboard, but not to flash, stimuli and (b) were significantly larger at the RH site.

Temporal Cortex

Temporal cortex has been implicated in visuopsychic aspects (e.g., selective attention, discrimination, cross-modal integration, categorization, learning, and recognition) of processing complex visual stimuli (Jackson, 1874, cited in Milner, 1971; Kolb & Whishaw, 1985, chap. 17).

These behaviors have been correlated with this region on the basis of the following convergent evidence:

1. Human electrical stimulation data (Penfield & Perot, 1963).

2. Human lesion data (Kimura, 1963, cited in Fedio & Buchsbaum, 1971); Landsell, 1968; Milner, 1968, 1971; Taylor, cited in Milner, 1968).

3. Nonhuman primate lesion data (Blum, Chow, & Pribram, 1950; Chow, 1951; P. Dean, 1982; Hagger, Brickson, & Bachevalier, 1985; Iwai & Mishkin, 1967, 1969, cited in

Iverson, 1983; Iwai & Mishkin, 1968, cited in Ungerleider & Mishkin, 1982; Martin-Elkins & Horel, 1985; Milner, 1954; Mishkin, 1954, cited in Iverson, 1983; Weiskrantz, cited in Iverson, 1983).

4. Nonhuman primate single-unit data (M. W. Brown, Wilson, & Riches, 1986; Desimone, Schein, Moran, & Ungerleider, 1985; C. Gross, 1973, 1984; C. Gross, Desimone, Albright, & Schwartz, 1985; Iwai, 1985; Moran & Desimone, 1985; Perret et al., [1982], Rolls [1983], Schwartz et al. [1983], all three studies cited in C. Gross et al., 1985; Spitzer & Richmond, 1985).

The Limbic System

(a) Rhinal cortex has been implicated in visual recognition memory (Murray, Bachevalier, & Mishkin, 1985); (b) hippocampus, in memory encoding (Scoville & Milner, 1957, cited in Kolb & Whishaw, 1985, chap. 20) and in recognition per se (Rolls, 1985); and (c) amygdala, in the learning of stimulus and reinforcement associations during the acquisition phase of recognition processing (Rolls, Ibid.).

Occipito-Temporal Cortex

Agnosia Data

Visual agnosiacs, those with damaged occipito-temporal cortex, demonstrate such visuopsychic disorders as the inabilities to (a) recognize, (b) verbally identify (name), (c) properly use and/or graphically reproduce objects and their pictorial representations, and (d) combine individual visual impressions into a single picture (Brown & Schafer, 1888, cited in C. Gross, 1973; Geschwind, 1965, cited in Kolb & Whishaw, 1985, chap. 19; Klüver & Bucy, 1938; Kolb & Whishaw, 1985, chap. 10).

Agnosiacs cannot recognize the class to which a given stimulus belongs (A. Damasio & H. Damasio, 1983; A. R. Damasio et al., 1982) partially because they cannot form correct and stable categories; they form categories which are broader or narrower than normal and change those categories relatively frequently (D. Levine, 1982). They display a

> "defect in recognition of previously familiar visual stimuli . . . . A previously familiar visual stimulus, correctly perceived, fails to evoke pertinent nonverbal and verbal memories." (A. R. Damasio et al., 1982, p. 337)

Hence, visual agnosiacs, those with damaged interpretive cortex (Penfield & Perot, 1963), can see stimuli, but cannot see what those stimuli are; they form meaningless percepts of their visual world (Teuber, cited in Benson, 1984). The different names for this disorder, that is, agnosia, associative mind blindness (Lissauer, cited in Klüver & Bucy, 1938), and psychic blindness (Klüver & Bucy, 1938), refer to the visuopsychic nature of this disease. (Note. The term agnosia is derived from Greek words meaning not to know [Freud, 1891, cited in Nielson, 1935].)

Because this disorder is characterized by (a) the ability to see combined with (b) the inabilities to associate verbal labels with the object of vision and/or match that object with its description (von Senden, 1949, cited in Berkley, 1984), Geschwind (1965, cited in Kolb & Whishaw, 1985, chap. 19) postulated that some agnosias are caused by a disconnection between neural representations of visual and verbal information in the brain.

For example, a lesion located in the pathway between either RH or LH visual association cortex and LH-based language regions might result in this type of visual recognition deficit. Historically, some of the earliest clinical reports (late 1800s-early 1900s) concerning agnosiac cases do cite splenium damage (Nielson, 1937), as Geschwind suggested.

Finally, when predominantly LH damage is found, alexia (the ability to read combined with the inability to comprehend the mearning of what is read) results. Hence, posterior association cortical damage correlates with cognitive dysfunctions (semantic and memory processing); whether that damage affects visual or verbal processing depends on its lateral location.

Temporal Cortex

Lesion Data

Temporal cortex alone (consisting of areas 20 [inferotemporal {IT} cortex]); 22 [superior temporal cortex]; 21, 37, 38 [medial temporal {MT} cortex]; and 41 and 42 [Heschl's Gyrus]) has also been implicated in visuopsychic aspects of visual recognition.

For example, monkeys with bilateral lesions in the ventral temporal lobe from superior temporal sulcus to (a) the medial and inferior temporal gyri and (b) IT cortex displayed deficits in learning to discriminate and retain visual patterns (Mishkin, 1954). Monkeys with RH and/or LH, and humans with RH, temporal lobe lesions were impaired in their abilities (a) to form spatial relationships among separate features and (b) to perform visuoconstructive tasks (map-drawing and block design) (Milner, 1954).

Further, humans with varying degrees of right temporal lobe damage demonstrated the following abnormalities: (a) reduced accuracy in the graphic reproduction of the Rey-Osterrieth figure (Taylor, cited in Milner, 1968); (b) deficient performance during a closure task (Landsell, 1968); (c) impaired recognition of overlapping nonsense figures (Kimura, 1963, cited in Fedio & Buchsbaum, 1971); and (d) the inabilities for learning, retaining, and recognizing complex visual stimuli (abstract and nonsense patterns) (Milner, 1968), "seizing the individual within a class" (Milner, Ibid., p.204), and "distinguishing and remembering intricate visual patterns that share many structural attributes" (Milner, Ibid.).

Milner (1968) also noted that (a) right-temporal-lobe-damaged patients demonstrated normal perceptual and mnestic processing of nonpatterned stimuli (e.g., different shades of red or flashing lights [Prisko, 1963, cited in Milner, Ibid.]); (b) left-temporal-lobe-damaged subjects demonstrated normal processing of complex visual stimuli.

She concluded that right temporal cortex is involved in the processing of patterned visual material.

Milner also found that right-temporal-lobe-lesioned humans (a) performed poorly during the delayed recall of geometric designs (Milner [1960], Taylor, both cited in Milner, 1968) and (b) performed better on an immediate reproduction than delayed recall task to facial stimuli (Milner, 1968). She interpreted these findings to indicate that temporal cortex is relatively more involved in the memory- than sensory-related component of visual processing.

These lesion and lobectomy data corroborated the early electrical stimulation data of Penfield and his colleagues (1930s, cited in Kolb & Whishaw, 1985, chap. 14). Their data showed that such stimulation of the right temporal lobe evoked vivid visual memories.

Inferotemporal Cortex

Lesion data have implicated one area of temporal cortex, namely, MT cortex, in memory processing: Its removal resulted in global amnesia (Iverson, 1983). A substantial amount of lesion and electrophysiological data have indicated that another temporal region, IT cortex, may play an active role in the higher level processing of complex visual stimuli (see Figure 16).

Due to IT cortex's visuopsychic functions, the region as a whole has been described as the "cortical retina" (Polyak, 1957, cited in C. Gross et al., 1985, p. 179), and its constituent neurons, as "gnostic cell[s]" (Kornorski, 1967,

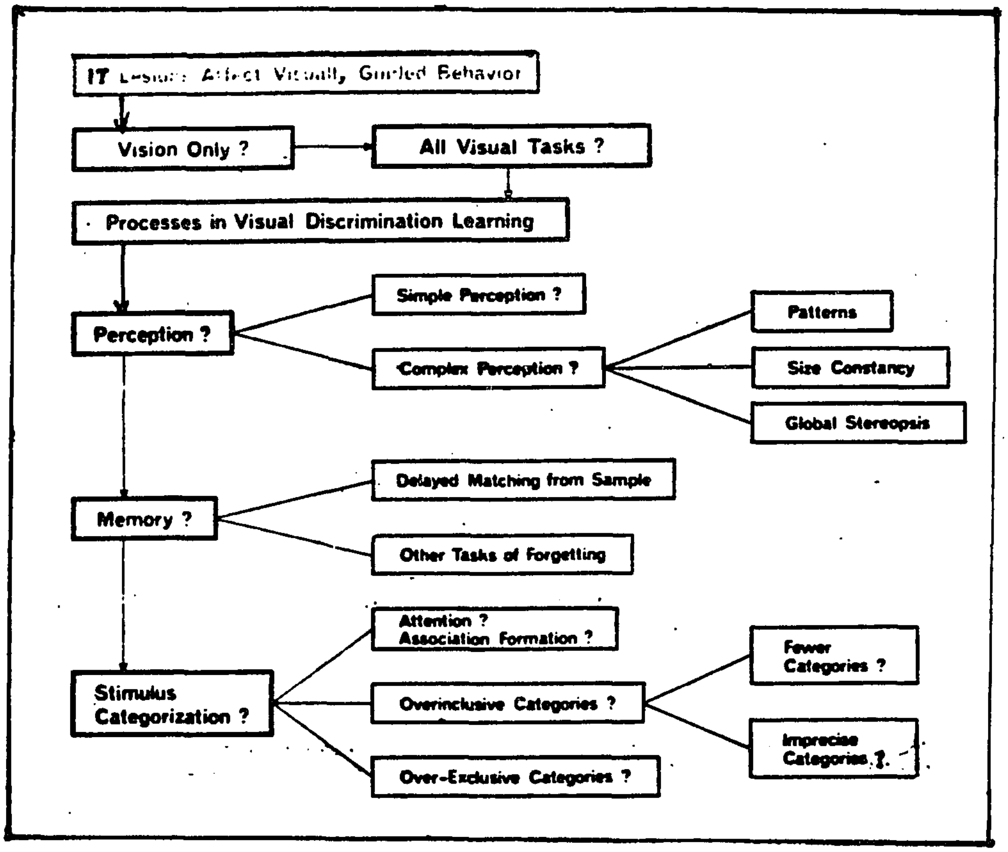


Figure 16. Questions asked about the inferotemporal defect.

Note. From "Visual Behavior in Monkeys With Inferotemporal Lesions" by P. Dean. In Analysis of Visual Behavior (p. 601) by D. J. Ingle, M. A. Goodale, and R. J. W. Mansfield, 1982, Cambridge, MA: MIT Press.

cited in C. Gross et al., 1985, p. 198).

(Note. The following fact is necessary to understand the data below: Because bilaterally IT-lesioned monkeys demonstrate the same visual learning and memory deficits as RH-IT-lesioned humans, the same functions are thought to be mediated by IT cortex in both hemispheres in monkey and in the RH alone in humans [Gross, 1984].)

Lesion data. First, Iwai and Mishkin (1968, cited in Ungerleider & Mishkin, 1982) found that IT-lesioned monkeys were deficient in visual discrimination tasks. Desimone et al. (1985) reported a similar finding: IT-lesioned macaques demonstrated impaired performance in learning to discriminate both patterned stimuli and objects. They also showed a reduced capacity to distinguish between novel and familiar objects.

Next, Martin-Elkins and Horel (1985) found that, in a delayed matching-to-sample task with varied delay durations, IT-lesioned monkeys showed deficits in remembering black-and-white patterned stimuli for relatively long durations (a minute or more), but not for shorter ones. P. Dean (1982) implicated IT cortex in both learning and remembering: He reported that its bilateral removal in monkey resulted in abnormally slow learning and retrograde amnesia (the monkey forgot visual discriminations it had learned prior to the lesion).

Single-Unit Data. Consistent with some of the lesion data reviewed by Desimone et al. (1985) cited above, single-unit data showed that some cells (12% of 177 from which recordings were taken) in monkey IT cortex maximally responded to novel stimuli and showed attenuated responses to repeated stimuli (M. W. Brown et al., 1986).

1. Selective attention cells. Single-unit data (recorded from 161 IT cells in 2 Rhesus monkeys) also showed that another type of IT cell responds to stimuli in a location to which a subject has been trained to attend; conversely, this cell does not respond to stimuli in a different location which that subject has been trained to ignore (Moran & Desimone, 1985). These researchers noted the contribution made by these "selective attention cells" to memory processing:

> "In . . . IT cortex, selective attention may allow the animal to identify and remember the properties of a particular stimulus." (p. 784)

Hochstein and Maunsell (1985) also found selective attention cells in area V4, a visual area adjacent to temporal cortex, in Rhesus monkey. These subjects were required to press a key when they saw a stimulus containing a dimension identical to that presented in a prior cue.

For example, when a red patch (the cue stimulus) followed by a series of gratings that varied in color (but not in orientation) were presented, a keypress to a red grating constituted the correct response; when a vertical black-and-white grating (the cue stimulus) followed by a series of gratings that varied in orientation (but not in color) were presented, a keypress to a vertical grating was the correct response.

These investigators found that in one-third of the cells studied, the tuning curves to the attended dimension were sharper than those to the irrelevant one.

Areas TE and TEO. The functions of the anterior (area TE) and posterior (area TEO) subregions within IT cortex have been examined separately by both lesion and single-unit techniques. These methods have implicated the former area in the cognitive aspects of pattern recognition (e.g., learning, remembering, and categorizing of patterned input) and the latter, in its perceptual aspects (Iwai, 1985).

For example, regarding area TE's putative cognitive functions, Spitzer and Richmond (1985) found that some TE cells differentially responded to the identical compound stimulus as a function of the dimension to which the subject (N = 2 adult monkeys) was attending. Hagger et al. (1985) found that, in adult Rhesus monkeys with bilateral TE lesions, fixation time to novel stimuli did not significantly differ from that to familiar stimuli; in contrast, that to novel stimuli was significantly longer than that to familiar stimuli in normal controls.

Contour-sensitive IT cells. Finally, another higher level processing capacity of IT cortex, suggested by single-unit data, is the global analysis of patterned stimuli (i.e., the encoding of patterns in their entirety, rather than component-by-component).

1. Desimone et al.'s (1985) hypothesis. These

investigators have argued that, at least for macaque, the larger receptive fields (625 degrees squared) and broader tuning curves of IT cells relative to cells in lower visual cortical regions (e.g., receptive fields in V4, the region immediately prior to IT cortex, measure only 1 degree squared) underlie this capacity for global analysis. They support their argument by the following two points.

First, the V4 cells, with smaller receptive fields, can only "see" small sections of the visual field; thus, they can only encode local information. In contrast, IT cells, with larger receptive fields, see a larger section of the visual field; hence, they can compare and integrate many bits of local information within that section.

Second, partially due to their smaller receptive fields, many V4 cells are sensitive to the size and retinal position of a given stimulus; hence, they calculate the overall shape of that stimulus on the basis of the size and location of its local contours. In contrast, in part due to their larger receptive fields, many IT cells respond to stimuli on the basis of overall shape independent of their size and retinal position (see C. Gross et al., 1985, immediately below); these cells calculate stimulus shape on the basis of global contour per se.

2. C. Gross et al.'s (1985) Fourier descriptor data. This research group also presented data showing single-unit sensitivity to overall pattern. First, they found, as did Perrett et al. (1982) and Rolls (1983) (both cited in C.

Gross et al., Ibid.), that (a) a small percentage of IT cells responded to facial patterns and (b) the magnitude of these responses decreased when the facial features were scrambled. These investigators concluded that these cells were selective for the "overall configuration" (p. 188) of the face, rather than for its local features.

Second, Gross et al. used Fourier descriptor stimuli (Zahn & Roskies, 1972, cited in C. Gross et al., Ibid.) to test IT shape sensitivity. Each such stimulus, which represents an integrated value of local boundary values, is generated by two fundamental steps: (a) calculating a boundary orientation function from the values of the orientation and tangent angle of a given shape's boundary at periodic points around its perimeter; and (b) transforming that function into a Fourier series, that is, a description of the overall shape in terms of frequency, amplitude, and phase, which is independent of size and position information.

These researchers found, as did Schwartz et al. (1983, cited in C. Gross et al., Ibid.), that many IT cells were selective for overall shape, even when size and retinal position were varied. They concluded that shape appears to be the salient stimulus dimension processed by a large proportion of IT units. Hence, whereas lower visual cortical regions (e.g., area 17) analyze local boundary information, higher regions (e.g., IT cortex) analyze global boundary information.

3. Iwai's (1985) study. Iwai recorded from 295 single units in areas TE and TEO of macaque (N = 107) while he presented four patterned stimuli or component parts of those stimuli. He found that some TE cells responded to (a) the stimuli as a whole, but not to their parts and (b) whole stimuli independent of orientation (i.e., they fired to both upright and rotated versions of the same stimulus).

Within this second cell group, some responded to more than one of the four patterns; a smaller percentage (the Type 1 neurons), to one pattern only. Further, a small group of TEO units (the atypical Type 1-Subgroup 3), like the TE units, fired to the stimuli as a whole independent of orientation, but unlike the TE units, fired to components extracted from the most preferred patterns.

Iwai commented that (a) the response characteristics of the Type 1 neurons suggest that monkeys can perceive patterns as a whole and (b) those of the atypical Type 1 neurons, that they act as a "mechanism of synthesis of components to construct a specific pattern" (p. 435).

Iwai was cautious in discussing these data: Although he acknowledged that they contribute to our understanding of the cellular substrates of pattern vision, he concluded that "sufficient data have not yet been accumulated to discuss the neural mechanisms of pattern vision from the neuron level" (p. 435).

The Limbic System

Rhinal Cortex

This structure has been implicated in visual recognition. Murray et al. (1985) compared the performance of two groups of monkeys, both of which had had ablations of the amygdaloid complex and hippocampal formation, but only one of which had been spared rhinal cortex. On a delayed matching-to-sample task, in which the number of objects to be remembered and the duration for which they were to be remembered were used as measures of memory performance, the "rhinal cortex" group performed better than the "no rhinal cortex" one.

Hippocampus

The hippocampus has been implicated in memory processing in general: Its removal results in material-specific global amnesia as a function of hemisphere of loss (hippocampectomies in the LH result in the inability to remember verbal material; those in the RH, nonverbal [Milner, 1968]).

This region has also been implicated in a specific aspect of visual memory processing, namely, the encoding of new memories. Scoville and Milner (1957, cited in Kolb & Whishaw, 1985) found that H. M., who had undergone a bilateral hippocampectomy, demonstrated anterograde amnesia (he was unable to learn and store new information).

Concluding Comments

This discussion concerning the regional substrates of recognition in primate cortex concludes this subsection. Thus far, hemispheric specialization, spatial frequency, and recognition have been defined; hence, the data concerning hemispheric specialization for spatial frequency during recognition are presented next.

1.4] HEMISPHERIC SPECIALIZATION DURING PATTERN RECOGNITION

> "The characteristics of the neural representations on which cognitive operations are performed may constitute the basis on which cerebral lateralization is built. This is not to deny the existence of the more traditional dichotomies, but rather to argue that such dichotomies result from--and are explained by--a more fundamental dissociation (Sergent, 1982a, p. 268) . . . . Any process requiring a high level of sensory and/or motor resolution--be it verbal, analytic, visuospatial or holistic--will preferentially engage the LH, whereas low-resolution processes will preferentially implicate the RH." (Sergent, 1982a, p. 270)

Some data and hypotheses concerning hemispheric specialization during pattern recognition have been cited above, for example, (a) Milner's clinical data (1954, 1968, 1971) suggesting right temporal involvement in nonverbal complex pattern recognition; and (b) A. R. Damasio et al.'s hypothesis (1982) that the RH uses parallel processing, and the LH, serial, when performing a template match during facial recognition.

To specify the aspects of patterned stimuli for which each of the cerebral hemispheres is putatively specialized, several researchers have manipulated spatial frequency and presented the stimuli in a divided visual field paradigm. They have used different classes of stimuli and different tasks: (a) global-local letters (a large letter composed of small letters [Navon, 1977, see subsection 1.2/4]) in a visual search task (Sergent, 1982a), (b) letters in a same/different recognition task (Sergent, 1983b), (c) faces in a recognition task (Sergent, 1982c), and (d) square waves in a go/no go identification task (Previc, 1982).

The results of these normative psychophysical studies have indicated that hemispheric specialization for spatial frequency during a cognitive task (a) depends on such procedural factors as: stimulus spatial frequency range, stimulus energy (controlled by luminance and duration), retinal site of stimulation, and task difficulty (partially controlled by degree of similarity among stimuli) and (b) emerges at a processing level higher than the sensory one.

The current subsection presents the data yielded by the above-cited studies. The "level of emergence" issue is addressed in subsection 4.5 of the Discussion.

1/ Sergent's 1982a Study

Experiment 1

Procedure

Sergent (1982a) presented global-local letter stimuli (F, H, L, and T, in which the global level [large letter] contained low spatial frequencies [subtended a visual angle of 1.9 x 1.3 degrees], and the local level [small letters] contained high frequencies [subtended a visual angle of 0.21 x 0.13 degrees]).

The letters H and L were designated as targets. The subjects' (6 male and 6 female dextral 20- to 31-year-olds) task was to press a "+" key if a target (H and/or L) was present in a given test stimulus and a "-" key if a target was not present in a test stimulus. Subjects were instructed to respond as quickly and accurately as possible. They were given 54 practice trials with feedback concerning response accuracy and 270 experimental trials without feedback.

As shown in Figure 17, six stimulus conditions were possible: In the first two (the conflict [interference] conditions), either the target was present in the large letter, but not in the small ones (Condition 1 [L+S-]) or the target was not present in the large letter, but was in the small ones (Condition 2 [L-S+]).

In the third through sixth conditions (the nonconflict ones), either the target was present in both the large and small letters (Condition 3 [L+S+]) or the target was not present in either the large or small letters (Condition 4 [L-S-]).

Finally, each of the nonconflict conditions contained an identity condition (Condition 5 [Id.]) in which the large letter was the same as the small letters constituting it and a nonidentity condition (Condition 6 [N. Id.]) in which the large letter was different from the small letters constituting it.

The test stimuli, black letters on a white ground mounted on black cards, were binocularly presented (by a tachistoscope) for 150-ms durations, either at the fixation point (central visual field [CVF] condition) or 1.4 degrees to the right or left of fixation (RVF and LVF conditions). The fixation point was a centrally located white dot on a

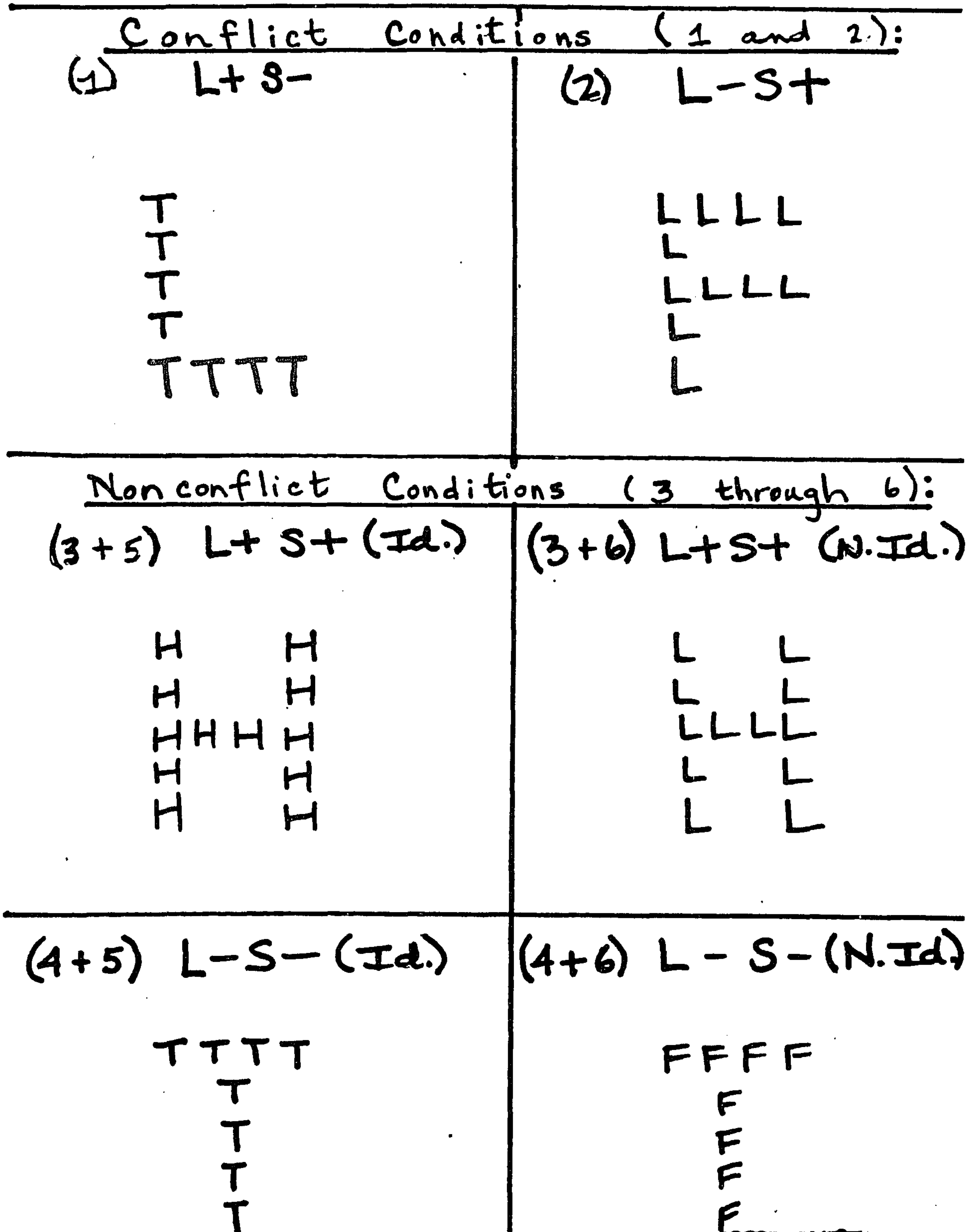


Figure 17. The six stimulus conditions in the Sergent 1982a study. (L+ = target (H, L) present in large letter. L- = target absent from large letter. S+ = target present in small letter. S- = target absent from small letter. Id. = Identity condition. N. Id. = Nonidentity condition.)

Note. From "The Cerebral Balance of Power: Confrontation or Cooperation?" by J. Sergent, 1982, Journal of Experimental Psychology: Human Perception and Performance, 8(2), p. 256.

black field, the luminance of which was 3 millilamberts (mL) during fixation and 10 mL during test stimulus presentation.

Results

RT and accuracy were used to measure visual field (hemisphere) advantage. Results suggested that the RH processed low spatial frequencies, and the LH and CVF, high frequencies. For example, response latencies to LVF presentations were faster than those to RVF and CVF presentations when the subject could make a decision based on a large letter alone (L+S+ and L+S−); conversely, latencies to RVF and CVF presentations were faster than those to LVF presentations when the subject had to consider small letters to reach a decision (L−S+ and L−S−).

Further, equal latencies resulted when the target was presented as a large letter (L+S+ [N. Id.] and L+S−) in the LVF; this finding suggests that "yes" decisions in the L+S+ condition were based on large letters presented in the LVF. Conversely, equal latencies resulted when the target was presented as a small letter (L+S+ [N. Id.] and L−S+) in the RVF; this result suggests that "yes" decisions in the L+S+ condition were based on small letters presented in the RVF.

Regarding the CVF condition, (a) the mean RT to the L+S− stimuli presented in this region was longer than to the L−S+ ones presented here, and (b) the L+S− stimuli presented in the CVF yielded the maximum error rate. Sergent explained these findings and the one mentioned above (viz., that RTs to stimuli presented in this part of the visual field matched those to stimuli presented in the RVF) on the basis of the fact that the central retina (like the LH) putatively processes high spatial frequencies more efficiently than low ones (see subsection 1.2/3 for anatomical and physiological evidence for this position).

These findings have implications for the global precedence model (Navon, 1977) discussed in subsection 1.2/4. Just as Kinchla and Wolfe (1979), J. Hoffman (1980), and Paquet and Merikle (1984) specified conditions under which global precedence does not hold, (viz., when stimulus size, distortion or duration favor high-frequency processing), so do Sergent's results show that retinal site of stimulation affects global precedence: When large stimuli are presented in the LVF, global precedence holds; when they are presented in the RVF and/or CVF, local precedence results.

Finally, Sergent found that latencies to Id. letters were faster than those to N. Id. letters. To test whether this effect was due to the parallel encoding of the large and small letters (J. Hoffman, 1980) or to operations performed on more quickly processed large letters and more slowly processed small ones, Sergent administered a second experiment.

Experiment 2

Procedure

In this study, Sergent binocularly presented the nonconflict stimuli (L+S+ and L-S-) in a divided visual field paradigm (again including the CVF control) to 6 male and 6 female dextral young adults (different from those in the first study). She required them to press a "yes" key if a large test stimulus letter was a target letter (H, L) and a "no" key if a large test stimulus letter was not a target.

Test stimulus duration was brief (62 ms, i.e., 10 ms less than the mean time required by all subjects to correctly identify 25% of the small letter stimuli on 20 trials), and a 1-second backward mask (random lines or dots) appeared at stimulus offset. Again, subjects were given practice trials with feedback (32 in this case) and experimental trials without feedback (192 in this study).

The following rationale was used for this design: If the Id. effect results when the small letters are made unavailable for processing (by the brief stimulus durations and the backward mask), then this effect is not due to the early simultaneous processing of both letters.

Results

The Id. effect did, in fact, result, hence indicating that the large and small letters were serially processed. Further, consistent with this finding, the data suggested that low spatial frequencies were encoded prior to high (identification of the large letters approximated perfect performance, whereas that of the small letters only reached chance levels).

Finally, like the first study, this experiment suggested that the RH is more competent and efficient than the LH and

CVF in processing low frequencies: The most accurate and fastest responses to the predominantly low frequencies which were extracted were found to the LVF presentations; the second most accurate and fastest, to the CVF; and the least accurate and slowest, to the RVF.

2/ Sergent's Spatial Frequency Model of Hemispheric Specialization

> "My own guess is that what will eventually be found is that the left hemisphere typically has what might be called `a finer grain', that is, anatomical and chemical specializations that permit greater registration of small details. As a natural consequence of this, one would expect the typical spatial functions of the left hemisphere, which appear to be concerned with small details . . . . Conversely, the right hemisphere would have a less fine grain, so that it would be specialized for larger units. This would thus lead to the typical right hemisphere spatial functions which seem to be more concerned with external outlines . . . . Another way of thinking about this would be to suggest that the left hemisphere is specialized for high spatial frequencies while the right hemisphere might be more specialized for low spatial frequencies." (Geschwind, 1985, pp. 275-276)

The Basic Features of the Model

Sergent's model proposes the following:

1. A RH advantage emerges when low spatial frequencies are required by a given task and/or made available by the stimuli (characteristics and presentation conditions); conversely, a LH advantage arises when high frequencies are required and/or made available. (Note. Examples of task demands and stimulus parameters resulting in each of these advantages are provided below.)

2. Greater RH proficiency in the processing of low frequencies, and LH, vis-à-vis high, result in the cerebral lateralization of cognitive functions: The characteristic

RH cognitive functions (nonverbal and holistic processing) use the type of neural representation (low-resolution) more efficiently produced in the RH; the typical LH cognitive functions (verbal and analytic) use the type of neural representation (high-resolution) more efficiently produced in the LH.

This model is ambiguous with respect to the level at which lateral differences in spatial frequency processing emerge. Also, it does not specify a neural mechanism underlying hemispheric specialization for spatial frequency. Hence, the general, "black box" description of this effect herein is due to its similar description in the model's initial formulation (Sergent, 1982a).

(*Note*. The weaknesses of this model, both in terms of its logic and counterevidence, are addressed in subsections 4.4 and 4.5 of the Discussion.)

Explication of the Basic Features

Point 1: Procedural Determinants of Hemispheric Advantage

Task requirements. Discrimination tasks involving highly dissimilar stimuli and/or small stimulus sets require low spatial frequency processing. In contrast, those involving highly similar stimuli and/or large stimulus sets require high-frequency processing.

Stimulus characteristics and viewing conditions. Large and small stimuli respectively make available low and high spatial frequencies. Stimulus viewing conditions, however, affect which frequencies will actually be processed by the visual system. For example, predominantly low spatial frequencies are able to be extracted from "low-energy" visual stimuli (those that are dim and/or briefly presented), whereas higher frequencies are also able to be extracted from "high-energy" stimuli (those that are bright and/or presented for long durations).

Also, lower frequencies tend to be extracted from peripherally presented stimuli, and higher ones, from stimuli presented to more central retinal sites. (Note. Sergent discussed the luminance and duration effects in terms of time-intensity reciprocity; see Riggs, 1965, for explanation of retinal mechanisms underlying time-intensity and area-intensity reciprocity.)

Data. Hence, Sergent proposed that only when low frequencies are required or made available will the RH be substantially involved in the processing of that stimulus; conversely, only when high frequencies are required or made available will significant LH engagement occur.

For example, Sergent (1983b) found that when dextral 18- to 30-year-olds were required to match pairs of letters of same or different case or name (Posner's paradigm) that were manipulated in terms of size, duration, and eccentricity (two levels of each independent variable), the following occurred:

1. RTs to LVF presentations of large letters were shorter than to their RVF presentations; conversely, RTs to RVF presentations of small letters were shorter than to

their LVF presentations.

2. RTs to brief (20 ms) LVF presentations were shorter than those to brief RVF presentations, whereas RTs to long (150 ms) LVF presentations equalled those to long RVF presentations.

3. RTs to LVF presentations at large eccentricities were faster than those to similar presentations in the RVF; RTs to RVF presentations at small eccentricities were faster than those to similar presentations in the LVF.

Finally, concerning the effect of luminance on hemispheric performance, Sergent (1982c) administered a divided visual field facial recognition study (stimuli were presented 3 degrees to the left or right of central fixation to 12 dextral 19- to 28-year-old males). She found that as stimulus luminance increased (from 0.8 to 12 to 120 mL), recognition performance to RVF stimulus presentations improved (RTs decreased), whereas that to LVF presentations remained constant.

Point 2: Sensory Determinants of Cognitive Processing

Stimulus material. Sergent argued that low spatial frequencies are sufficient for the discrimination and recognition of nonverbal stimuli, whereas high frequencies are necessary for the identification of verbal stimuli. Hence, RH mediation of nonverbal processing, and LH, of verbal, are due not to two cognitive operations differing with respect to linguistic processing, but rather to greater RH proficiency in processing the neural substrates of nonverbal processing (viz., low spatial frequencies) and greater LH efficiency in processing the high-frequency susbstrates of verbal processing.

Processing mode. Sergent also argued that low frequencies constitute the neural units underlying holistic processing, and high, the neural units used by analytic processes. Hence, RH mediation of holistic, and LH, of analytic, processing modes are due not to two cognitive operations differing in terms of conceptual processing, but rather to "similar processing applied to different neural representations, which suggests that the analytic-holistic dichotomy may merely represent an epiphenomenon" (Sergent, 1982a, p. 268).

Summary

Thus, Sergent posited that the fundamental source of the dichotomy between the hemispheres is not differential lateral capacities with respect to cognitive functions per se. Rather, it is the different proficiency levels of each hemisphere in processing the neural units underlying those cognitive functions.

Advantages of the Current Model

As suggested above, one advantage of the spatial frequency model of hemispheric specialization is that it is parsimonious (S. Novak, personal communication, November, 1984; Sergent, 1982a):

> "Instead of developing drastically different processing mechanisms in each hemisphere, . . . a differential sensitivity to neural inputs, beyond the sensory areas,

> may have proven a better adapted means of providing refined cognitive processing (in the LH) while keeping possible more elementary, yet necessary, operations (in the RH)." (Sergent, 1982a, p. 269)

A second advantage is that its complementary specialization type of functional organization permits a wide range of cognitive processes:

> "The same cognitive operation may require the involvement of both hemispheres, with the RH more adept at preliminary and low-resolution processing and the LH at later and high-resolution processing. This points to a cooperation between the hemispheres [with] . . . complementary capacities in processing incoming information, with the RH providing the frame within which the LH performs its more refined operations." (Ibid.)

Conclusion

In essence, Sergent has proposed a lateral mechanism to add to the attentional, regional, and cellular mechanisms described above for the localization and discrimination functions of the visual system (see susbsection 1.2/3). Just as the preattentive mode, parietal cortex, and Y-cell system putatively provide the frame within which the respective focal attentive mode, temporal cortex, and X-cell system perform their more refined operations, so has Sergent argued that the RH might provide "the frame within which the LH performs its more refined operations" (Ibid.).

3/ Other Data Concerning Hemispheric Specialization for Spatial Frequency

Previc's (1982) Study

It is impossible to assess the validity of Sergent's model without additional data yielded by studies using nonsymbolic, nonverbal stimuli. Previc (1982) performed such a study. He binocularly presented square-wave stimuli, varied in spatial frequency (0.9-5.5 cpd) and contrast (.1, .4, and .6), for 100-ms durations in a divided visual field paradigm.

In a go/no go orientation identification task, subjects (24 dextral 18- to 45-year-old males) were instructed to raise one hand (left- and right-hand usage was counterbalanced) to one of two (45 and 135 degrees) orientations and to make no response to the other orientation. Previc found that the Spatial Frequency x Visual Field interaction effect did not reach significance (as measured by RT and false alarm rate).

Previc did not interpret his negative results to indicate that hemispheric specialization for spatial frequency does not exist. Rather, he suggested that (a) this study may not have tapped the higher cognitive operations that, when performed on different spatial frequency ranges, selectively engage the cerebral hemispheres; and/or (b) the spatial frequency range used may have been too low to differentially engage the hemispheres. (Previc noted that 2-3 cpd are the salient frequencies in facial form perception [Tieger & Ganz, 1979], and frequencies higher than 5.5 cpd are required for the perception of internal facial features [Ginsburg, 1978, cited in Previc, 1982].)

Concluding Comments

Hence, one question raised by both Previc's and

Sergent's studies is: At what processing level does hemispheric specialization for spatial frequency emerge? This fundamental issue is thoroughly examined in the Discussion section below.

1.5] METHODOLOGICAL APPROACH

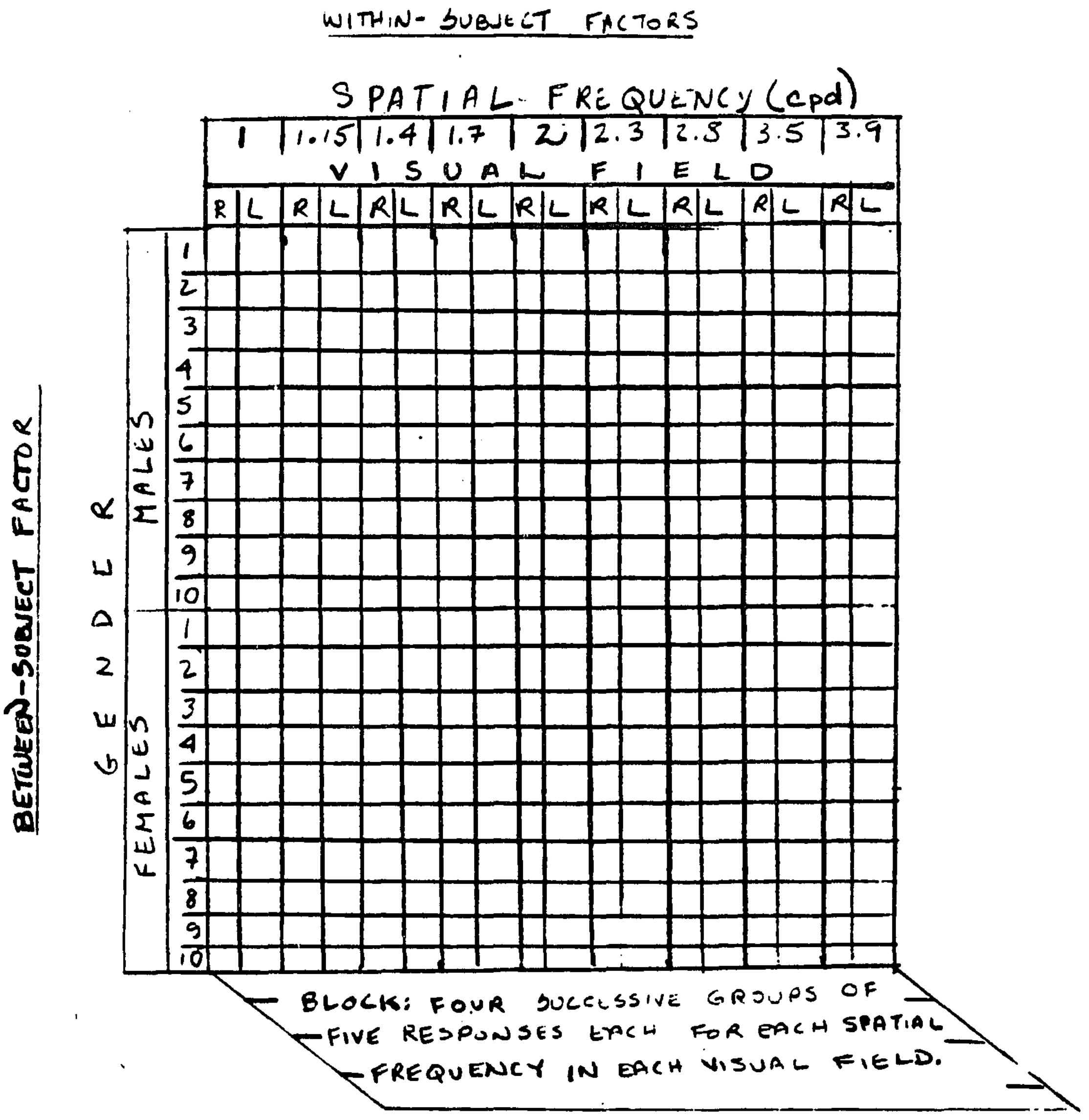
This subsection describes the author's considerations concerning how to test the current hypotheses and to analyze the results. Why each of the experimental manipulations were selected, and what results were expected, are also discussed herein.

1/ Paradigm

Experimental Design

The current study consisted of two experimental designs: (a) a multifactor single-subject design (also called a within-subject or repeated measures design), with respect to the spatial frequency, visual field, and block factors; and (b) a mixed factorial, with respect to the gender factor (see Figure 18). The first design entails each subject's being exposed to all levels of the independent variables. This method is advantageous because each subject's acting as his/her own control substantially reduces variability.

The second design also involves each subject's being exposed to all experimental conditions. This approach differs from the first in that it entails (a) the grouping of individual subjects according to one trait and (b) the analysis of their performance in terms of between-group differences. In the current study, subjects were grouped



cpd = cycles per degree. R = right. L = left.

Figure 18. Multifactor single-subject mixed factorial experimental design.

according to gender, and their recognition judgements were analyzed in terms of intergender differences.

Task

Psychophysical Foundations

The type of recognition task used in the current study was a same/different match between two successively presented stimuli. The logic of this task derives from the classical psychophysical method of constant stimuli for difference threshold determination (Fechner, 1860/1966, cited in D'Amato, 1970, chap. 5).

A psychophysical procedure was drawn upon because although the current problem contains a cognitive component, it is essentially psychophysical: It concerns how the spatial frequency dimension of a stimulus affects a given recognition response. This problem meets the criterion formulated by Stevens (1951):

> "There is only one problem of psychophysics, namely, the definition of the stimulus . . . . The complete definition of the stimulus to a given response involves the specification of all the transformations of the environment, both internal and external, that leave the response invariant . . . . The question is: `What properties of stimulus objects do the stimulating?'" (pp. 31-32)

In the method of constant stimuli, each subject is required to judge whether a variable stimulus is greater than, less than or the same as the standard stimulus. In the current version of this task, the term *variable* is replaced by *test* (TES); *greater than* and *less than*, by *different*; and *standard*, by *target* (TAR). Also, the length of the ISI is increased, thereby transforming the test from one of perceptual discrimination into that of recognition memory.

Rationale for Selection

This same/different task was chosen for two reasons. First, it (a) is the most fundamental possible test of recognition and (b) contains the smallest number of confounding variables. The presentation of a single target stimulus, a delay, and a test stimulus is the simplest way to test one's capacity to remember if one has previously seen a given stimulus.

The current paradigm was selected from alternatives that (a) make more complex processing demands and (b) use independent variables with uncontrolled dimensions that affect performance. For example, in another widely used recognition task, a set of several target stimuli, a delay, and a single test stimulus are presented, and subjects are instructed to identify whether or not the test stimulus was a member of the target set.

In that task, (a) more than one pair of visual inputs need be perceptually processed and stored, and (b) more than one match between one pair of present and past inputs need be made. Further, the numbers of such inputs and matches influence recognition performance.

The second reason that the same/different paradigm was chosen is that an ERP study has been designed to further investigate the question of emergent level of lateral asymmetry during pattern recognition. The clearest and most comprehensible "recognition" waveforms are produced when signal averaging is performed on neuroelectric activity during a single match between one pair of visual inputs.

The optimal paradigm for the ERP study was considered when designing the current one so that the behavioral and electrophysiological data will be comparable.

2/ Subject-Related Independent Variables

Sample Size

The sample size, 20, was selected for two reasons. First, 20 is the standard number used in psychophysical studies with comparable paradigms.

Second, a highly significant main effect for frequency (*F* (3,12) = 10.75, *p*<.001) and a marginally significant Visual Field x Gender interaction effect (*F* (1,12) = 6.74, *p* <.06) were found in a pilot study with the identical paradigm in which only 3 males and 3 females were tested. Hence, a sample consisting of 10 subjects of each gender appeared sufficient to investigate the current hypotheses.

Subject Characteristics

As mentioned in subsection 1.1/7, cerebral asymmetry is not species-specific, but rather class-specific: Anatomical, neurochemical, and behavioral asymmetries have been demonstrated across several mammalian species. Further, patterns of asymmetry have been found to vary both across and within these different species (Curtiss, 1985; Pedalty et al., 1985).

Within humans, such factors as gender, age, handedness, familial sinistrality, ethnic background, linguistic background, visual acuity, ocular dominance, and intelligence have been shown to affect asymmetry patterns. Hence, data concerning these factors were collected for subjects in the current study (see section 2.1 for descriptions of the screening tests).

The relationships between many of these factors, cerebral asymmetry, and pattern recognition were discussed above; these relationships and their effect on subject selection are briefly summarized herein.

Gender

To review, some normative and clinical anatomical and behavioral data indicate (a) male superiority in visuospatial processing (Kimura, 1985; see McGlone, 1980, for review) and (b) a relatively greater degree of cerebral lateralization in males than in females (de Lacoste-Utamsing & Holloway, 1982; Kimura, 1985).

When these gender differences fully mature and stabilize is not definitively known; data suggest that during developmental stages of increased hormonal activity, such as the prenatal and adolescent periods, intergender differences in cerebral organization are formed and strengthened (Geschwind, cited in Garman, 1985, and in Konner, 1985; McGlone, 1980; Reinisch et al., 1979, cited in Netley & Rovet, 1983). One reason that postadolescents were used in the current study is that gender differences in the brain are well-developed and relatively invariant in this age group.

Age

Just as gender differences in brain organization vary with age, so do visual and memory capacities. Young adults (range = 19-36 years; mean = 27.5 years) were chosen for the current study because their age bracket represents a relatively stable period of mature visual and memory function. Data show that before and after this period, normal developmental changes occur in (a) sensitivity to spatial frequencies, (b) interhemispheric communication, and (c) control (voluntary) processes used to enter and store information in short-term and long-term memory, respectively.

Spatial frequency sensitivity. To review, the sensitivity function to high frequencies does not approximate the adult function until late childhood (Spekreijse, 1978). In mid-late adulthood, this function changes again: Sokol et al. (1981) showed that, among 125 13- to 82-year-olds (mean age = 43 years), the VEP P1 latency to pattern-reversed checks increased with age, and the rate of this latency change was faster to high than to low frequencies. These latter investigators suggested that normal optical and neural developmental changes may underlie the behavioral developmental changes that they observed.

Interhemispheric communication. Another normal developmental change that occurs outside of the age group currently tested involves the myelination of the corpus callosum: This process may remain incomplete until adolescence (Yakolev & LeCours, 1967, cited in Desmedt, 1977; see subsection 1.1/8). Hence, pubescent subjects, labile in this respect, may have different rates of interhemispheric information transfer than the more stable postpubescent ones selected for testing.

Memory. Use of the control processes respectively associated with each of the three storage structures postulated in the multistore model of memory (Atkinson & Shiffrin, 1968, cited in Wingfield & Byrnes, 1981; see subsection 1.3/3) improves with age; the precise age during late childhood-adolescence at which such use reaches maturity is uncertain (T. F. Gross, 1985, chap. 6). These normal developmental changes in memory include the following:

1. Selective attention to visual stimuli, the control process associated with iconic storage, is more refined in adults than in children.

2. (a) Rehearsal, the control process used to transfer input from short-term into long-term storage, and (b) chunking, the control process used to reorganize individual items into categories in short-term memory, are more effectively used by older than younger children.

3. The organization of items, the control process used in long-term memory to maximize retention, is qualitatively different between adults and younger age groups. Whereas adults create complete categories from which irrelevant

information is deleted, children and young adolescents form fragmented and illogical categories that often include irrelevant items (Ibid.).

In sum, the fact that all of the control aspects of memory do not attain stable adult levels until a currently unknown age during adolescence provides yet another reason for choosing postadolescents for the current study concerning recognition memory.

Handedness and Familial Sinistrality

To maximize the probability of a homogeneous lateralization pattern characterized by RH control of visuospatial processing, and LH, of linguistic, only dextral subjects were used.

Incidence of familial sinistrality was noted for each subject because patterns of cerebral organization may differ between those with and without left-handed relatives. Hécaen and Sauguet (1971, cited in Kolb & Whishaw, 1985, chap. 15) found, for example, that among unilaterally lesioned left-handers, those without a family history of sinistrality performed like right-handers on a neuropsychological test battery; those with such a family history performed significantly differently.

Ethnic Background

Some data suggest that hemispheric organization may vary between different ethnic (cultural) groups. For example, Risse et al. (1983, cited in LeMay, 1985) found that whites, American Indians, and blacks differed with respect to gross cerebral anatomical measurements including hemisphere widths. Hence, each subject's ethnic background was noted.

Bilingualism

A record was made of the number of languages fluently spoken by each subject, as pattern of lateralization may vary with this factor in the following ways. Five out of seven studies have reported that LH involvement in linguistic processing in bilinguals is significantly less than that in monolinguals, especially when the second language was acquired at a relatively late age. Three out of nine studies have further suggested a substantial amount of RH involvement in the acquisition of the second language (see Obler et al., 1982, cited in Springer & Deutsch, 1985, chap. 8, for review; Springer & Deutsch, Ibid.).

An ERP study (Donald, Meuter, & Ardal, 1986) showed that although the same component (N400) was elicited by a particular linguistic manipulation (viz., the presentation of final words in sentences that were semantically incongruous with the preceding words) in 12 monolingual and 24 bilingual males, the amplitude and lateral distribution of that component differed between these two groups: (a) The amplitude of the "bilingual" N400 was lower than that of the "monolingual" one to "second-language" stimuli, and (b) the bilingual N400 was characterized by either a LH parietal peak or a bilaterally symmetrical distribution to both first- and second-language stimulation. Neither result significantly correlated with age of second-language acquisition.

Donald et al. concluded that (a) bilinguals process their first language differently from monolinguals; (b) mastery of a second language, acquired at any age, results in modified electrophysiological processing of both first and second languages; and (c) "the bilingual brain reallocates the division of labor between the right and left sides of the cortex, for both languages, in the processing of reading material" (p. 721).

Visual Acuity and Ocular Dominance

Subjects were screened for roughly perfect visual acuity (20/30-20/20) to assure that they could meet the visual demands of the task: The capacities to detect and discriminate presuppose the capacity to recognize.

Subjects' ocular dominance was tested as well. Ocular dominance refers to the tendency for one eye to form better quality representations than the other: In the dominant eye, (a) the retinal image is more stable and clear, and (b) the eye muscles are less susceptible to fatigue and, hence, more capable of precise fixation than in the nondominant one.

Most humans (65% of the population) are right eye dominant. Although the exact age this dominance is established is unknown, there is little evidence for any significant developmental change (Porac & Cohen, 1981).

Ocular dominance was noted for each subject in the current study because although the dominant eye projects to both hemispheres (to review, the right and left hemiretinas of each eye respectively project to the right and left hemsipheres) and, hence, suggests no correlation between ocular and hemispheric dominance, some electrophysiological and psychophysical data do suggest such a correlation.

First, the amplitudes of left eye dominant females' VEPs, recorded over RH and LH occipital sites to RVF and LVF stimulus presentations, were higher than those of "right-eyed" females (Culver, Tanley, & Eason, 1970). Second, acuity in the "sighting" eye was found superior to that in the "nonsighting" one. Third, target recognition in right eye dominant subjects was better than that in "left-eyed" ones (Porac & Cohen, 1981).

Intelligence

Finally, the intelligence level of each subject was noted because VEP data have shown that asymmetry varies with this factor. As mentioned in subsection 1.1/6, two such studies have demonstrated greater interhemispheric amplitude differences (favoring the RH) in subjects with relatively high IQ scores than in those with lower ones.

Callaway (1973), for example, found greater differences between RH- and LH-recorded VEPs to sinewave-modulated light stimulation in bright adults than in dull ones. Rhodes et al. (1969) found that the exogenous components of 40 10- to 11-year-olds' VEPs, recorded at RH and LH central sites, showed (a) a greater RH than LH amplitude in bright children and (b) no significant interhemispheric amplitude difference in dull ones.

3/ Procedure-Related Independent Variables:

Stimulus Type and Presentation Parameters

> "What is really needed to test the visual spatial frequency model is a more direct variation of the spatial frequencies contained in a set of stimuli with all other parameters of stimulation held constant . . . . Equal consideration must be given to the range of spatial frequencies required to meet the task demands." (Hellige, Corwin, & Jonsson, 1984, p. 107)

The checkerboard stimuli in the current study were created and presented such that (a) spatial frequency was the only stimulus parameter that varied and (b) each hemisphere was selectively activated. Each checkerboard stimulus, unilaterally presented in the right or left visual field, binocularly stimulated the parafoveal to near-peripheral regions of the subjects' retinal fields (see subsection 2.2 for description of apparatus used to effect this stimulus display).

The rationale for selecting stimulus parameters and presentation methods is the topic treated in the current subsection.

Stimulus Set Size and Spatial Frequency Range (Independent Variable 1)

The stimulus set contained nine values (specified in subsection 2.2) ranging (inclusively) from 1 to 3.9 cpd. (*Note*. (a) One cycle refers to one pair of black-and-white checks; (b) a low cpd value corresponds to a large check, and a high cpd value, to a small one; see Figure 4.)

The central frequency value, 2 cpd, served as TAR, and all nine values, as TES. Both the set size and the approximately symmetric placement of the eight TES stimuli around centrally located TAR was adopted for this study from standard psychophysical procedure (Woodworth & Schlosberg, 1954). The spatial frequency range was selected on the following basis.

Rationale for, and Method of, Frequency Range Selection

A wider range (viz., 0.5, 0.7, 1, 1.4, 2.0, 2.8, 3.9, 5.7, and 8.1 cpd) was initially chosen because these frequencies fall roughly symmetrically around the peak of the curve that depicts human contrast detection threshold as a function of spatial frequency at 1 degree of retinal eccentricity (Koenderink, Bouman, Bueno de Mesquita, & Slappendel, 1978).

When this range was presented in a pilot study that used the same paradigm as the current one, the three lowest and three highest frequencies yielded recognition judgements approximating a 100% accuracy rate. The 1.4 and 2.8 values, on the other hand, resulted in 65% and 72% correct judgements, respectively. The two lowest and two highest values were then eliminated and replaced by four new values determined as follows.

Mean percentages of correct accuracy judgements as a function of the remaining five frequencies (1-3.9 cpd) were plotted on semilogarithmic graph paper. The frequency corresponding to the value falling halfway between the two respective responses to each pair of the four successive frequency pairs was selected as a "new" frequency; four new frequencies were ascertained in this manner.

This method was used because perceived spatial frequency changes as a logarithmic function of physical frequency. Hence, to place the new frequencies at equal perceptual intervals from one another, the frequencies constituting the X-axis of the above-described graph were placed on a logarithmic scale.

In the resultant set, the low-high pairs symmetrically placed around TAR were roughly the same logarithmic distance from TAR. For example, in the pair closest to TAR (1.7 cpd and 2.3 cpd), the former was 0.07 log units, and the latter, 0.06 log units away from TAR. In the pair next closest to TAR (1.4 cpd and 2.8 cpd), the former was 0.084 log units, and the latter, 0.087 log units away from TAR. This pattern held for the next two pairs progressively further from TAR on either side of this centrally placed value.

Summary. Thus, this derived range contained frequencies that elicit slightly less-than-maximal to maximal parafoveal responses in a recognition task; the TES frequencies near the TAR frequency were difficult to distinguish from TAR, whereas the TES frequencies distant from TAR were easily distinguished from it.

In sum, the spatial frequency range used in the current study provided optimal stimulation during a moderately difficult task.

Stimulus Luminance

Whereas stimulus spatial frequency was varied, stimulus luminance, a photopic (activates the cone photoreceptor system) value (80 candles [cd]/square meter), was held constant for two reasons: To ensure that (a) spatial frequency alone, rather than its interaction with luminance and/or contrast, mediated the experimental effects; and (b) photopic adaptation level did not fluctuate during the course of the session. Such fluctuations could result in resolution difficulty within the photopic range and/or activation of the scotopic system (the rod photoreceptors).

The pattern onset/offset procedure (Halliday & Michael, 1970; Sokol, 1976), that is, the alternating presentation, onto a rear-illuminated screen of checkerboard and blank slides equated for mean luminance, was the method used to maintain constant luminance. A 10-minute period of light adaptation to the blank stimulus field prior to trial onset ensured that the photopic system was operative at a constant level.

A secondary effect of constant luminance and adaptation state was that, because these are the critical factors affecting pupil diameter, the latter was therefore likewise constant and, hence, did not require independent control. Finally, the level at which luminance was held constant was a moderate photopic value to ensure that no afterimages would interfere with pattern processing.

Retinal Site of Stimulation

The Central Retina's Role in Pattern Vision

Stimulation of the photopic, rather than scotopic, system was chosen because the latter, having a lower threshold to photic stimulation, is relatively more involved in light detection, whereas the former, with a higher threshold, mediates pattern discrimination.

Other than being activated by an appropriate luminance value, the cone system can be activated by foveal or parafoveal stimulation. The basis of this latter method is twofold: (a) The concentration of cones relative to rods is high in these sites (cone density decreases with increasing distance away from the fovea); and (b) retinal ganglion X-cells, implicated in pattern discrimination, are more prevalent than Y-cells, putatively more involved in stimulus location and motion detection, in the central than peripheral retina (see subsection 1.2/3).

The central retina is important to pattern recognition due not only to its containing the first- and third-order neurons involved in this type of processing (the photoreceptors and ganglion cells, respectively), but also to the cortical magnification factor: Cortical representation of central retinal pattern-related activity is significantly larger than that of peripheral activity. Roughly 85% of the primate visual cortical topographic map is composed of foveal projections (Kandel, 1981c; Talbot & Marshall, 1942).

VEP data demonstrate this central retinal mediation of pattern processing. Jeffreys and Axford (1972a, 1972b) showed that the pattern-related components, CI (65-80 ms) and CII (90-110 ms), of occipital VEPs are respectively generated by activity originating in a 2-6 degree retinal field adjacent to the fovea and in the central 1 degree retinal strip. Rietveld, Tordoir, Hagenouw, Lubbers, and Spoor (1967) similarly found that pattern-related components of occipital VEPs decreased and eventually disappeared as stimulation shifted from foveal to peripheral retinal regions.

Finally, Harter (1970) showed that centrally presented high frequencies (small checks, 0-7.5 degrees from fixation) correlated with larger occipital VEP amplitudes than peripherally presented ones (12.5 and 27.5 degrees from fixation). Conversely, peripherally presented low frequencies (large checks) correlated with larger VEP amplitudes than centrally presented ones. He attributed these results to the increasingly large receptive fields, which mediate low-frequency processing, with increasing retinal eccentricity.

Calculation of Retinal Site of Stimulation

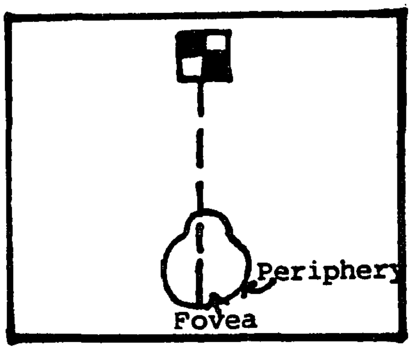
The retinal site of stimulation is determined by three factors: (a) the relative positions of the eye and the stimulus, (b) the distance between the eye and the stimulus, and (c) stimulus size.

When the forward-looking eye and stimulus are aligned, the eye is foveally stimulated; when the forward-looking eye and stimulus are not aligned (by either the eye's turning away from the stimulus or the stimulus' being presented at a point in the LVF or RVF that is distant from the CVF where the eye is gazing), the eye is peripherally stimulated. (Note. Distance between gaze and stimulus reflects degree of peripheral stimulation.) (see Figure 19).

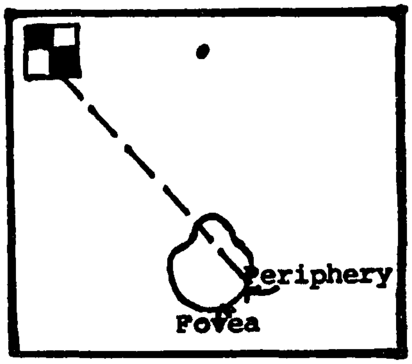
The stimulus size and distance parameters determine retinal image size due to the geometric relationship between the points describing size and distance in the visual field and their mirror-reversed images in the retinal field (see Figure 20). A triangle in "visual field space," in which stimulus size and distance from eye respectively constitute its base and median, is mirror-reversed in "retinal field space." Because the apical angles of the two triangles are congruent, the bases subtended by those angles, respectively representing the stimulus in the visual field and its retinal image, are congruent as well.

In the current study, to assure that a site 0.77-7 degrees of visual angle to the left or right of the fovea in the subjects' retinal fields was stimulated, subjects viewed a 100 mm (height) x 71 mm (width) checkerboard stimulus at a distance of 60 cm. This retinal site of stimulation was selected not only to excite predominantly the photopic and X-cell systems, but also to (a) assure that the blind spot was not included in the stimulated site and (b) selectively activate one hemisphere.

Avoiding the blind spot, located 15 degrees laterally from the fovea (Massaro, 1975, p. 150), was accomplished by



Foveal stimulation.



Peripheral stimulation.

Figure 19. Retinal sites of stimulation.

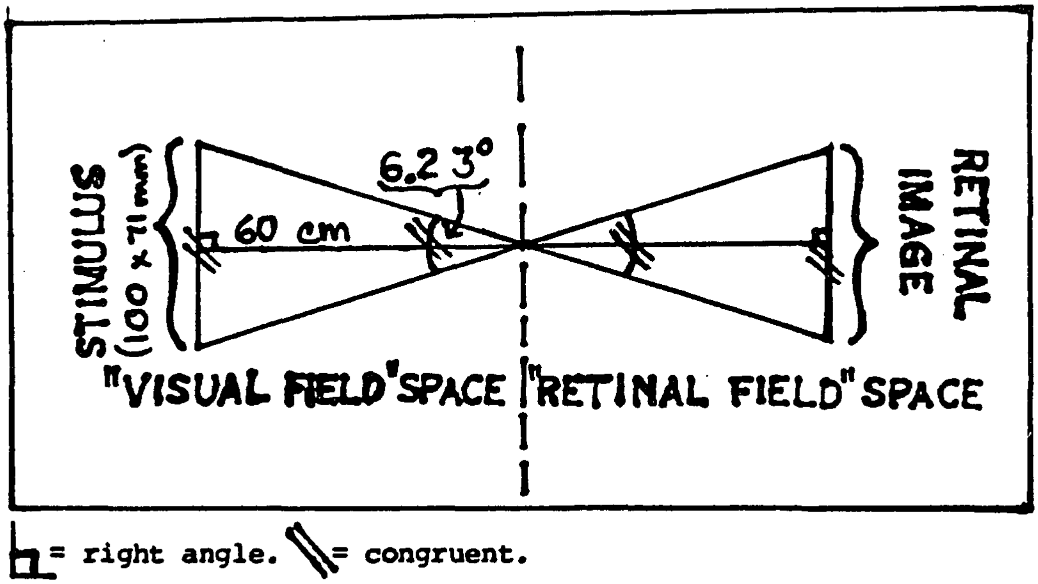


Figure 20. Determination of retinal image size from stimulus size and viewing distance information.

stimulating no further than roughly half of that distance. Right or left hemispheric engagement was achieved by presenting the slides outside of the central 1 degree strip (0.5 degrees to the right and left of fixation) that projects to both hemispheres.

Visual Field of Stimulus Presentation
(Independent Variable 2)

(Note. Parts of this discussion reviews information initially presented in subsections 1.1/3 and 1.1/7.)

Human eye-brain wiring is such that (a) a RVF image (greater than 0.5 degrees to the right of fixation) stimulates the left hemiretina that, in turn, projects (by uncrossed pathways from the left eye and crossed pathways from the right eye) to the LH; and (b) a LVF image (greater than 0.5 degrees to the left of fixation) stimulates the right hemiretina that, in turn, projects (by uncrossed pathways from the right eye and crossed pathways from the left eye) to the RH (see Figure 21). This neuroanatomical pattern provides the basis for the divided visual field paradigm (Beaumont, 1982; Mishkin & Forgays, 1952) used in the current study.

In this procedure, stimuli are displayed in one visual field to selectively activate the contralateral hemisphere. Such selective hemispheric activation refers only to initial activation prior to the callosal transfer of the input to the opposite hemisphere. The initially stimulated hemisphere, contralateral to the visual field in which the

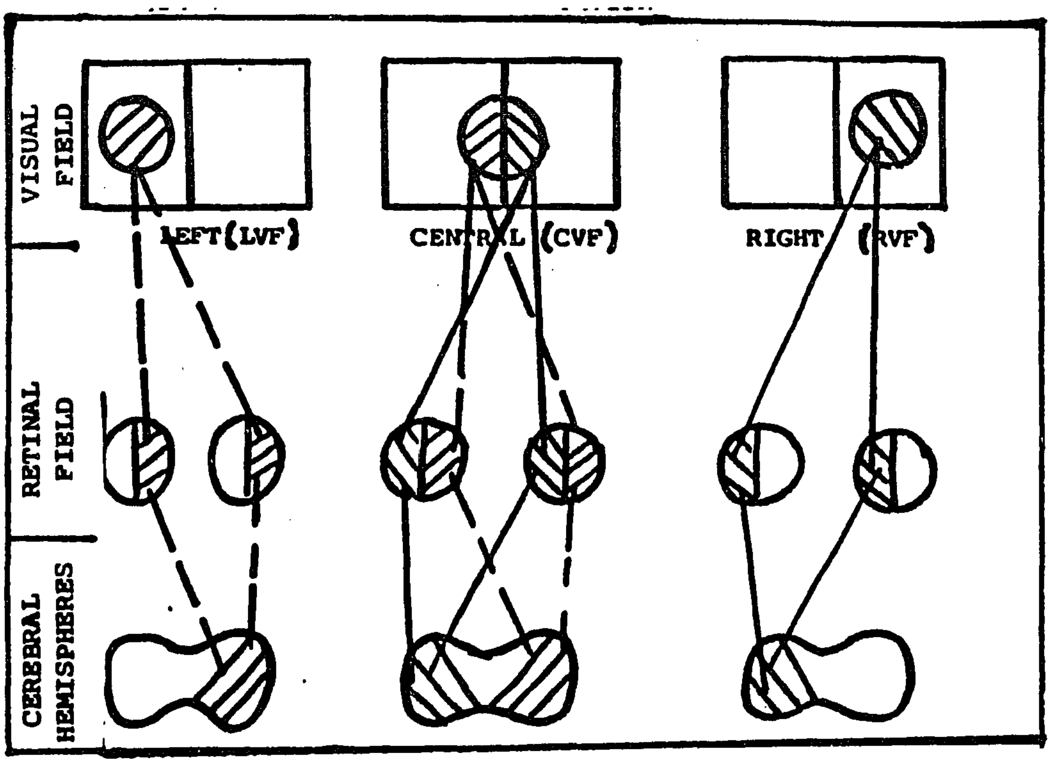


Figure 21. The relationship between visual field of stimulus presentation and cerebral hemispheric activation.

stimuli are presented, is referred to as _directly_ stimulated; the later stimulated hemisphere, ipsilateral to the visual field in which the stimuli are presented, is considered _indirectly_ stimulated.

Temporal Sequencing of Stimulus Presentation

To simplify the amount and type of interhemispheric communication, the stimuli in each visual field were unilaterally (successively), rather than bilaterally (simultaneously), presented. In the unilateral condition, input transfer provides the major source of interhemispheric communication; in the bilateral, interhemispheric competition, in addition to transfer, contributes to the interactions between the right and left hemispheres (see M. J. White, 1969, for discussion) (see Figure 22).

Type of Ocular Stimulation

The stimuli were presented to both eyes (binocular stimulation), rather than to one eye alone (monocular stimulation), because the latter type of stimulation is used to study intraocular characteristics or to make interocular comparisons, neither of which was currently done.

Total Number of Stimuli Presented and Number of Responses Constituting Each Data Analysis "Block" (Independent Variable 3)

The nine different TES frequencies were each presented 20 times, once in each visual field, yielding a total of 360 trials. This number of trials was chosen because it is the standard number used in psychophysical detection and

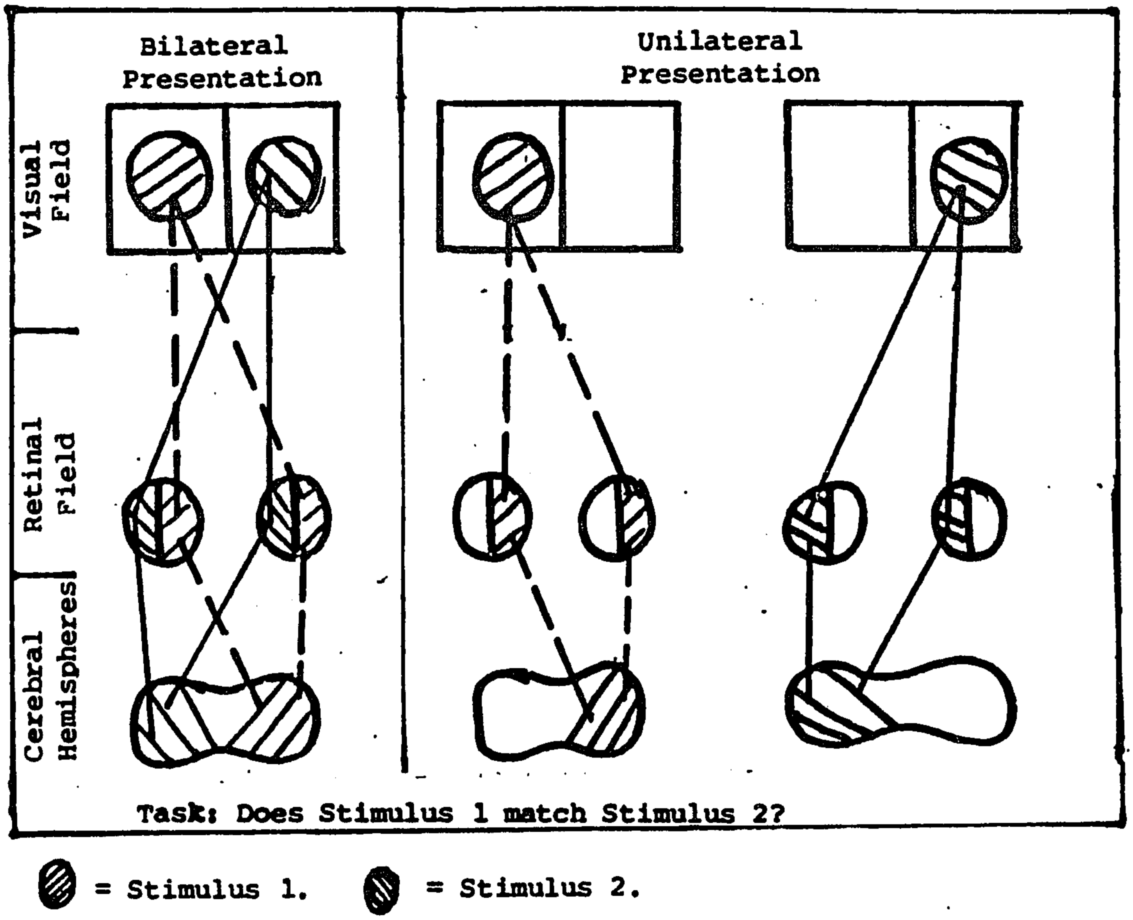


Figure 22. Temporal sequencing of stimulus presentation.

discrimination threshold experiments.

During data analysis, each set of 20 same/different responses elicited by the 20 presentations of each spatial frequency in each visual field was subdivided into four "blocks" of five trials each. A comparison of responses across blocks provided a measure of changes in recognition processing with increasing stimulus familiarization (Ross & Turkewitz, 1982).

Order of Stimulus Presentation

Random Interdigitation

Random interdigitation, the method used to determine the order in which the nine frequencies constituting the TES stimulus set were presented, was chosen on the same basis as number of presentations: It is standard psychophysical procedure.

The TES and TAR stimuli were each presented as the first member of the stimulus pair, in the successive presentation of TES and TAR stimuli in a given trial, 180 times, that is, on half of the total number of 360 trials. As with order of TES presentation, the distribution of the respective TES first and TAR first conditions was random.

Negative Time Error

The TES and TAR stimuli were presented in this manner to control for negative time error, that is, the situation in which the presentation of TAR prior to TES in all trials results in the subjects' incorrect perception that TES is equal to TAR when, in fact, TES is physically smaller than

TAR. This misperception arises for the following reason (D'Amato, 1970, p. 128):

1. The degraded memory trace of TAR with time causes TAR to be perceived as smaller than it physically is (e.g., perceived TAR = 5 units; physical TAR = 10 units).

2. TES is physically smaller than TAR (e.g., TES = 5 units).

3. TAR is perceived as equal to physical TES. The value at which these two stimuli are perceived as equal is called _the point of subjective equality_ (PSE) (e.g., PSE = 5).

In the term _negative time error_, _negative_ refers to the fact that because the TES value perceived as equal to TAR (the PSE) is physically smaller than the physical TAR value, the arithmetic difference between PSE and TAR is negative (e.g., PSE = 5; physical TAR = 10; 5 minus 10 = -5). _Time error_ refers to the fact that the biased perception arises from the temporal arrangement of TAR prior to TES for the reason explained immediately above.

Stimulus and ISI Durations

Stimulus duration was set at 150 ms because this amount of time is brief enough to preclude eye movements, yet long enough to extract higher spatial frequencies. Concerning the first point, eye movements, which begin occurring at about 200 ms poststimulus onset, prevent fixation; lack of fixation, in turn, prevents selective hemispheric activation.

Concerning the second point, because low spatial frequencies are processed more rapidly than high, only low frequencies are extracted from briefly presented stimuli; higher frequencies become available from more extended presentations, beginning at roughly 120 ms (Sergent, 1982d). Also, a 150-ms display, approximately equal to 7 Hz, stimulates both the transient and sustained subsystems of the human visual system.

The 3-second ISI was chosen because this duration is brief enough to prevent severe stimulus trace degradation, yet long enough to prevent masking effects between the TES and TAR stimuli.

Summary

The guideline used to select all stimulus presentation conditions was to maximize stimulus representation quality, both at sensory and memory levels, within the framework of selective hemispheric activation. A high-quality (informative) image, resulting from increased duration, increased luminance, and decreased retinal eccentricity (Riggs, 1965), permits all stimulus dimensions to be made available to the subjects.

High-quality stimulus representations were generated in the current study in the following ways:

1. Luminance level was moderately bright: It was far above detection threshold, yet not so bright as to cause afterimages.

2. Retinal site of stimulation was as close to the fovea (region of maximal acuity) as possible while still

activating only one hemisphere.

3. TES and TAR were alternately presented as the first member of the stimulus pair in each trial to minimize the perceptual errors that tend to arise due to trace decay of the first stimulus presented in the pair (negative time error).

4. Stimulus duration was as long as possible to allow for the extraction of the entire range of spatial frequencies while still selectively engaging one hemisphere; ISI duration minimized both stimulus degradation and masking effects.

4/ Dependent Variables

Three dependent variables, (a) the percentage of correct recognition judgements, (b) d', and (c) the visual field advantage index (VFAI), were used in the current study. The sources of, and reasons for, their selection are as follows:

"Percent Correct"

This variable was adopted from its standard psychophysical usage as a measure of sensory threshold judgements in the method of constant stimuli, the paradigm from which the current same/different task is derived.

d'

The standard theory of signal detection (TSD) dependent variable in both sensory (Green & Swets, 1966; Swets, 1964; Tanner & Swets, 1954) and recognition (Banks, 1970; Green & Swets, 1966; Parks, 1966; Wingfield & Byrnes, 1981, chap. 8) paradigms was used to provide a measure of the sensory component, disengaged from the cognitive one, of information processing.

VFAI

This index, a ratio in which (a) the numerator is the difference between the number of errors in recognition judgements to RVF and LVF presentations, and (b) the denominator is the sum of the recognition errors made to presentations in each visual field, was used to provide a relative measure of the direction and magnitude of visual field advantage. It was adopted from the facial recognition research of Turkewitz & Ross-Kossak (Ross & Turkewitz, 1982; Turkewitz & Ross-Kossak, 1984; Ross-Kossak & Turkewitz, 1984).

The current subsection contains: (a) a brief comparison between the theoretical frameworks of the classical psychophysical and contemporary TSD schools, (b) a description of the TSD paradigm (the above two points are necessary to understand the meaning of d'), and (c) a critical evaluation of the three dependent variables currently used.

Theoretical Differences Between Classical Psychophysics and Contemporary TSD

The central differences between classical psychophysics and TSD lie in (a) their accounts of the mechanism underlying detection and (b) their corollary analyses of the contributing factors to a given detection response. Psychophysical theory postulates that a fixed threshold, the value of which is determined by the sensory capacity of a given organism, and which divides sensory experience into discrete supra- and subthreshold categories, provides the basis for detection. This response is considered to be shaped solely by sensory factors.

TSD, in contrast, maintains that a variable criterion, the placement of which on a sensory continuum is decided by a subject on the basis of cognitive factors, determines detection judgements; this theory analyzes these judgements in terms of their separate sensory (d') and nonsensory (β) components.

Psychophysics: The Threshold Concept

Threshold, referred to in classical psychophysics as *limen*, the Latin word for boundary, is viewed by this school of thought as a "barrier to be overcome" (Green & Swets, 1966, p. 117). Absolute threshold is the point at which a given stimulus is "just noticeable" (i.e., detected); difference threshold, the point at which two stimuli are "just noticeably different" from one another (i.e., discriminated).

Suprathreshold sensory events are detectable and discriminable; subthreshold, undetectable and indiscriminable. According to this view, a subject's report that a given stimulus is above or below threshold is a function of biologically determined threshold placement over which that subject has absolutely no control.

TSD: The Decision Concept

TSD, on the other hand, views sensory experience as a continuum characterized by an ongoing baseline of (a) noise-induced sensations, caused by events internal and external to the organism (e.g., spontaneous neural discharge and sensory stimulation, respectively), and (b) periodic signal-induced sensations, caused by specific external stimuli.

According to this model, a subject's report that he/she detects a signal is based on (a) sensory factors (e.g., the subject's capacity and stimulus magnitude) and (b) his/her decision regarding the location of the criterion to be used for those reports.

That decision is determined by many cognitive components: (a) response bias (preference for a given response category and a particular point on the laxness/rigidity dimension in risk-taking and, therefore, criterion-setting); (b) expectation (a priori stimulus probability); (c) differential reinforcement per response category (payoff matrix and motivation); (d) set; (e) habituation; (f) guessing strategy; and (g) processing strategy (G. Turkewitz, personal communication, June, 1986).

A subject's detection report is thus viewed as a "mediated judgemental response" (Swets, 1964, p. 55) involving (a) probabilities and values mediated by higher brain centers and (b) responses controlled by lower level (sensory) receptors. According to TSD, in forming a detection judgement, "the observer relates sense data to previously acquired information and goals in a manner specified by statistical decision theory" (Ibid.).

Hence, a detection judgement is viewed by TSD as a centrally determined perceptual process in which the subject actively participates (Ibid.), not, as in the classical view, a peripherally determined sensory process in which the subject is passively involved.

The Confounding of Sensory and Cognitive Processing in Classical Psychophysics Versus the Separation of These Two Factors in TSD

A major criticism of the classical psychophysical approach to the analysis of detection and discrimination behaviors is the following:

> "Difference threshold measures something different from judgement accuracy; it measures directly S's [subject's] inclination to use the middle category, and indirectly the complex of factors responsible for this inclination. It does not measure S's differential sensitivity, his keenness of discrimination . . . . The dependent variable of constant stimuli is a measure of attitude rather than of discrimination." (Woodworth & Schlosberg, 1954, p. 215)

TSD, by providing separate measures of attitude and sensitivity, corrects this error:

> "The separation of factors influencing the observer's attitude from those influencing sensitivity is the major contribution of the psychophysical application of statistical decision theory." (Swets, 1964, p. 52)

The Application of TSD to Lateralization Research

Some lateralization studies have been criticized for their assumption that a change in hemispheric advantage, as measured by either accuracy or RT, necessarily indicates a change in cognitive strategy (Young, in press). Koss (1981) suggested that because TSD data analysis separates sensory from cognitive factors, it should be used to show whether hemispheric advantage and strategy correlate.

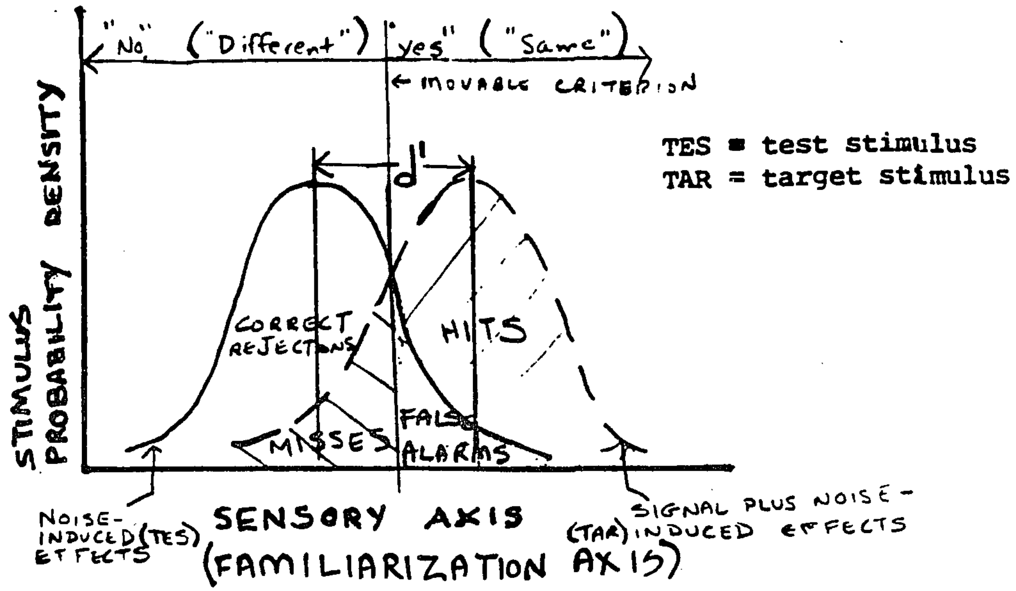
The current study, in the effort to clarify the cognitive contribution to hemispheric involvement during pattern recognition, used both d' and percent correct measures. Differences between these separate measures of "recognition sensitivity" and "recognition sensitivity and attitude" revealed the cognitive contribution to the behavior under investigation.

Derivation of d'

Definition of d'

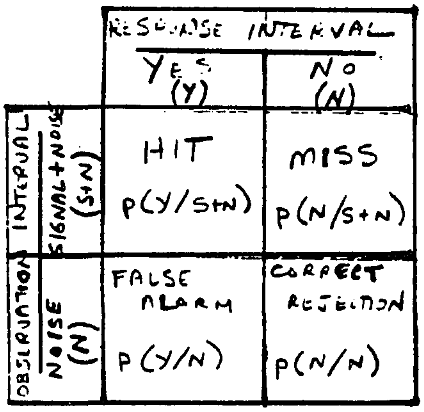
d', the measure of sensitivity to a comparison between a given TAR and TES stimulus pair, is derived as follows. As shown in Figure 23, a subject's sensory experience can be described by a function in which the Y-axis represents stimulus probability density, and the X-axis, the continuum of sensory experience. The function consists of two Gaussian distributions: (a) the probability of noise (N) events and (b) that of signal plus noise (SN). The degree of overlap between the two distributions (i.e., the distance between their means) expressed as normal deviates (z-scores) determines the value of d'.

If the two distributions barely overlap, the contrast of signal relative to noise will increase; consequently, the probability that a subject will detect the signal increases as well. Conversely, if they largely overlap, the



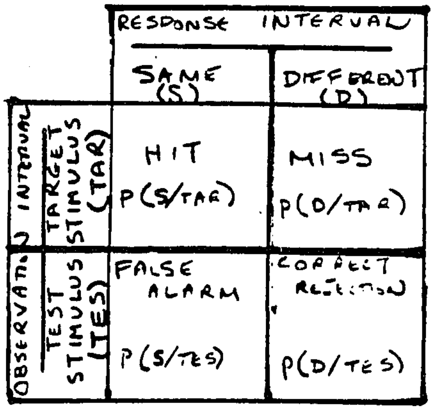
TES = test stimulus
TAR = target stimulus

Figure 23. The decision process according to the theory of signal detection (TSD). (Note. Terms in parentheses refer to the recognition paradigm.)



		RESPONSE INTERVAL	
		YES (Y)	NO (N)
OBSERVATION INTERVAL	SIGNAL+NOISE (S+N)	HIT p(Y/S+N)	MISS p(N/S+N)
	NOISE (N)	FALSE ALARM p(Y/N)	CORRECT REJECTION p(N/N)

Figure 24. Sensory matrix.



		RESPONSE INTERVAL	
		SAME (S)	DIFFERENT (D)
OBSERVATION INTERVAL	TARGET STIMULUS (TAR)	HIT p(S/TAR)	MISS p(D/TAR)
	TEST STIMULUS (TES)	FALSE ALARM p(S/TES)	CORRECT REJECTION p(D/TES)

Figure 25. Recognition matrix.

Figures 23-25. Theory of signal detection (TSD) sensory and recognition paradigms.

differentiation between signal and noise will decrease as will the probability of a subject's detecting the signal.

Hence, the further the distance between the two means, the greater the subject's sensitivity (reflected in a relatively large d' value); the closer the inter-mean distance, the less the subject's sensitivity (and the smaller the d' score).

<u>The Sensory Paradigm</u>

The location of a subject's criterion along the X-axis determines that subject's response: He/she reports "Yes" (Y) to any perceived sensory event falling to the right of the criterion and <u>no</u> (NO) to any such event falling to its left.

<u>The response matrix</u>. Four possible outcomes can occur as a result of the correctness value of a subject's response (see Figures 23-24 that depict these four response types in both graph and matrix forms):

1. A <u>hit</u> results when the subject reports Y during the SN condition (a correct Y response).

2. A <u>false alarm</u> occurs when the subject reports Y during the N condition (an incorrect Y response).

3. A <u>miss</u> results when the subject reports NO during the SN condition (an incorrect NO response).

4. A <u>correct rejection</u> occurs when the subject reports NO during the N condition (a correct NO response).

<u>The effect of criterion placement on response type</u>. If a subject chooses to place the criterion to the far left of

the function, then he/she will (a) report Y often, both when the events are attributed to N alone and when they are attributed to SN, and (b) increase his/her number of false alarms and hits. Conversely, when a subject places the criterion to the far right, he/she will (a) report NO often, both when the events were caused by N and when they were caused by SN and (b) increase his/her number of correct rejections and misses.

Calculation of d'. Because each of these four possible response outcomes falls in the areas under the two distributions (see Figure 23), the ratio between any two of these areas specifies a particular distance between the means of these two distributions, that is, d'. Typically, the ratio between the respective percentages of hits and false alarms is used to calculate the value of d' (Swets, 1964, Appendix 1).

The Recognition Paradigm

In the current recognition paradigm, in which subjects judged whether a TAR and TES stimulus pair were the same (S) or different (D), TAR presentation corresponded to the SN distribution, and TES, to the N.

Response matrix. As shown in Figures 23 and 25, in both graph and matrix forms, the following represents the four possible response outcomes for this situation:

1. A hit occurred when a subject reported S during a match, that is, when the TES stimulus was, in fact, identical to TAR (both were Stimulus 5 with a spatial

frequency value of 2 cpd; a correct S response);

2. A false alarm occurred when a subject reported S during a mismatch, that is, when TES was physically different from TAR (TES was Stimulus 1 to 4 or 6 to 9 in comparison to TAR [Stimulus 5]; an incorrect S response);

3. A miss occurred when a subject reported D during a match, that is, when the TES and TAR stimuli were physically identical (both were Stimulus 5; an incorrect D response);

4. A correct rejection occurred when a subject reported D during a mismatch, that is, when TES and TAR were, in fact, different from one another (TES was Stimulus 1 to 4 or 6 to 9, whereas TAR was Stimulus 5; a correct D response).

Calculation of d'. Finally, d' was determined from the ratio of hits and false alarms, which, in the recognition paradigm, are the correct and incorrect S responses, respectively.

The Visual Field Advantage Index

The dependent variables drawn from psychophysics and TSD for use in the current study, namely, percent correct and d', reveal if a visual field advantage exists. In the percent correct case, this advantage is based on the greater absolute number of correct recognition judgements (reporting "Different" to all matches except the 40 trials when same was the correct response, i.e., those trials during which the TAR value appeared as the TES stimulus and, therefore, matched TAR). In the d' case, this advantage is based on the higher ratio of correct to incorrect same responses.

Definition

Given the existence of a visual field advantage, the VFAI reveals the size and direction of that advantage. This measure is calculated by the following ratio:

$$\frac{\text{number of errors (LVF)} - \text{number of errors (RVF)}}{\text{number of errors (LVF)} + \text{number of errors (RVF)}}$$

This value indicates the proportion of the number of fewer errors in the "advantaged" visual field to the total number of errors in both visual fields. For example, if 4 errors were made in the RVF, and 10, in the LVF, 6/14 or .43 indicates that there were 43% fewer errors in the RVF (the advantaged one) than in both visual fields.

The possible values of this index range between -1 and 1 such that negative values represent a LVF advantage, and positive, a RVF advantage. The more closely a given value approximates -1 or 1, the greater the advantage in the respective visual field. A value of 0, reflecting that the same number of errors was made in each visual field, thus indicates that no advantage exists.

Critique

Hence, the size of the VFAI quantifies relative advantage, and its sign reveals direction of advantage. Providing these two bits of information is the major strength of this index; its major drawback is that its lack of information concerning absolute performance results in its being ambiguous in certain cases.

For example, the same values of either -1 or 1 result no matter how many errors were made to presentations in one visual field if none were made to presentations in the other. Furthermore, in those cases when only one or a few errors were made to presentations in one visual field in contrast to no errors in the other, the resultant indices of -1 and 1 are especially misleading: They imply huge advantages when, in fact, small advantages actually exist (Ross-Kossak & Turkewitz, 1986).

Visual Field and Hemisphere Advantage

The interpretation of the VFAI in relation to hemispheric advantage is based on the neuroanatomy of the human visual system. Because RVF stimulation directly projects to and is processed first in the LH, and LVF stimulation directly projects to and is processed first in the RH, a RVF advantage may be mediated by relatively more LH activity, and a LVF advantage, by relatively more RH activity.

Summary

This, this measure was selected for the current study because it contributes information concerning both direction and size of visual field (and, hence, hemisphere) advantage. Its values, however, must be interpreted (a) with the above considerations in mind and (b) in conjunction with the percent correct and d' data to gain a more complete description of hemispheric activity during pattern recognition.

5/ Data Analysis

The statistical tests and measures selected to analyze the current results are listed below. It should be noted at the outset that these analyses were performed on data for Stimuli 3 (1.4 cpd), 4 (1.7 cpd), 6 (2.3 cpd), and 7 (2.8 cpd), that is, the two spatial frequencies falling relatively closest to TAR (2 cpd) in the low and high ranges, respectively. Data for the other four stimuli were not analyzed because response accuracy to them approximated 100%.

Subject Characteristics (Percent Correct Data)

The Pearson r product-moment correlation coefficient (SAS program) was used to evaluate subject characteristics in relation to response accuracy (percent correct). This coefficient is defined as follows:

$$\frac{\text{covariance } (x,y)}{(\text{standard deviation } x)(\text{standard deviation } y)}$$

This statistic was used because it evaluates the degree of linear relationship between nonranked variables each of which may be formulated in a unit different from those with which it is being compared.

(a) Effects of Frequency Range on Asymmetry and Performance and (b) Gender Differences (Percent Correct and d' Data)

Two three-way (2 x 2 x 4) analyses of variance (ANOVAs) and post-hoc Tukey studentized range (HSD) tests (SAS programs) were used to analyze the main and interaction effects of gender, visual field of stimulus presentation, and spatial frequency on (a) response accuracy (percent correct) and (b) sensitivity (d').

These analyses tested Hypotheses 1 concerning hemispheric specialization for spatial frequency; 2 regarding gender differences in visuospatial processing; and 3 concerning spatial frequency range and recognition performance.

Although the response accuracy ANOVA was performed on number correct values, the data are presented herein as percent correct because comparisons and contrasts in the latter form are more easily comprehended than in the former.

The ANOVA on number correct is equivalent to that on percent correct for the following reason: Because a fixed number of stimuli of each spatial frequency was presented, each number correct value was in proportion to a constant denominator (20); hence, the number correct and percent correct data were linear transformations of one another.

Second, the distributions of number correct on which the ANOVA was performed were not skewed; hence, they did not require any type of mathematical transform to be normalized. Most values fell close to neither the minimum (0) nor the maximum (20); rather, they fell in the middle (between 5 and 15) (M. Chodorow, D. Rindskopf, J. Gordon, personal communication, July, 1986).

An ANOVA was performed on untransformed d' values because, as in the case of number correct, these values (a) were ratios with constant denominators and (b) had normal distributions (Chase, Bugnaki, Braida, & Durlach, 1983).

(a) Effects of Frequency Range and Familiarization on Asymmetry and (b) Gender Differences (VFAI Data)

(a) A three-way (2 x 4 x 4) ANOVA and post-hoc trend analysis (BMDP-2V ANOVA with repeated measures program) was used to evaluate the main and interaction effects of gender, spatial frequency, and block on the VFAI for the total session; and (b) four two-way (2 x 4) ANOVAs and post-hoc trend analyses were used to evaluate the effects of gender and spatial frequency on the VFAI within each of the four separate blocks.

Hence, this set of analyses, like the one described immediately above, was used to test Hypotheses 1 and 2; in addition, it tested Hypothesis 5 concerning stimulus familiarization effects. ANOVAs were able to be performed on untransformed VFAI values for the same two reasons listed above for the percent correct and d' data.

Effect of Asymmetry on Proficiency Including Gender and Familiarization Effects (VFAI and Percent Correct Data)

Four sets of Pearson r product-moment correlation coefficients (SAS program) were generated to analyze the relationship between magnitude of visual field advantage (VFAI) and proficiency (number correct): (a) Two sets analyzed the data of the entire sample during the total session and the four separate blocks, and (b) two sets analyzed the data of the separate genders also during the total session and the individual blocks.

This coefficient was selected for this analysis for the same two reasons described above with respect to the subject characteristics-response accuracy relationship. Finally, it was used to test Hypothesis 4, concerning the relationship between lateralized processing and proficiency, as well as Hypotheses 2 and 5.

Sensory and Cognitive Components of Processing
(Number Correct and d' Data)

By-hand comparisons between number correct and d' data were used to reveal the relative contributions of sensory and cognitive levels to recognition processing and performance.

6/ Expected Results

The author expected to find differences in visual field advantage during pattern recognition (Hypothesis 1), but expected those differences to be due relatively more to the recognition than pattern component of the processing sequence. She further expected them to vary with dependent variable, degree of stimulus familiarization (Hypothesis 5), and level of task difficulty.

The author also anticipated that task difficulty would influence whether (a) asymmetry positively or negatively affects recognition accuracy (Hypothesis 4), and (b) relatively low frequencies suffice for accurate recognition

(Hypothesis 3). Finally, she expected (a) male superiority in recognition performance and (b) a greater probability of finding gender differences in pattern than magnitude of asymmetry (Hypothesis 2). Discussion of these various positions follows.

Concerning the first point, although it is reasonable to expect that the human cerebral hemispheres may be specialized for spatial frequency processing because such specialization (a) has adaptive advantages, (b) is consistent with putative asymmetries for other behaviors, and (c) has some psychophysical support, the symmetrical lateral distribution of the transient and sustained systems (the putative neural substrates of spatial frequency processing) does not suggest such specialization. Elaboration of these points follows.

Arguments for Expected Asymmetry During Spatial Frequency Processing (Hypothesis 1)

Adaptive Advantages

Hemispheric specialization for spatial frequency recognition permits (a) the processing of a wide range of frequencies; (b) the typical division of labor advantages (e.g., stimulus analysis by specialized processors [and hence, the production of high-quality output] and load distribution [and thus, decreased fatigue]); and (c) the separation of possibly incompatible mechanisms, that is, one that localizes and detects large forms and one that discriminates fine patterns.

Finally, this type of functional organization, namely, one in which the same cognitive operation is performed on either low- or high-resolution neural representations to which each of the hemispheres is differentially sensitive, is more parsimonious than a design entailing different hemisphere-specific cognitive mechanisms.

Other Asymmetries With Which This One Is Consistent

These other asymmetries include: (a) LH specialization for refined motor behaviors in general and the motor component of language (speech) in particular; (b) differential vigilance capacities such that the RH tends to maintain a constant level of relatively poor visual signal detection performance, whereas the LH shows an initially superior performance followed by a rapid decline; and (c) the diffusely organized RH and focally organized LH (as measured by both lesion and gray matter-to-white matter ratio data) that may be related to RH-based synthetic, and LH-based analytic, processing.

Supportive Psychophysical Data

To briefly summarize the supportive data, Sergent (1982a) presented global-local letter stimuli (a large letter composed of small letters) in a divided visual field paradigm to subjects instructed to report the presence or absence of a target stimulus in a given test stimulus. She found that the mean RT to LVF presentations was faster than that to RVF presentations when subjects could reach a decision based on a large letter alone; conversely, the mean

RT to RVF presentations was faster than that to LVF presentations when subjects required small letters to make a decision.

Arguments Against Expected Asymmetry During Spatial Frequency Processing (Hypothesis 1)

Symmetrical Organization of the Transient and Sustained Systems

Contrary to the above arguments for the asymmetrical processing of spatial frequencies are the following points. First, within the transient and sustained systems, the size of individual cells and their component parts (e.g., receptive fields and axons), the distribution of those cells on the retina, and the layout of their retinocortical projections are the same in the right and left sides of monkey and cat brain. Further, they are predicted to be the same in both sides of the human brain (J. Gordon, personal communication, August, 1986).

Counterevidence

Second, some psychophysical data (Previc, 1982) and most electrophysiological data concerning the asymmetrical processing of spatial frequencies in nonverbal stimuli (see subsection 4.5) corroborate the anatomical data: They do not report significant Frequency x Visual Field interactions.

Impure Measurement of Spatial Frequency Processing in Sergent's (1982a) Study

Third, the stimuli used in Sergent's study were composed not only of different-sized elements, but also of those elements organized in spatial relationships so as to form "linguistic configurations" (i.e., letters). Hence, her study measured the processing of language and part-whole relationships in addition to that of spatial frequency.

It is therefore difficult to predict from Sergent's findings (viz., such stimuli were asymmetrically processed) that nonlinguistic stimuli that measure solely the processing of absolute size will likewise be differentially processed by the cerebral hemispheres.

Too Low a Frequency Range to Elicit Asymmetrical Processing

Fourth, the range of stimuli used in the current study (1-3.9 cpd), selected because it provides optimal parafoveal stimulation during a moderately difficult task, may be too low to differentially engage the hemispheres (Previc, 1982). Previc cited Ginsburg's (1978, cited in Previc, Ibid.) finding that frequencies higher than 5.5 cpd are required for the perception of internal facial features.

Previc's discussion suggests that, according to Sergent's model of RH processing of low frequencies and LH, of high, frequencies lower than 5.5 cpd would trigger RH activity; those greater than 5.5, LH involvement. Hence, this view suggests that the current frequency range would engage the RH only.

Arguments for Expected Asymmetry During Recognition Processing (Hypothesis 1)

Cognition-Induced Asymmetries

The author anticipated that the task itself, namely, recognition, would contribute to the expected asymmetries in the current study. Cognitive processing in general (e.g., language, strategy-utilization, attention, and recognition), putatively introduces asymmetries into a given processing sequence.

Use of Dependent Variables to Differentiate Sensory From Cognitive Bases of Asymmetries

The author further anticipated that the relative contributions of the sensory and cognitive components of recognition processing would be reflected in discrepancies between the measure of pure sensitivity (d') and those of sensitivity combined with cognitive processing (percent correct and VFAI). (Note. Precise measurements of the contributions of the spatial frequency and recognition aspects of processing require electrophysiological, rather than psychophysical, methodology.)

Same/Different Judgement-Induced Asymmetries

One reason that recognition introduces asymmetries into information processing is that it entails a same/different judgement. Such a judgement may selectively engage the hemispheres due to (a) the qualitatively different processes involved in formulating same versus different decisions (see subsection 4.1/3) and (b) the verbal nature of that judgement during both mentation and vocalization.

Dynamic Nature of the Predicted Asymmetry

Finally, the direction of the anticipated asymmetry during spatial frequency recognition was expected to vary with levels of stimulus familiarization (Ross & Turkewitz, 1982) and task difficulty (Sergent, 1983a). (*Note*. It was also expected to vary with processing stage [A. Damasio & H. Damasio, 1983], but, as mentioned above, such microscopic variation requires VEP methodology to be detected.)

Expected Familiarization Effects (Hypothesis 5)

The author predicted that, if pure spatial frequency is processed in the same way as other complex nonverbal (e.g., facial and musical) stimuli, the following triparite shift pattern in hemispheric advantage would occur across the experimental session: (a) either a RH, LH, or no hemisphere advantage to novel stimuli (this pattern reflects individual variation in hemisphericity); (b) a LH advantage to moderately familiar stimuli; and (c) a RH advantage to highly familiar stimuli.

Expected Task Difficulty Effects

Task Difficulty and Hypothesis 1: The Effect of Task Difficulty on Asymmetry During Spatial Frequency Recognition

The author anticipated finding that the relatively difficult tasks would require the utilization of either (a) a putatively LH-based analytic strategy and/or (b) the strategy different from the one typically used for the task-at-hand, that is, trial-and-error usage of a RH-based synthetic strategy if the analytic approach is generally used, and conversely, the analytic strategy if the synthetic one is usually used.

Hence, the author expected to find either (a) a LH advantage during difficult tasks (viz., judging whether the TES stimuli most similar to TAR are the same as or different from TAR) independent of spatial frequency or (b) a hemispheric advantage opposite to the one found during the relatively easy task (viz., judging whether the TES stimulus most dissimilar from TAR is the same as or different from TAR) within a given frequency range.

Task Difficulty and Hypothesis 4: The Relationship Between Task Difficulty, Asymmetry, and Recognition Accuracy

The author expected that, if pure spatial frequency is processed similarly to other nonverbal stimuli (straight lines of different orientations, random shapes, and faces), lateralized processing would improve performance. For the difficult recognition tasks (defined immediately above), she predicted that both RH- and LH-based processing modes would be used, particularly by the most intelligent and creative subjects.

(Note. Although such a pattern may appear to be one of no hemispheric advantage when measured psychophysically, it is really one of "dual hemispheric advantage." However, it can be accurately and reliably detected as such only by a high-resolution measure [e.g., EP recording].)

Task Difficulty and Hypothesis 3: The Relationship Between Task Difficulty, Frequency Range, and Recognition Accuracy

The author predicted that task difficulty would interact with frequency range as a determinant of performance: The easier tasks would yield higher accuracy rates than the difficult; within each of those pairs, recognition accuracy to the lower frequencies would surpass that to the higher.

Expected Gender Effects

First, male superiority was predicted in the current study because males have been shown to excel in nearly all visuospatial tasks (facial processing is the single consistent exception). Second, gender differences in pattern of asymmetry were expected primarily because the data and arguments concerning their ontogenetic and phylogenetic origins are fairly strong. No specific male or female asymmetry pattern was predicted due to the wide range of patterns documented in the literature (see list below).

Third, the author maintained a conservative position regarding expected gender differences in magnitude of asymmetry: Such a finding would not have been surprising, but a strong body of evidence necessary to formulate such a prediction does not currently exist:

> "From an anatomical perspective, at least, global statements on the degree of lateralization in males and females are premature. Sex differences, however, in the patterns of asymmetry may have some functional significance." (Horvath et al., 1986, p. 719)

Hence, the author made few specific predictions regarding gender differences in functional asymmetry during pattern recognition for the following reasons:

Contradictory Intergender Effects

(a) Greater bilateral procesing in females than in males and vice versa, (b) greater RH involvement in visuospatial processing in males than in females and vice versa, and (c) no differences between males and females in functional asymmetry have been demonstrated by clinical and normative behavioral and physiological studies. (*Note*. A substantial number of studies have yielded negative results, but it is difficult to discern whether these findings are real or artifactitious, e.g., sample sizes may have been too small to detect what is probably a small effect.)

Also, greater magnitude of asymmetry in males than females during visuospatial processing in general, but no significant Gender x Visual Field effects during visual recognition processing have been reported in the clinical data.

Anatomical Data

The finding that the splenium is broader in female than male brains, one of the most important human anatomical data supporting gender differences in visuospatial processing to date, requires replication. Also, these data have been shown to contain a high degree of individual variability.

Task-Specificity

Gender differences in functional asymmetry appear to be task-specific (and even "subtask-specific" [Kimura, 1985]). Because the common factors of different tasks correlated with this aspect of gender differences have not been identified and systematically analyzed, it is difficult to predict in which tasks these differences will appear.

Concluding Comments

It is important to emphasize that whatever results emerge, they reflect pure spatial frequency recognition processing under optimal conditions for the following reasons:

1. The frequency range provides slightly less-than-maximal to maximal parafoveal stimulation.

2. Task requirements and viewing conditions (e.g., 150-ms exposure durations) ensure that the entire range is made available to the subjects.

3. The quality of the neural representations of the stimuli are maximized by the following: (a) light adaptation and a constant level of luminance to minimize resolution difficulties due to alternating activation of the scotopic and photopic systems; (b) moderate photopic stimulation that is bright enough for the formation of clear images, but not so bright as to cause afterimages; (c) parafoveal stimulation (i.e., activation of the high-acuity region of the retina that mediates fine discrimination and is well-represented in visual cortex [due to the cortical magnification factor]); (d) 3-second ISIs that avoid masking and trace degradation effects; and (e) the alternating presentation of the TES and TAR stimuli to avoid negative time error effects.

4. The sample consists of postpubescent dextral males and females in whom (a) gender differences as well as visual and memory processing are fully mature and relatively stable; and (b) lateralization patterns probably entail the

RH control of visuospatial and synthetic, and the LH control of verbal and analytic, processing.

[2] METHODS

2.1] SUBJECTS

Twenty Hunter College students, 10 males and 10 females, ranging from 19-36 years of age with a mean age of 27.5 years, volunteered to serve as subjects. Their demographic characteristics and visuosensory and intellectual capacities are described in the text and in Table 3.

1/ Handedness; Ethnic and Linguistic Backgrounds

The entire sample was right-handed, with 70% extremely right-handed, according to the Bryden Hand Preference Questionnaire (1970, cited in Bryden, 1982; see Appendix A). Seventy percent reported no incidence of familial sinistrality, whereas 5% reported maternal; 10%, paternal; and 15%, sibling.

Regarding their ethnic and linguistic backgrounds, 70% was Caucasian; 5%, Black; and 25%, Hispanic. Seventy-five percent was monolingual, and 25%, bilingual.

2/ Visual Capacities and Optical Characteristics

All subjects scored between 20/30 and 20/20, with either corrected or uncorrected vision, on the Snellen Visual Acuity Test administered monocularly to both eyes.

No subject evidenced strabismus (weak eye muscle control) on the standard test for this condition: The subject fixates binocularly on a target 20 feet in front of him/her. The experimenter covers, with a 3" x 5" white index card, one of the subject's eyes. Next, the experimenter slowly removes the card and, then, returns it

Table 3

Subject Characteristics of Each Gender

	Gender	
Characteristics	Males	Females
Age (years)		
Range	19-33	21-36
Mean	26.0	28.5
Hand Preference		
1. Bryden Test		
RH	50	10
ERH	50	90
2. Familial Sinistrality		
Maternal	10	0
Paternal	0	20
Sibling	10	20
None	80	60
Ethnic Background		
Caucasian	60	80
Black	0	10
Hispanic	40	10
Linguistic Facility		
Monolingual	60	90
Bilingual	40	10

Note. All values except age are in percentage relative to the respective total of 10 for each gender. RH = right-handed; ERH = extremely right-handed.

(*table continues*)

	Gender	
Characteristics	Males	Females
Visual Acuity		
RE and LE: 20/20	50	20
RE: 20/30 LE: 20/20	10	20
RE and LE: 20/30	40	60
Eye Dominance		
RE	30	60
LE	40	20
None	30	20
Intelligence		
1. GPA		
A	30	30
B	40	30
C	10	20
No response	20	20
2. SAT		
M/V: 600-800	50	20
M/V: 400-599	10	30
No response	40	50

Note. All values except age are in percentage relative to the respective total of 10 for each gender. RE = right eye; LE = left eye; GPA = grade point average; SAT = Scholastic Aptitude Test; M = math; V = verbal.

to its original position in front of the hidden eye. The experimenter observes, and the subject reports, whether his/her eye moved from fixation when the card was moved. Upon completion of this sequence, the entire test is repeated on the other eye.

Seventy-five percent of the subjects demonstrated eye dominance, with 45% favoring the right eye, and 30%, the left. The Miles Test (1930) was used to screen subjects on this dimension. In this test, the subject is instructed (a) to look through the wide end of a funnel at a 3" x 5" white index card on which two black discs are drawn and (b) to report which disc is larger and which, darker. The eye over which the subject places the funnel to complete this task is his/her dominant eye.

3/ Cognitive Characteristics

Two measures, subjects' reported grade point average (GPA) and Scholastic Aptitude Test (SAT) scores, were used as measures of the subjects' intelletual capacities. Regarding GPA, 30% reported an A; 35%, a B; 15%, a C; and 20% did not reply.

With respect to the SAT scores, 35% scored between 600-800 on both the math and verbal sections; 20%, between 400-600 on both sections; and 45% did not report their scores.

4/ Ethical Treatment of the Subjects

Finally, the Hunter College Committee for the Protection of Human Subjects from Research Risks approved this study on

December 3, 1984; hence, all participants were treated in accordance with the ethical standards of this Committee.

2.2] STIMULI AND THEIR PRESENTATION

The stimuli consisted of 35 mm slides that, when projected onto a rear-illuminated screen, measured 100 mm (height) x 150 mm (width). Slightly more than half of the projected slide (100 x 79 mm) was blank; the remaining portion (100 x 71 mm) contained one of nine high-contrast (ranging from 93.75 foot-Lamberts [ft-L] in the smallest, to 96.5 ft-L in the largest, pattern) black-and-white checkerboards.

These patterns had a space average luminance value, well above photopic threshold, of 80 cd/square meter (as measured by a Photo Research Spectra Pritchard Photometer). Neutral density filter was placed over the blank portion of the slide to equate its luminance value with the space average luminance of the patterned portion.

The stimuli, viewed binocularly at a distance of 60 cm, were unilaterally presented in the subjects' RVF or LVF. The 71-mm patterned portion of each slide fell to the right or left of a 1-mm black fixation point centrally located in the 100 x 150 mm section of the white screen filled by the entire slide (see Figure 26). The retinal site of stimulation was parafoveal and near-peripheral; it extended laterally from 0.77 to 7 degrees of visual angle to the right or left of the fovea in the subjects' respective retinal fields.

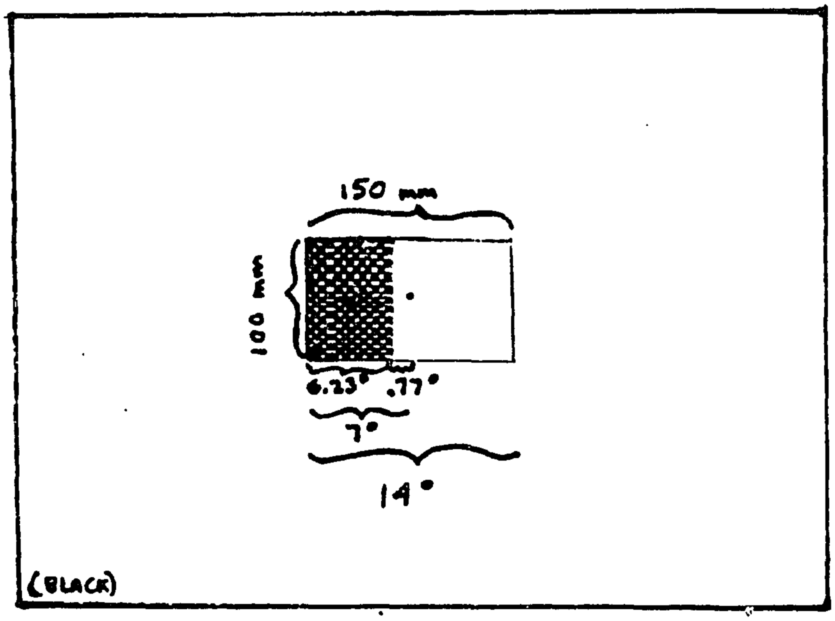


Figure 26. Stimulus size and presentation parameters.

TAR = target stimulus
TES = test stimulus
ISI = interstimulus interval

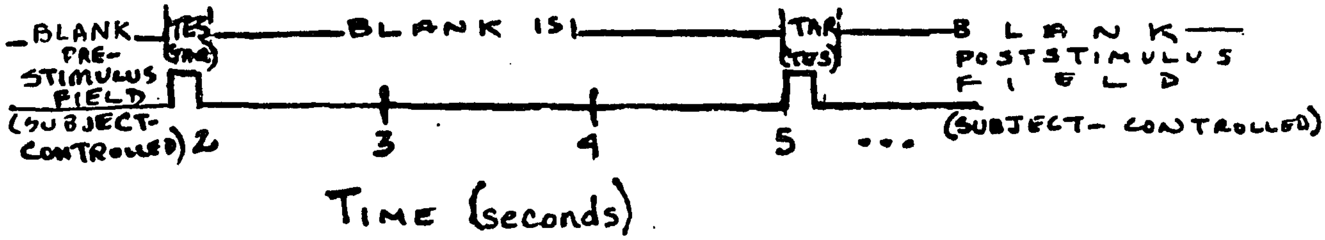


Figure 27. Sequence of stimulus presentation events in a single trial.

The checkerboard pattern on each slide contained one of the following nine spatial frequency values (in cpd), ordered from low (large checks) to high (small checks): 1, 1.15, 1.4, 1.7, 2, 2.3, 2.8, 3.5, and 3.9. (*Note*. These values represent spatial frequency calculated from the length of a side of a given check. The fundamental frequency of a given checkerboard falls on the diagonals of its constituent checks and is calculated by multiplying the value of one side by 1.414.)

The central frequency value (2 cpd) served as TAR, and all nine values, as TES. Nine of the total number of 18 TES slides contained checkerboards on the left side of the slide; nine contained them on the right. One TAR slide, containing the check pattern on one side of the slide, was used throughout the entire experiment. It was appropriately manipulated by the experimenter (see Procedure subsection) so that TES and TAR were presented for a recognition match in the same visual field.

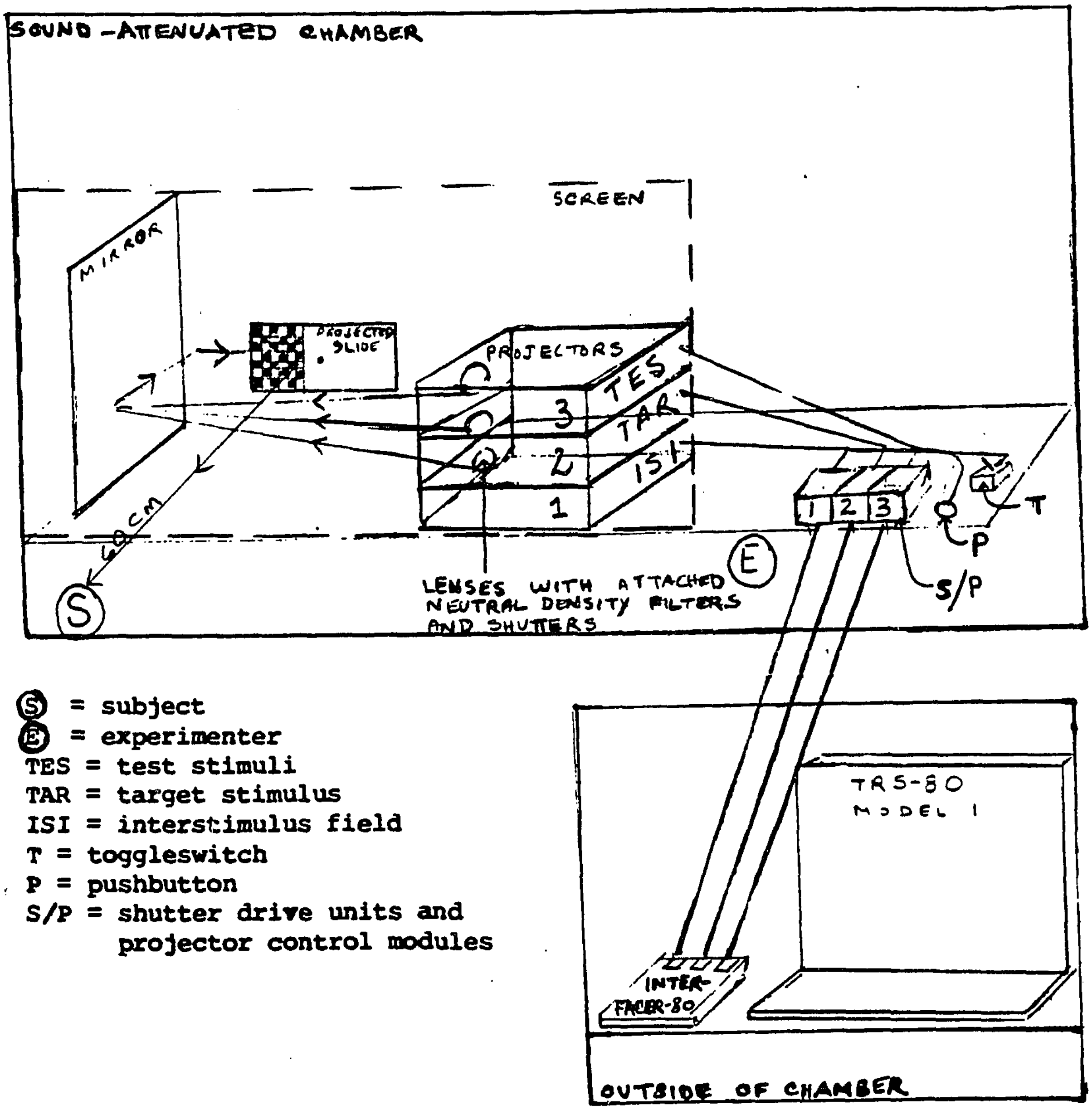
The pattern onset/offset procedure (Halliday & Michael, 1970; Sokol, 1976), that is, the alternating presentation of patterned and blank slides equated for mean luminance, was used to present these stimuli: TAR and TES were successively presented with a blank interstimulus field of the same 80 cd/square meter mean luminance interposed between them (see Figure 27). Neutral density filters were again used: In this case, they equalized the brightness levels among the three different fields.

2.3] APPARATUS

All stimulus presentation apparatus, except for a computer and interfacer controlling projector and shutter operation, was situated on a black wall-to-wall shelf in a sound-attenuated chamber (Industrial Acoustics Co., Bronx, N.Y.). Black felt material was hung between the two walls from the ceiling to the shelf. Hence, all equipment was covered, and no extraneous light was reflected.

As shown in Figure 28, the apparatus consisted of three Kodak carousel slide projectors (Models #600, 850H, and Ektagraphic IIIe). These were vertically stacked such that the lowest one rested on the center of the shelf, and the two upper ones, on a two-tier, custom-built black stand. The topmost projector contained the 18 TES slides; the middle projector, the TAR slide; and the bottommost projector, the interstimulus blank field.

Appropriate neutral density filters were firmly clamped to a vertical metal stand 6.4 cm in front of the lens of each projector to equate field luminance among the three projectors. Three electronic shutters (one Uniblitz Model #225L2A0T5 [Vincent Associates, Inc., Rochester, N.Y.] and two Lafayette Models #41010 and #41010-A) were attached to the respective projector lenses. The shutter drive units (one Uniblitz Model #100-2B/B and two Lafayette Models #41010 and #41010-A Projection Tachistoscope) and projector control modules were situated in the righthand portion of the shelf next to which the experimenter sat during the



Ⓢ = subject
Ⓔ = experimenter
TES = test stimuli
TAR = target stimulus
ISI = interstimulus field
T = toggleswitch
P = pushbutton
S/P = shutter drive units and projector control modules

Figure 28. Schematic of apparatus.

session.

Although the experimenter (a) initiated a given TES-TAR-interstimulus field sequence (with a pushbutton) and (b) controlled the order of TES and TAR presentation (with a toggle switch), the above two sequences, once initiated, were electronically controlled by an Interfacer-80 (Alpha Products, Inc., Queens, N.Y.) and a Radio Shack Model 1 TRS-80 Computer. Upon receipt of the pushbutton- and toggle-switch-coded inputs, the interfacer provided the gating mechanism for shutter operation and presentation of the TES and TAR slides (in the order encoded by the toggle switch position). The computer controlled (a) the length of time each of the three shutters remained open and (b) the synchronization of their onset and offset times.

An 8 " x 10 " first-surface mirror (Edmund Scientific Corporation) was placed in the lefthand rear corner of the shelf; it reflected the images from the projectors onto a 30 " x 30 " rear-projection screen (Lenscreen). The screen, supported by the front edge of the shelf, stood in front of and entirely covered the mirror and projectors.

The entire screen except for the central 100 x 150 mm white rectangular portion containing the centrally placed black fixation point and onto which the slides were projected was covered with black masking tape and the black felt material mentioned above. The ambient light level of the central white screen was 0.25 ft-L; that of the black surround, 0.001 ft-L.

Finally, the subject's chair containing a writing shelf to which a chin rest was attached was placed so that his/her eyes were 60 cm in front of the screen.

2.4] PROCEDURE

1/ Pretests

Prior to each testing session, each subject was given the Subject Characteristics Questionnaire that requested the following data: (a) age, (b) education level, (c) ethnic background, (d) number of languages fluently spoken, (e) grade point average (GPA), (f) Scholastic Aptitude Test score (SAT), and (g) familial sinistrality. Each subject was also given four pretests: (a) the Bryden Handedness Test, (b) the Snellen Visual Acuity Test, (c) a test for strabismus, and (d) the Miles Eye Dominance Test.

2/ Instructions

The subject was then taken into the testing booth. There, he/she was light adapted while the experimenter adjusted and stabilized the chin rest in a position such that the fixation point on the screen fell halfway between the subject's eyes at eye level. The experimenter then described the subject's recognition task to him/her.

The experimenter stated that a pair of checkerboard slides would be successively briefly flashed in the same visual field; the subject's task was to say "Same" if the check sizes in both slides were identical or "Different" if the check size in one slide was larger or smaller than that in the other.

The experimenter stressed that the subject must fixate on the central black dot on the screen. She further explained that she would say "Fixate" prior to each stimulus presentation both to remind the subject not to move his/her gaze and to warn him/her of impending stimulus onset.

Next, the experimenter instructed the subject (a) to be as accurate as possible, (b) not to expect any feedback concerning the correctness value of his/her responses, and (c) not to rush because stimulus presentation was subject-controlled (the following slide was presented after task completion, not automatically at a predetermined time).

Finally, in accordance with the Hunter College Human Subjects Committee regulations, the experimenter informed the subject that he/she had the right to terminate participation, either temporarily or permanently, at any time for any reason during the course of testing.

3/ Procedure

No practice trials were administered. Each 1-hour testing session consisted of 360 trials with a 5-minute rest period after the first 180. The trials consisted of 40 blocks each containing (a) nine TES slides and (b) nine presentations of the same TAR slide. All slides in a given block were presented in the same visual field; all the slides in the successive block were presented in the opposite visual field. Thus, visual fields were alternated between blocks.

Although the order of individual TES slide presentation was random, each of the nine TES slides was presented 20 times in the RVF and 20 times in the LVF during the course of one session; hence, the total of 360 trials.

TAR was always presented in the same visual field as TES. On half of the total number of trials, TES was presented first; on the other half, TAR was presented first. Thus, the orders of presentation of (a) TAR in relation to TES and (b) individual TES slides were random. The sequence, different for each subject, was generated by a computerized program (in BASIC). It was printed and used by the experimenter for two purposes during testing: (a) as a stimulus presentation guide for rotating the TES slide tray in the top projector prior to each trial and (b) as a data sheet on which to graphically record the subjects' responses.

4/ Description of a Single Trial

A given trial consisted of the following sequence of events:

1. The experimenter (a) arranged the position of the TES slide tray and (b) adjusted the toggle switch to the TES or TAR position in accordance with the computerized random sequence for that subject. Between blocks, the experimenter reversed the position of the TAR slide in the middle projector so that its visual field of presentation would match that of the TES slides in the forthcoming block.

2. The experimenter said "Fixate."

3. The experimenter pressed the pushbutton that

controlled projector operation. As shown in Figure 27, TES (or TAR) was flashed in the RVF or LVF from a prestimulus field of equal luminance for 150 ms. A 3-second ISI, consisting of a blank field also of equal luminance, then occurred. Next, TAR (or TES) was flashed, also for 150 ms, in the same visual field as the immediately prior patterned stimulus had been; it was followed by a poststimulus field, again equated for luminance.

4. The subject verbally reported to the experimenter whether the TES and TAR stimuli were the same as or different from one another. The experimenter recorded the subject's reponses on the computer-generated data sheet.

[3] RESULTS

The most striking finding in the current study was that visual field superiority for spatial frequency recognition was conditional: The direction of field advantage was shown to vary with (a) dependent variable, (b) task difficulty, (c) stimulus familiarization, and (d) gender, as well as with frequency. Four distinct response patterns in direction of advantage emerged as a function of these factors.

The size of advantage, recognition proficiency, and the correlation between the two were also found to be a function of the Task Difficulty x Spatial Frequency interaction. Finally, gender differences in proficiency varied with (a) dependent variable, (b) visual field, (c) task difficulty, and (d) spatial frequency.

Several points need be made at the outset of the current subsection regarding data presentation herein:

1. No significant correlations (Pearson r product-moment) were found between subject characteristics and response accuracy to stimuli presented in both visual fields. Hence, no subgroups requiring separate data analyses were identified. This finding was not surprising because the sample was predominantly homogeneous in all respects except eye dominance, and no strong evidence exists for a significant correlation between this trait and cerebral asymmetry.

2. As mentioned in subsection 1.5/5, the responses to

the two frequencies closest to TAR in the low and high ranges, respectively, were subjected to data analysis. These frequencies are referred to herein as: F1 (1.4 cpd), F2 (1.7 cpd), F3 (2.3 cpd), and F4 (2.8 cpd). (Note. To review, TAR [2 cpd] was centrally placed between F2 and F3).

3. The term advantage has a different connotation vis-à-vis each dependent variable: When applied to percent correct, it connotes better absolute accuracy; to d', greater absolute sensitivity; and to the VFAI, better relative accuracy in a given visual field.

4. The ANOVAs on the accuracy, sensitivity, and VFAI data are respectively presented in Appendices B, C, and D. (Note. To review the statistical treatment of the following data, refer to subsection 1.5/5).

3.1] THE ASYMMETRICAL PROCESSING OF SPATIAL FREQUENCY (HYPOTHESIS 1)

1/ Percent Correct and d' Data

The percent correct and d' data form similar U-shaped functions reflecting greater accuracy and sensitivity at F1 and F4 relative to F2 and F3 (see Figures 29-30 [and Tables 4-5 for variability data]). Each curve contains a significant Frequency x Visual Field interaction the major effects of which are a RVF advantage at F2 and a LVF advantage at F3; for percent correct, F (3, 54) = 7.64, $p<.0003$; for d', $F(3, 54) = 6.83$, $p<.0006$).

A LVF advantage at F1, extremely small in the percent correct data, but equal in magnitude to the relatively large

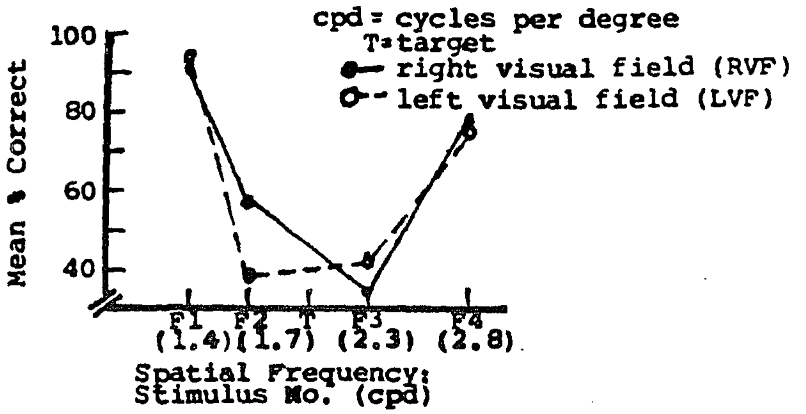


Figure 29. Frequency x Visual Field interaction effects in the accuracy data.

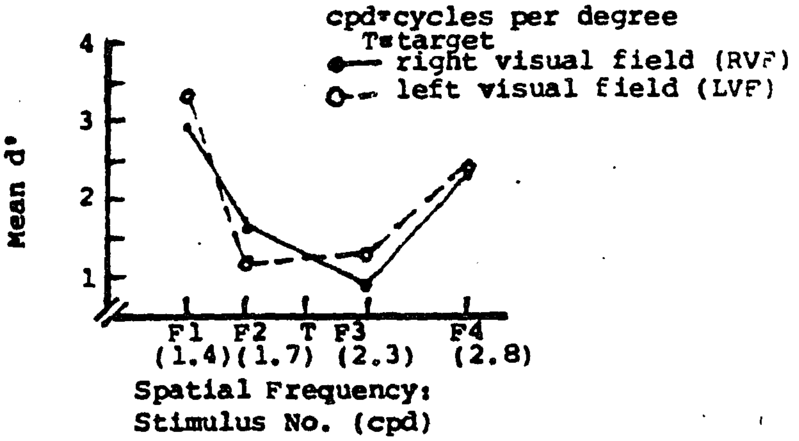


Figure 30. Frequency x Visual Field interaction effects in the sensitivity data.

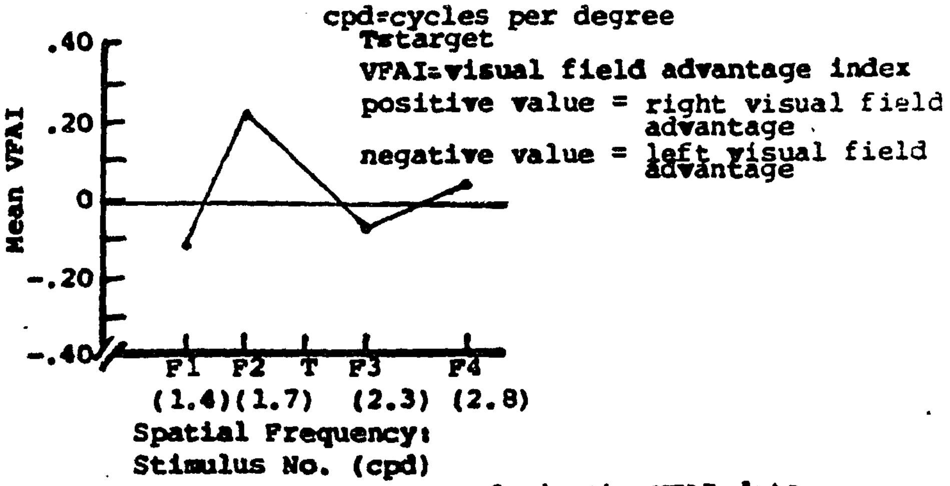


Figure 31. Significant cubic and quadratic trends in the VFAI data.

Table 4

Descriptive Statistics of Percent Correct Responses

	Stimulus no. (cpd)							
	F1 (1.4)		F2 (1.7)		F3 (2.3)		F4 (2.8)	
	Visual field							
Group[a]	RVF	LVF	RVF	LVF	RVF	LVF	RVF	LVF
Males								
M	92	93	62	42	37	47	78	73
SE	0.62	0.62	1.54	1.85	0.96	1.68	0.79	1.61
Females								
M	89	95	50	35	31	37	81	77
SE	0.70	0.46	1.40	0.57	1.14	0.93	0.82	0.93
Combined								
M	91	94	56	38	34	42	79	75
SE	0.46	0.38	1.05	0.95	0.74	0.97	0.56	0.91

Data collapsed across visual fields

	F1 (1.4)	F2 (1.7)	F3 (2.3)	F4 (2.8)
Combined				
M	92	47	38	77
SE	0.30	0.75	0.61	0.53

Note. cpd = cycles per degree. RVF = right visual field. LVF = left visual field.

[a] *n* = 10 for each gender.

Table 5

Descriptive Statistics of d' Scores

	Stimulus no. (cpd)							
	F1 (1.4)		F2 (1.7)		F3 (2.3)		F4 (2.8)	
	Visual field							
Group[a]	RVF	LVF	RVF	LVF	RVF	LVF	RVF	LVF
Males								
M	2.84	3.26	1.57	1.27	0.76	1.36	2.02	2.33
SE	0.35	0.38	0.29	0.28	0.24	0.38	0.28	0.33
Females								
M	3.05	3.30	1.65	1.14	1.04	1.16	2.59	2.35
SE	0.19	0.25	0.23	0.13	0.20	0.19	0.25	0.20
Combined								
M	2.94	3.28	1.61	1.20	0.90	1.26	2.30	2.34
SE	0.20	0.22	0.18	0.15	0.15	0.21	0.20	0.19
	Data collapsed across visual fields							
Combined								
M	3.11		1.41		1.08		2.32	
SE	0.15		0.12		0.13		0.13	

Note. cpd = cycles per degree. RVF = right visual field. LVF = left visual field.

[a] *n* = 10 for each gender.

F3 advantage in the d' data, is also found. Finally, F4 in each function contains small, nonsignificant advantages.

(<u>Note</u>. The discrepancy between percent correct and d' at F1 is discussed in the Gender Effects subsection herein and subsection 4.1/1 below.)

The relatively low level of variability in the percent correct data versus the relatively high in the d' (see Tables 4 and 5) suggests that the above-described effects are robust with respect to accuracy but require replication to confirm their strength with respect to sensitivity.

2/ VFAI Data

The shape of the third function (see Figure 31 [and Table 6 for variability data]) is defined by (a) a significant cubic trend, $\underline{F}(1, 18) = 12.94$, $\underline{p} < .002$, describing the interfrequency shifts in the direction of advantage and (b) a significant quadratic trend, $\underline{F}(1, 18) = 5.06$, $\underline{p} < .04$, in its latter two-thirds revealing the diminished magnitude of those advantages at the two high frequencies.

Both the direction and magnitude of the visual field advantages herein are consistent with these characteristics of the advantages found in the accuracy and sensitivity curves: A RVF advantage, the largest of the four, is found at F2; LVF advantages of comparable size are found at its two adjacent frequencies, F1 and F3; and a miniscule RVF advantage exists at F4. The relatively large F2 advantage is the major source of the significant frequency effect, $\underline{F}$

Table 6

Descriptive Statistics of Visual Field Advantage Indices

Group[a]	Stimulus no. (cpd) F1 (1.4)	F2 (1.7)	F3 (2.3)	F4 (2.8)
Males				
M	-.01	.23	-.13	.06
SE	.00	.05	.03	.06
Females				
M	-.22	.20	-.03	.02
SE	.05	.02	.03	.05
Combined				
M	-.12	.21	-.08	.04
SE	.02	.01	.02	.05

Note. cpd = cycles per degree.

[a] *n* = 10 for each gender.

(3, 54) = 5.15, $p < .003$, also found in this curve.

Individual Data

The low level of variability in these data (see Table 6) affirms the strength of these effects. As low variability also indicates, the individual data did not greatly deviate from the group data. Sixty-five percent of the individual subjects exhibited response patterns roughly consistent with those of the group.

For example, 15% demonstrated a cubic trend followed by a quadratic one highly similar to that just described. Twenty percent showed a predominantly cubic curve characteristic of the Blocks 1 and 2 functions discussed below; 15% showed a cubic trend followed by a linear one characteristic of the Blocks 3 and 4 curves also discussed below. Finally, 15% demonstrated a shift in advantage from the RVF to the LVF between F2 and F3 as occurred in both the entire session and separate block functions.

In contrast, 35% of the individual subjects yielded functions that deviated from the mean. Of these individuals, 5% also showed a field advantage shift in the same direction as, but later than, the majority (i.e., between F3 and F4). Twenty percent showed shifts in the opposite direction. Finally, 10% showed no LVF advantage at any frequency: Five percent moved from an initial no field advantage to a small RVF advantage; 5% moved from a total RVF advantage (VFAI = 1.00) to a substantially smaller one.

3/ Task Difficulty Effects

Hence, both the majority of individuals and the mean group data show that accuracy and sensitivity were higher to RVF than to LVF low-frequency stimulation and to LVF than to RVF high-frequency stimulation when the given frequencies were closest to (i.e., uneasily distinguished from) TAR (F2 and F3). The shift from a RVF advantage during low-frequency stimulation to a LVF advantage during high also occurred during the relatively more difficult recognition judgements (at F2 and F3).

In contrast, the response patterns at the frequencies further from (i.e., more readily discriminable from) TAR (F1 and F4) suggest two possibilities: (a) the annihilation of the Frequency x Visual Field effect or (b) a trend toward the reversal in its direction as recognition became easier.

Both possibilities are supported by the facts that (a) accuracy was slightly higher, and sensitivity substantially so, to LVF than to RVF presentations of F1; and that (b) accuracy was slightly higher to RVF than to LVF presentations, and sensitivity roughly the same to stimulation in both visual fields, of F4.

In the VFAI data, the trends toward visual field advantages at F1 and F4 in the respective fields opposite to those with advantages at F2 and F3 support the "reversal" possibility.

Magnitude of Advantage

Just as the largest mean field advantages in the sensitivity data occurred at both low frequencies (F1 and

F2) and at the "difficult" high frequency (F3), so did the largest mean VFAIs occur at these same frequencies. This index was larger to low than to high frequencies, and within each of those ranges, larger to the difficult than to the easy tasks.

The maximum mean group magnitude (.21) occurred at the "difficult" low frequency near TAR (F2); the second largest (-.12), at the "easy" lowest frequency (F1); the third largest (-.08), at the "difficult" high frequency near TAR (F3); and the smallest (.04), at the "easy" highest frequency (F4) (see Table 6). Hence, although the differences between the latter three values were slight, the magnitude of field advantage did vary with both spatial frequency range and task difficulty.

4/ Familiarization Effects (Hypothesis 5)

A factor besides (a) measurement by d' versus percent correct and (b) TES placement in relation to TAR that influenced the pattern of visual field advantage for spatial frequency was the block (i.e., the temporal division of the entire session) for which the effect was analyzed. The significant frequency effect and the significant cubic and quadratic trends in frequency in visual field advantage were further analyzed to see whether they were static effects (characteristic of the total session) or dynamic ones (which held only for particular parts of that total).

Four separate 2 x 4 ANOVAs (with frequency and gender as levels) were performed on the VFAIs for the respective blocks. As shown in Figure 32 (with the variability data in Table 7), a significant frequency effect emerged only in the second block, $F(3, 54) = 4.28$, $p<.008$). The quadratic trend in frequency likewise changed across blocks: It reached significance only in Block 2. (*Note*. Because this effect was part of a gender interaction, it is discussed in the appropriate subsection below.)

The cubic trend also changed during the course of the session: It existed in the first half (Blocks 1 and 2 likewise contained significant cubic trends, Block 1: $F(1, 18) = 5.37$, $p<.03$; Block 2: $F(1, 18) = 13.27$, $p<.002$); it did not exist in the second half. Although cubic components are apparent between F1 and F3 in the third and fourth blocks, the small magnitude of the LVF advantage at F3 and a linear component between F3 and F4 precluded their reaching significance.

Overall Trend Throughout the Session

Hence, subjects shifted from (a) an initial LVF advantage at F1 to (b) a RVF advantage at F2 and then back to (c) a LVF advantage at F3. At F4, the shift pattern in field advantage changed across blocks: In the earlier part of the session, subjects shifted back toward a RVF advantage at F4; in the later part, they maintained the same LVF advantage at F4 that they showed at F3.

Interpretation of Trend in Terms of Learning

Since no practice trials were administered, Block 1 (Trials 1-5) represents the subjects' initial field

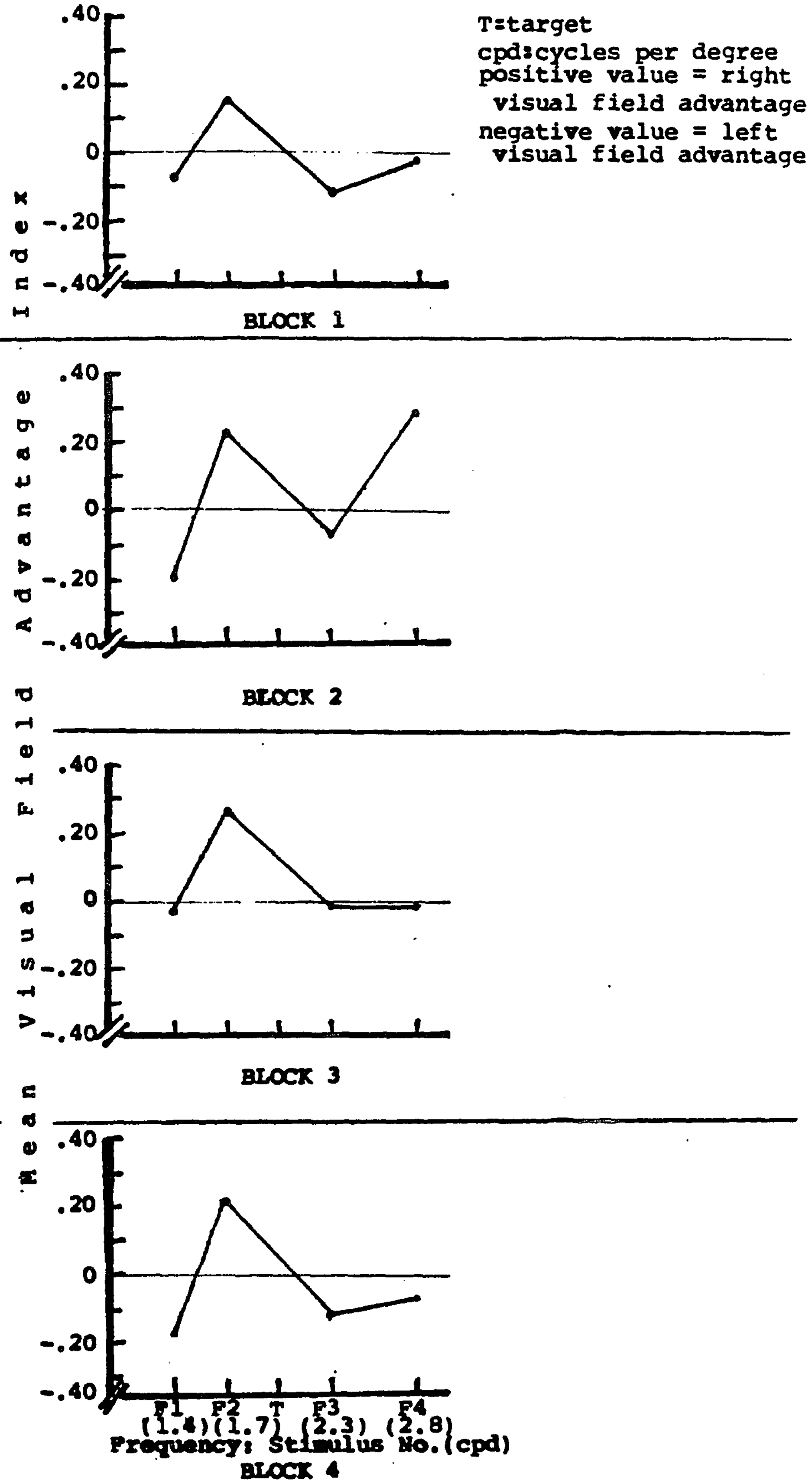


Figure 32. Familiarization effects on visual field advantage as a function of spatial frequency.

Table 7

Descriptive Statistics of Visual Field Advantage Indices for Each Block

	Block 1			
	Stimulus No. (cpd)			
Group[a]	F1 (1.4)	F2 (1.7)	F3 (2.3)	F4 (2.8)
Males				
M	.00	.05	-.13	-.09
SE	.26	.15	.10	.20
Females				
M	-.13	.25	-.14	.03
SE	.23	.10	.12	.16
Combined				
M	-.07	.15	-.13	-.03
SE	.17	.09	.08	.13
	Block 2			
Males				
M	.00	.23	-.25	.33
SE	.15	.10	.11	.15
Females				
M	-.40	.23	.10	.20
SE	.22	.12	.12	.21
Combined				
M	-.20	.23	-.08	.27
SE	.14	.08	.09	.13

Note. cpd = cycles per degree.

[a] *n* = 10 for each gender.

(*table continues*)

Block 3				
	Stimulus no. (cpd)			
Group[a]	F1 (1.4)	F2 (1.7)	F3 (2.3)	F4 (2.8)
Males				
M	−.02	.43	−.04	−.08
SE	.22	.13	.08	.20
Females				
M	−.05	.08	.01	.04
SE	.22	.14	.08	.21
Combined				
M	−.03	.26	−.02	−.02
SE	.15	.11	.06	.14
Block 4				
Males				
M	−.02	.19	−.12	.08
SE	.15	.19	.17	.18
Females				
M	−.30	.24	−.09	−.20
SE	.15	.14	.08	.21
Combined				
M	−.16	.21	−.11	−.06
SE	.11	.11	.09	.14

Note. cpd = cycles per degree.

[a] *n* = 10 for each gender.

advantage to novel stimuli; Blocks 2 (Trials 6-10) and 3 (Trials 11-15), their advantages due to trial-and-error learning; and Block 4 (Trials 16-20), either their stable response to familiar stimuli or continued learning effects. Further testing need be administered to determine the precise stage of stimulus familiarization that Block 4 represents.

Thus, only a cubic trend in visual field advantage was operative during early learning, and a cubic trend followed by a linear one appeared later. These different time-dependent trends indicate that a given field advantage at a given frequency is a function of stimulus familiarization, spatial frequency, and task difficulty.

Response Pattern to Unfamiliar Stimuli

To novel and somewhat familiar stimuli (Blocks 1 and 2), within the respective low- and high-frequency ranges, the field advantage during the easy task was either toward or in the field opposite to that during the difficult one. In the low range, in Blocks 1 and 2, the LVF advantage that existed at the easy frequency (F1) shifted to a RVF advantage at the difficult one (F2).

In the high range, the miniscule LVF advantage in Block 1 and the large RVF advantage in Block 2 that existed at the easy frequency (F4) shifted, in both of these blocks, to a LVF advantage at the difficult one (F3). Although the initial (Block 1) F4 advantage was not actually in the RVF, it was sufficiently different (with respect to direction) from the F3 LVF advantage for a significant cubic trend to have been reached. Further, the fact that the magnitude of the Block 2 F4 RVF advantage was so great strongly suggests that the Block 1 F4 advantage was in the direction of the RVF.

Response Pattern to Familiar Stimuli

To more familiar stimuli (Blocks 3 and 4), the pattern just described occurred in the low-frequency range, but a different one emerged in the high: The same LVF advantage that appeared at F1 appeared at F4.

Although the easy (F1 and F4) LVF advantages in Blocks 3 and 4 are small, they are sufficiently similar to the difficult high-frequency (F3) LVF advantage to preclude a significant cubic trend from being attained. Further, the F4 advantages seem to fall on a line defined by three points representing a shift from (a) a RVF advantage in Block 2 through (b) a small LVF advantage in Block 3 to (c) a larger LVF advantage in Block 4; the Block 3 LVF advantage appears to be a transitional point towards a stronger Block 4 LVF advantage.

Summary: Frequency, Task Difficulty, and Familiarization Effects

Hence, with increasing stimulus familiarization, subjects showed (a) the identical visual field advantage during the easy recognition judgements independent of frequency value and (b) opposite advantages during the difficult judgements as a function of frequency value.

3.2] GENDER EFFECTS (HYPOTHESIS 2)

The principal findings concerning gender differences in spatial frequency recognition were the following (regarding points 1-3, see Figure 33 [and Tables 4-5 for variability data]; regarding point 4, see Figure 34 [and Table 7 for variability data]):

1. (a) The same overall accuracy and sensitivity levels as a function of frequency and (b) the Frequency x Visual Field interaction that were found for the total sample were found for the separate male and female groups.

2. Which gender demonstrated superiority in recognition processing was a function of dependent variable, visual field, and spatial frequency: Accuracy data showed nonsignificant male superiority in both visual fields, whereas sensitivity data showed nonsignificant female superiority in the RVF and male superiority in the LVF; these effects emerged predominantly at F2 an F3, that is, at the stimuli involved in the more difficult recognition judgements.

3. No significant difference between the magnitudes of the respective mean male and female field advantages was found.

4. Direction of advantage was found to be dynamic: Intergender differences in the field advantage shift patterns across blocks occurred: (a) Only the females corroborated the group effect in which the identical field advantage emerged during the easy tasks independent of

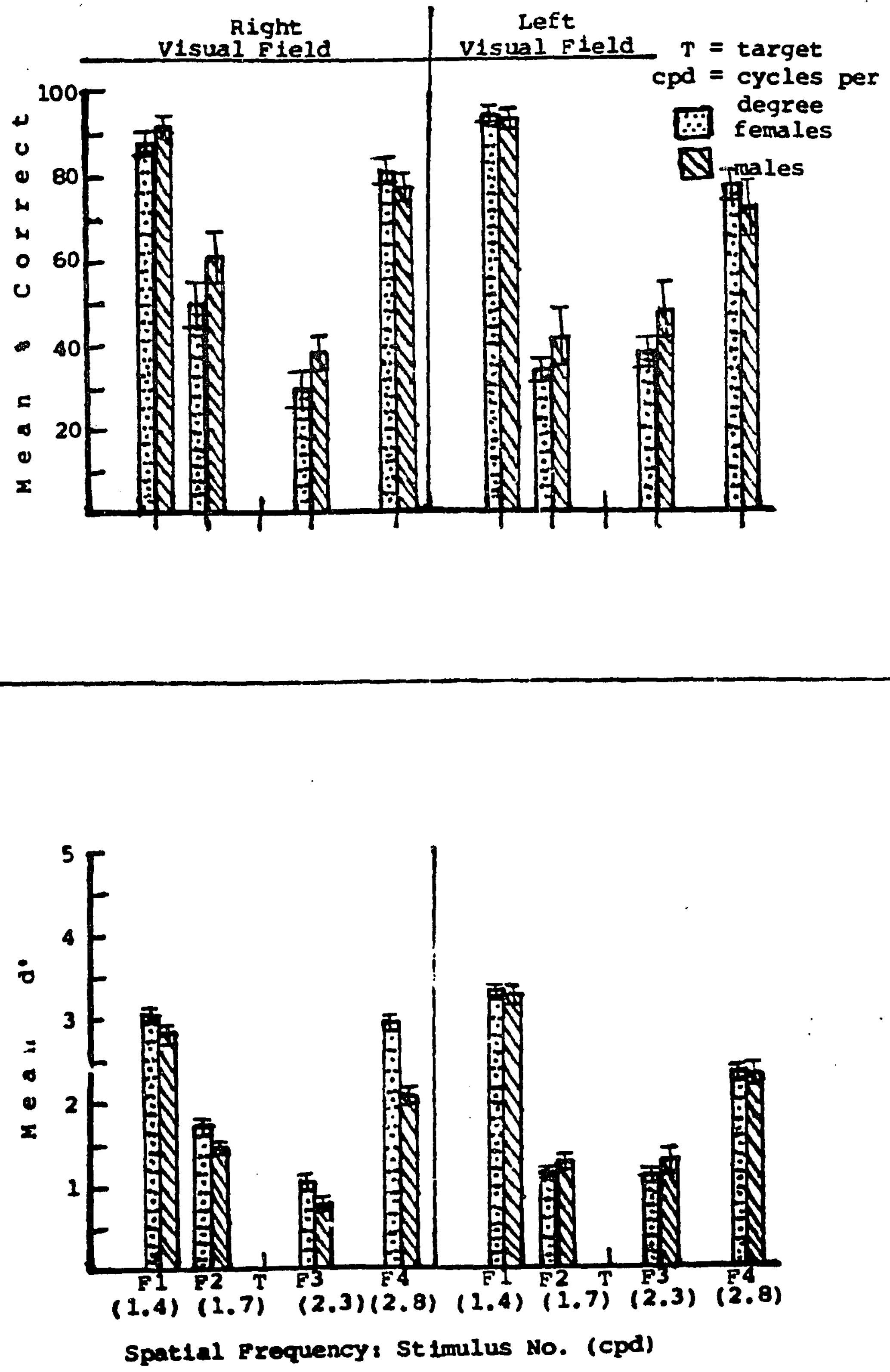


Figure 33. Gender differences in performance in the accuracy and sensitivity data.

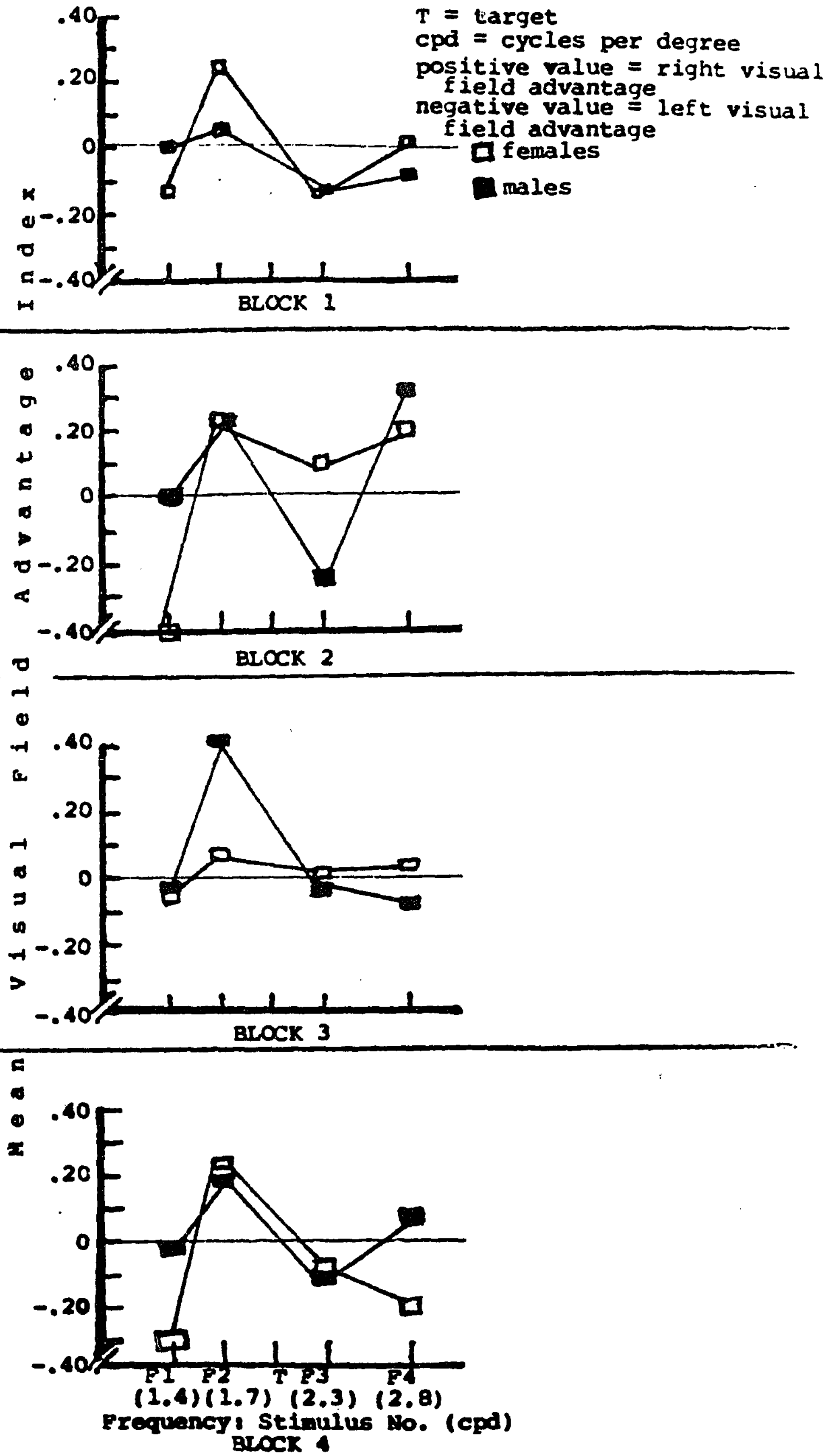


Figure 34. Familiarization effects on gender differences in visual field advantage as a function of spatial frequency.

frequency value to the more familiar stimuli; and (b) in Block 2 only, a significant quadratic trend in the Frequency x Gender interaction such that males and females had opposite field advantages at F3 was found.

Elaboration of these results follows.

1/ Percent Correct and d' Data

Performance and Response Patterns

Both the percent correct and d' data of the separate male and female means corroborated those data of the combined male and female means with respect to (a) the overall accuracy rate and sensitivity level between frequencies and to (b) the Frequency x Visual Field interaction (compare Figures 29-30 and 33).

Regarding the first point, as in the case of the total sample, accuracy and sensitivity for each gender were greater at F1 and F4 than at F2 and F3. Concerning the second point, also as in the total sample, male and female accuracy and sensitivity were greater in the RVF than in the LVF at F2; conversely, male and female accuracy and sensitivity were greater in the LVF than in the RVF at F3.

Whereas the above-described pattern of results was significant for the combined means, it did not reach significance for the separate means. Given the relatively high degree of variability in the sensitivity data of the males and females (see Tables 4 and 5), this finding was not surprising.

Finally, small field advantages emerged at F1 and F4 in both the accuracy and sensitivity data of the separate males and females, again with relatively high variability in the sensitivity measure. Thus, both the total and gender data showed a Frequency x Visual Field effect (significant in the former and a trend in the latter) at F2 and F3, the more difficult recognition judgements.

Gender Reversal in Field Superiority as a Function of Dependent Variable

Although the three-way interaction effect of Frequency x Visual Field x Gender was nonsignificant, an interesting result concerning the effect of Frequency x Visual Field on gender emerged: A nonsignificant trend for this effect appeared in the sensitivity data only (see Figure 33).

The accuracy data showed that males and females responded in the same way: The males' accuracy rate was higher than the females', particularly during the more difficult tasks (at F2 and F3), in both visual fields.

In contrast, the sensitivity data showed that males and females responded in a different way in each visual field: Female sensitivity was higher than the males' in the RVF, whereas male sensitivity was higher than the females' at F2 and F3, and roughly equal to the females' at F1 and F4, in the LVF. Due to the high variability in the d' data (see Table 5), this experiment need be replicated to confirm this finding.

Account of This Effect

The source of this gender reversal in superiority as a function of dependent measure lies in the hit rate of a given subject. In the current task, even if a male had a higher accuracy rate (correctly reported "Different" during a TES-TAR mismatch) than a female, if that female had a higher hit rate (correctly reported "Same" during a TES-TAR match) than the male, she would likewise have a higher d' score than he would.

For example, a male scored 80% correct at F1 in the RVF, had a 65% hit rate, and yielded a resultant d' (determined from the ratio of 0.65 hits to 0.20 false alarms [i.e., the incorrect reporting of "Same" during a mismatch]) of 1.22. In contrast, when a female responded to the same stimulus in the same visual field, she yielded a lower accuracy rate of 65%, a higher hit rate of 99%, and a substantially higher d' of 2.70.

2/ Magnitude of Advantage

Intergender differences in VFAI size were used to measure gender differences in magnitude of advantage. (Note. This measure was selected instead of a comparison between the respective male and female magnitudes of the interfield arithmetic differences between percent correct scores at each frequency. The reason that the VFAI measure was chosen is that a comparison between relative indices of field advantage more precisely assesses gender differences in magnitude of asymmetry than one using absolute indices).

The VFAI data did not reveal a significant Frequency x Gender interaction effect, that is, the current study found that degree of lateralization during visual pattern recognition did not significantly differ between males and females.

3/ Familiarization Effects (Hypothesis 5)

Although the responses of each gender did not significantly differ in magnitude either for the total session or between blocks (see Figure 34), they did show differences in shift patterns.

The Male Pattern

In every block, males showed effectively no field advantage at the easy low frequency (F1); a large RVF at the difficult low frequency (F2); a shift to a LVF advantage at the difficult high frequency (F3); and an alternating pattern at the easy high frequency (F4) (i.e., a LVF advantage in the first and third blocks and a RVF advantage in the second and fourth).

The Female Pattern

Females, in contrast, showed a LVF advantage at F1 and a RVF advantage at F2 in every block. They demonstrated inconstant patterns at the two high frequencies across blocks.

At F3, they displayed a LVF advantage followed by an apparent linear progression consisting of a RVF advantage, a miniscule RVF advantage effectively equivalent to no advantage, and a LVF advantage; the Block 3 advantage seemed transitional between advantages in opposite visual fields at different stages of stimulus familiarization.

At F4, the females initially displayed a RVF advantage that increased in magnitude in Block 2, decreased to such a small size that it approximated no advantage in Block 3, and finally shifted to a large LVF in Block 4. Again, as at the F3 stimulus, the Block 3 advantage seemed transitional between advantages in opposite fields at different learning stages.

The Frequency x Gender Effect

One of these intergender differences in shift patterns reached significance: A significant quadratic trend in the Frequency x Gender interaction emerged in Block 2, $F(1,18) = 4.37$, $p<.05$. The source of this effect was the maintenance of a RVF advantage at F2 and F3 in the female response pattern in contrast to a shift in advantage from the RVF at F2 to the LVF at F3 characteristic of the cubic trend in the male function during that block.

Summary

Thus, both genders showed a field advantage shift in the low spatial frequency range as a function of task difficulty. The females alone showed the same pattern as the total sample, namely, the identical field advantage in the low and high frequency ranges during the easy recognition judgements to familiar stimuli.

3.3] SPATIAL FREQUENCY AND PROFICIENCY (HYPOTHESIS 3)

As mentioned above, the U-shaped functions for both the separate and combined male and female means show that accuracy and sensitivity were greater at F1 and F4 than at

F2 and F3. Whereas the above two subsections analyzed this finding with respect to the interactions between frequency, visual field, and/or gender, the current one focuses on the main effect for frequency, independent of visual field and gender effects.

Both the percent correct and d' ANOVAs revealed a significant main effect for frequency; for percent correct, $\underline{F}(3, 54) = 90.54$, $\underline{p} < .0001$; for d', $\underline{F}(3, 54) = 82.66$, $\underline{p} < .0001$). Post-hoc Tukey tests performed on these two data sets showed the identical pattern of results for both of them (see Figure 35 [and Tables 4 and 5 for variability data]) as follows.

Significant differences were found between responses to the four spatial frequencies in the following order: Accuracy and sensitivity were (a) greatest at the lowest frequency (F1); (b) second greatest at the highest frequency (F4); (c) third greatest at the low frequency adjacent to TAR (F2); and (d) least at the high frequency adjacent to TAR (F3); for percent correct, $\underline{MSE}(54) = 6.59$; for d', $\underline{MSE}(54) = .19$, $\alpha = .05$).

In sum, (a) F1 and F4 yielded the highest accuracy and sensitivity levels, and F2 and F3, the lowest, and (b) within each of these pairs, accuracy and sensitivity were greater at the low frequency than at the high one. The first point is consistent with the notion that the tasks at F1 and F4 were easier than those at F2 and F3 (due to the greater distance and, hence, greater discriminability, from

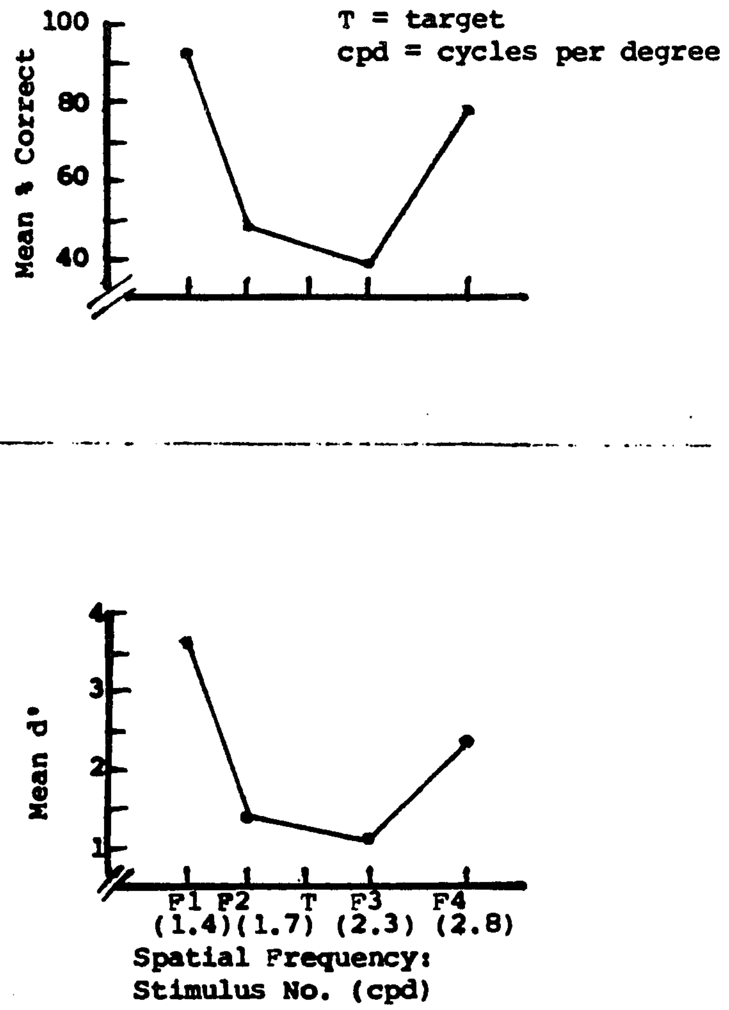


Figure 35. Mean accuracy and sensitivity as a function of spatial frequency.

TAR of the former two than latter two stimuli).

Finally, it should be noted that, given the extremely small level of variability in the percent correct data and the relatively large one in the d', the results reported herein are more robust with respect to the former than latter data set.

3.4] ASYMMETRY AND PROFICIENCY (HYPOTHESIS 4)

In this analysis, magnitude of advantage (indicated by the value of the VFAI), without direction of advantage (indicated by the sign preceding this value), was correlated (Pearson r product-moment) with each percent correct score. This correlation was performed to test whether (a) a "bigger" advantage correlated with "better" recognition performance for each response and (b) this effect changed through time.

More specifically, the absolute value of the VFAI at each frequency in each block was correlated with the accuracy score for each frequency presented in each visual field in each block for both the total session and the block data.

A strong pattern of results was found (see Table 8) (and the same pattern reported herein for the total sample was found for the males and females separately): For both the total session and the separate blocks, (a) a significant high negative correlation existed at F1, mean $r = -.44 \pm .09$, range of probability levels from $p<.0001$ to $p<.05$); (b) significant high positive correlations existed at F2, mean r

Table 8

Correlations[a] Between Visual Field Advantage Indices (Absolute Values) and Percent Correct Scores

	Stimulus no. (cpd)							
	F1 (1.4)		F2 (1.7)		F3 (2.3)		F4 (2.8)	
	Visual field							
	RVF	LVF	RVF	LVF	RVF	LVF	RVF	LVF
				Entire Session				
r =	-.41	-.33	.62	.25	--	.56	--	--
p <	.0001	.003	.0001	.02	--	.0001	--	--
				Block 1				
r =	--	-.44	.50	--	--	.58	--	--
p <	--	.05	.02	--	--	.008	--	--
				Block 2				
r =	-.59	--	.60	--	.73	.58	--	--
p <	.006	--	.005	--	.0003	.007	--	--
				Block 3				
r =	--	--	.74	.45	--	--	--	--
p <	--	--	.0002	.04	--	--	--	--
				Block 4				
r =	-.45	--	.65	--	.73	--	--	--
p <	.05	--	.002	--	.0003	--	--	--

Note. cpd = cycles per degree. *n* = 20.

[a] Pearson-r product moment.

= .54 ± .16, $p<.0001$ to .04, and F3, mean r = .64 ± .09, $p<.0001$ to .008, respectively; and (c) no significant correlations existed at F4.

The negative correlation at "easy" F1 indicates that when size of advantage in a given block increased, the percentage of correct judgements in that block decreased, or vice versa (when the former decreased, the latter increased). The lack of correlation at "easy" F4 shows that size of advantage did not systematically vary with response accuracy. Finally, the positive correlations at "difficult" F2 and F3 indicate that when size of advantage increased, the associated recognition judgements increased, or vice versa (when the former decreased, the latter decreased as well).

Summary: Task Difficulty Effects

Hence, the current statistic shows that the relationship between magnitude of field advantage and proficiency may be task-dependent: During the easier tasks, a larger advantage either significantly correlated with impaired performance or did not correlate with performance at all; during the difficult ones, a larger advantage significantly correlated with improved performance.

3.5] SUMMARY

The current data show that one visual field is not unconditionally superior to the other in recognizing spatial frequencies from 1 to 3.9 cpd. Rather, (a) the direction of field advantage was found to vary with task difficulty, dependent measure, gender, and degree of stimulus familiarization, in addition to frequency per se; and (b) the magnitude of advantage varied with task difficulty and frequency.

These data further show that (a) proficiency in recognizing the current frequency range and (b) the correlation between magnitude of advantage and proficiency were also a function of the Task Difficulty x Spatial Frequency interaction.

These effects are summarized herein (see Table 9).

1/ Direction and Magnitude of Visual Field Advantage During Spatial Frequency Recognition (Hypothesis 1)

Direction of Advantage

Dependent Variable Effects

All three dependent variables showed that direction of advantage varies with the Task Difficulty x Spatial Frequency interaction; the particular directions, however, varied between variables as follows:

1. The percent correct data showed that within the respective low- and high-frequency ranges, direction shifted from (a) no advantage during the easy task to (b) an advantage in the visual field opposite to that in the other range during the difficult task: A RVF advantage was found at the difficult low frequency (F2), and a LVF advantage, at the difficult high (F3).

2. The d' data revealed the same pattern with one modification: Within the low range only, an advantage in

Table 9

Summary: Visual Field Advantage, Proficiency, and Their Correlation as a Function of Frequency, Task Difficulty, Dependent Variable, and/or Familiarization (Entire Sample)

	Spatial frequency range			
	Low		High	
	Task difficulty level (stimulus no.)			
	Easy(F1)	Difficult(F2)	Difficult(F3)	Easy(F4)
Direction of Advantage:				
% Correct	--	RVF	LVF	--
d'	LVF	RVF	LVF	--
VFAI (less familiar)	LVF	RVF	LVF	{miniscule RVF}
VFAI (more familiar)	LVF	RVF	LVF	LVF
Magnitude of Advantage	second largest	maximum	third largest	minimum
Proficiency	maximum	third largest	minimum	second largest
Advantage-Proficiency Correlation	negative	positive	positive	--

Note. RVF = right visual field. LVF = left visual field.

the field opposite to that occuring during the difficult task existed during the easy one. Hence, a LVF advantage was found at the easy low frequency (F1); a RVF advantage, at the difficult low one (F2); and a LVF advantage, at the difficult high one (F3).

3. The VFAI data showed the same pattern as the d' data with one change: A minute, nonsignificant RVF advantage emerged at the easy high frequency (F4). Thus, a LVF advantage was found at the easy low frequency (F1); a RVF advantage, at the difficult low one (F2); a LVF advantage, at the difficult high one (F3); and a miniscule RVF advantage, at the easy high one (F4).

According to this measure, (a) within each frequency range, opposite field advantages existed during the easy and difficult judgements, and (b) this pattern in the low range was the reverse of that in the high.

Gender Effects (Hypothesis 2)

The directions of advantage found in the percent correct and d' data described above were found for both the combined and separate (male and female) means.

Familiarization Effects (Hypothesis 5)

The pattern of results described immediately above for the VFAI data emerged only when the stimuli were relatively unfamiliar to the subjects. When the stimuli became more familiar, the pattern changed in one respect: The same advantage (one in the LVF) occurred during both easy tasks independent of their frequency values.

Hence, whereas a shift in advantage occurred between the difficult and easy tasks in the high-frequency range when the stimuli were relatively unfamiliar, the identical advantage existed during both the difficult and easy tasks in the high-frequency range when the stimuli were relatively familiar.

Gender effects (Hypothesis 2). Thus, the response pattern to more familiar stimuli, characteristic of the total sample and the females alone, was a RVF advantage to the difficult low frequency (F2); a LVF advantage to the difficult high (F3) ; and a LVF advantage to both the easy low (F1) and high (F4).

Magnitude of Advantage

(a) Magnitude of visual field advantage (as measured by the VFAI) was larger to low- than to high-frequency stimulation, and (b) within each of these ranges, was larger during the difficult tasks than during the easy ones.

Gender Effects (Hypothesis 2)

No significant differences between the respective mean VFAI magnitudes of males and females emerged, that is, the genders were found to be equally lateralized with respect to the recognition of spatial frequencies ranging from 1 to 3.9 cpd.

2/ Recognition Proficiency and Frequency Range (Hypothesis 3)

(a) Accuracy rate and sensitivity level were higher during the easy tasks than during the difficult ones; and

(b) within each pair of stimuli presented during the easy and difficult tasks, performance at the low-frequency stimuli exceeded that at the high.

Gender Effects (Hypothesis 2)

In the gender data, performance was found to vary with dependent variable, visual field, and spatial frequency: Male accuracy exceeded that of females in both visual fields, but male sensitivity exceeded that of females only in the LVF; female sensitivity exceeded that of males in the RVF. These effects were most marked at the two difficult frequencies (F2 [low] and F3 [high]).

3/ Correlation Between Field Advantage and Proficiency (Hypothesis 4)

The existence and direction of a correlation between magnitude of advantage (VFAI) and response accuracy (percent correct) was likewise a function of the Task Difficulty x Spatial Frequency interaction: No significant correlation existed during the easy high-frequency recognition judgement, a negative correlation was found during the easy low-frequency one, and positive correlations emerged during the difficult tasks independent of frequency.

[4] DISCUSSION

The actual results in the current study were consistent with those predicted:

1. (a) The direction and magnitude of hemispheric advantage during spatial frequency recognition for the total group (Hypothesis 1) and for the separate males and females (Hypothesis 2), (b) the effect of lateralized processing on spatial frequency recognition accuracy (Hypothesis 4), and (c) the effect of spatial frequency range on recognition accuracy (Hypothesis 3) were all found to depend on level of task difficulty.

2. Both lateralized processing (Hypothesis 1) and direction of gender superiority (Hypothesis 2) during spatial frequency recognition varied with dependent variable.

3. Functional asymmetry (Hypothesis 1) and gender differences in asymmetry patterns (Hypothesis 2) during recognition varied with subjects' degree of stimulus familiarization (Hypothesis 5).

It should be stated at the outset of this subsection that interhemispheric differences during spatial frequency processing and gender differences therein both were expected to be and actually were small effects (see subsection 1.5/6 for explanation). Further, the d' data contained a relatively high degree of variability. Hence, both the small hemispheric effects shown by a given measure and the small discrepancies in magnitude of advantage between measures may not have been meaningful. Interpretations of the data are provided with the understanding that replication is required for their validation.

The current subsection is organized as follows:

Subsections 1 and 2 examine discrepancies between present and past findings as well those among past findings concerning pattern recognition processing and proficiency with respect to the following methodological factors: (a) dependent variables, (b) stimulus parameters, (c) task parameters, (d) degree of familiarization, and (e) subject characteristics.

Subsection 3 provides a summary of this analysis.

Subsection 4 critiques the spatial frequency model of hemispheric specialization on the following bases:

1. Psychophysical data have shown that the argument that hemispheric specialization for spatial frequency underlies hemispheric specialization for cognitive functions is incorrect.

2. The model is ambiguous with respect to the following issues: (a) whether such specialization is for spatial frequencies organized into a configuration or for spatial frequencies per se, (b) where along the processing sequence such specialization emerges, and (c) how such specialization operates.

Subsection 5 develops some of the issues raised in the fourth. Here, anatomical, physiological, and behavioral data concerning asymmetries at ascending levels of visual recognition processing (at rest and during the detection, discrimination, and recognition of unpatterned and patterned stimuli) are presented. Also, hypothetical neural mechanisms of the asymmetrical processing of spatial frequency (both in terms of its structural level and size connotations) are suggested.

Subsection 6 suggests ideas for further research in this area.

(*Note*. The terms *RVF* and *LVF* used in the Results section above are respectively replaced by the terms *LH* and *RH* herein.)

4.1] RECOGNITION PROCESSING: METHODOLOGICAL DETERMINANTS OF THE SPATIAL FREQUENCY x VISUAL FIELD EFFECT (HYPOTHESIS 1)

1/ Dependent Variables

Accuracy Versus Sensitivity Measures

The directions of advantage at each frequency were similar in the percent correct, d', and VFAI functions. The magnitudes of advantage were generally similar among these three measures, but some differences emerged: Size of advantage was smaller (a) at F1 in the percent correct than d' and VFAI functions and (b) at F4 in the d' than percent correct and VFAI functions.

(*Note*. Whether these differences were real is indeterminant without replication because both the within-measure interhemispheric differences in advantage and the between-measure dissimilarities in advantage were so small.)

The Sensory Component of Hemispheric Utilization

The overall similarity between the d' and VFAI functions suggests that pattern and magnitude of hemispheric advantage are in large part due to sensitivity. (*Note*. The reader is reminded that sensitivity in a recognition paradigm refers to level of responsivity at the sensory and/or memory [template match] levels. The current psychophysical study was unable to specify the relative contributions of each of these levels to the d' measure; a concurrent psychophysical and electrophysiological study is necessary to do so.)

It should be noted that the high degree of variability in the d' data suggests that the interhemispheric differences in advantage therein may not have been real. If replications of the current study show that to be the case, then cognitive strategy, rather than sensitivity, would be a major determinant of pattern and degree of advantage in visual pattern recognition.

Magnitude of Advantage

The intermeasure differences in magnitude of advantage were not surprising in that each measure tapped different processes from the other two; the reader is reminded of these different processes:

1. Percent correct (the subjects' reporting "Different" when TES and TAR were different), an index of absolute accuracy, reflected both sensitivity and cognitive strategy.

2. d' (the ratio of hits [the subjects' reporting "Same" when TES and TAR were the same] and false alarms [the

subjects' reporting "Same" when TES and TAR were different]) reflected sensitivity alone.

3. VFAI (the ratio of the difference between number of errors [one minus the subjects' "Different" responses when TES and TAR were different] in the right and left visual fields to the sum of errors in both visual fields), a measure of relative accuracy, reflected both sensitivity and cognitive strategy.

Speculative accounts of the intermeasure differences. One might speculate as to mechanisms underlying the differences listed above. For example, the greater magnitude of the RH advantage at the F1 stimulus in the d' than percent correct measure (causing the greater interhemispheric difference in advantage in the d' data) suggests: (a) greater RH than LH sensitivity to low-frequency stimulation during an easy recognition task and (b) the use of a LH-based cognitive strategy that interacted with, and consequently diminished the magnitude of, the RH advantage at the sensory and/or template match level.

The source of this LH "interference" may have been an incomplete shift from an analytic strategy used to process the more difficult-to-recognize low frequency (F2) to a synthetic strategy used to process the easier-to-recognize low frequency (F1). The fact that the magnitude of the LH advantage was consistently large at the F2 stimulus (both for the entire session and within each block) strengthens the possibility that the LH influenced the RH during F1 stimulus recognition.

A second reason for the use of a LH-based strategy is that because this task entailed recognition judgements concerning size, not configuration, a RH-based synthetic strategy typically used to process the latter type of stimulus was not required (G. Turkewitz, personal communication, June 1986).

Further speculative accounts of inconsistencies in results as a function of dependent measure are not offered because, as mentioned above, many of the interhemispheric differences found by all three measures were small (the responses at F2 provide the major exception). Hence, these slight between-measure discrepancies in magnitude may not have been meaningful; interpretations thereof would be overstatements, rather than true accounts, of the possible mechanisms underlying these effects.

Accuracy Versus Reaction Time Measures

Hemispheric Advantage as a Function of Dependent Variable

Other studies have likewise reported differences in accuracy and sensitivity measures of hemispheric advantage during the processing of nonverbal stimuli (e.g., line orientation detection [Koss, 1981]). Koss further found that a third measure, RT, provided similar results to the d' measure and, hence, different results from the accuracy measure. She cited six other studies that also used dual measures (accuracy and RT) of lateralized processing of nonverbal stimuli (e.g., color perception, cognitive processing of musical stimuli, and spatial orientation) and noted that five of them similarly found discrepant results.

Koss concluded that "accuracy and RT are not necessarily equivalent expressions of lateral differences" (Ibid., p. 104). E. Zaidel (1979, cited in E. Zaidel, 1985b) similarly suggested that one hemisphere may be faster but less reliable than the other during a given task.

Hence, both Koss' conclusions concerning accuracy and RT and the current findings concerning accuracy and sensitivity highlight the fact that caution must be taken when comparing lateralization studies and generalizing about lateralization magnitude and patterns. A given hemispheric advantage reflects, not overall hemispheric superiority, but rather superiority vis-à-vis the aspect(s) of processing measured by the particular dependent variable(s) used.

Between-Measure Differences in Studies of Hemispheric Specialization for Spatial Frequency

Between-study differences in dependent variables existed in the three studies concerning hemispheric specialization for spatial frequency: Sergent (1982a) used mean correct RTs and mean percentage of errors; Previc (1982), median RT and percentage of false alarms; and this author, percentage of correct responses, d', and VFAI.

Consistent with the above discussion, within-study differences appeared in result patterns as a function of dependent measure. Current examples are presented in the

Accuracy Versus Sensitivity Measures subsection herein (viz., [a] the difference in magnitude of advantage at F1 was smaller in the percent correct than d' and VFAI data, and [b] that at F4 was smaller in the d' than percent correct and VFAI data) and in the Results section above (viz., the higher hit rate in females than in males transformed an inferior female performance when measured by percent correct into a superior female performance when measured by d').

Previc provided other examples: He found two significant interaction effects ([a] Visual Field x Hand of Response and [b] Spatial Frequency x Hand of Response) with the false alarm measure that did not appear with the median RT measure.

The between-study differences in asymmetry patterns (viz., [a] a RH advantage to low-frequency, and a LH advantage to high-frequency, stimulation during a visual search task [Sergent]; [b] no Hemisphere x Frequency effect during an identification task [Previc]; and [c] a LH advantage to low-frequency, and a RH advantage to high-frequency, stimulation during difficult recognition tasks [current]), may likewise have been related to the between-study differences in dependent measures.

Sergent's data reflected asymmetry with respect to speed and absolute accuracy; Previc's, speed and absolute accuracy subjected to different statistical analyses than Sergent's; and the current, absolute accuracy, sensitivity, and relative accuracy. To extend Koss's conslusion concerning accuracy and RT, all of these measures "are not necessarily equivalent expressions of lateral differences."

Verbal Versus Motor Measures

According to G. Turkewitz (personal communication, April, 1986), no strong evidence exists in the lateralization behavioral literature showing that a verbal response measure during pattern recognition biases a given asymmetry pattern toward a LH advantage. Hence, it is unlikely that Sergent's use of a motor response versus Previc's and this author's use of a verbal response contributed to their discrepant findings summarized immediately above.

2/ Stimulus Parameters

Sergent's spatial frequency model of hemispheric specialization postulates that direction of advantage depends on which frequencies are made available by stimulus composition and presentation parameters. Hence, if, despite the similar range used in Sergent's (1982a), Previc's (1982) and the author's studies, different frequencies were made available in each study, then the between-study differences in pattern of asymmetry would not be surprising. The current subsection suggests that this situation, in fact, occurred and discusses the factors contributing to it.

Stimulus Material

Sergent used verbal stimuli (single letters), whereas Previc and the author used nonverbal stimuli (square-wave gratings in Previc's study and checkerboards in the current one). Although the most recent data show that the LH alone does not mediate all aspects of linguistic processing, those data do indicate that the pattern of hemispheric activation during linguistic processing differs from that during nonlinguistic processing (J. Gordon, personal communication, August, 1986; see subsection 1.1/3).

How the use of verbal versus nonverbal stimuli might have affected the patterns and magnitudes of asymmetry cannot be specified, but the anatomical and physiological data cited above suggest that stimulus material was a critical factor in the different Hemisphere x Frequency effects found by Sergent and this author.

Stimulus Configuration

Another difference in stimulus composition between Sergent's versus Previc's and the current studies was that the stimuli in the former study were configurational (large letters composed of smaller letters), whereas those in the latter two studies were nonconfigurational (gratings and checkerboards). The former thus measured the capacity to process low and high spatial frequencies relative to one another, and the latter two, that of processing absolutely low and high frequencies.

Hence, whereas the directions of advantage for the respective frequency ranges found by Sergent reflected the processing of spatial frequencies as well as that of embedded figures, figure-ground relationships, and structural levels, the results of Previc and this author reflected spatial frequency processing alone. It is likely that the configuration dimension, like that of stimulus material, substantially contributed to the different patterns of results revealed by Sergent and this author.

Stimulus Range

One stimulus dimension that was roughly the same in these three studies was spatial frequency range: Sergent's low and high frequencies were approximately 0.65 and 5 cpd, respectively; Previc's, 0.9 and 5.5; and the author's, 1 and 3.9. Hence, this factor probably did not contribute to the different directions of asymmetry shown by these studies.

Optimal Frequencies for Differential Hemispheric Engagement During Configurational/Feature Processing

As mentioned in subsection 1.5/6, (a) the perception of facial form depends most heavily on low-to-intermediate frequencies (2-3 cpd) (Tieger & Ganz, 1979), and (b) that of internal facial features requires frequencies higher than 5.5 cpd (Ginsburg, 1978, cited in Previc).

This fact suggests that if hemispheric specialization exists for configurational (relatively low frequencies) versus feature (relatively high frequencies) processing, then frequencies around 2.5 cpd and in excess of 5.5 cpd may be necessary to optimally engage the hemisphere respectively tuned to process low or high frequencies.

(Note. [a] Whether the hemispheres are specialized for processing absolute or relative frequency is discussed in subsection 4.4/1. [b] The values cited herein were found during foveal viewing; they must be modified for parafoveal stimulation, i.e., the viewing condition required to assure selective hemispheric activation.)

None of the studies cited herein used nonverbal, configurational stimuli composed of these frequencies. Hence, (a) Previc's finding of symmetrical processing and (b) Sergent's and this author's findings of different patterns of asymmetrical processing may relate to the fact that none of them provided the stimulation conditions necessary to elicit the "peak hemispheric advantage for spatial frequency" response. A logical next experiment would be to present the above-described stimuli, perhaps optimal with respect to hemispheric specialization for relative spatial frequency.

Physical Versus Perceived Frequency

Finally, the reader is reminded that the values of perceived frequencies (a) differ from those of the actual frequencies and (b) differ among themselves as a function of processing level because the input frequencies are continually transformed throughout the processing sequence (see E. Davis, Jones, & Yager, 1985, for model concerning the discrepancy between perceived and actual frequencies).

These two effects are due to such properties of visual processing as (a) nonlinear interactions between spatial frequency channels and (b) various operations performed by nonlinear and linear channels on spatial frequencies (e.g., rectification and attenuation, respectively).

Further, subjects' responses do not necessarily represent responses to the fundamental spatial frequencies of checkerboard stimuli. In the current study, for example, responses to the low values furthest from 3-5 cpd (i.e., the frequencies to which the human visual system is optimally sensitive) may have been to harmonics that were closer to the 3-5 cpd range. What was interpreted to be a response to a low frequency may have been one to a slightly higher frequency.

Hence, direction of advantage with respect to spatial frequency technically reflects such an advantage vis-à-vis perceived frequencies (i.e., those frequencies constituting the neural representations at the level where hemispheric specialization putatively emerges), rather than actual stimulus frequencies. Differences in perceived frequencies in the Sergent, Previc, and current studies may have contributed to the different directions of advantage found therein.

The Target Stimulus: Its Presence and Placement

To review, the recognition task in the current study involved a same/different judgement of check size in sequentially presented target and test stimuli. Depending on the trial-specific order of target and test stimulus presentation, one stimulus was the template with which the "current" stimulus was compared.

Hence, spatial frequency processing herein entailed, not the sensory processing of the current frequencies alone, but rather the sensory and memory processing of the current and template frequencies. Consequently, hemispheric advantages in this study reflected the processing of 2 cpd (the target value) and the given test stimulus frequency value.

Sergent's visual search task involved the recognition of a target embedded within a given test stimulus. Although the relationship between the target and test stimuli differed between the two studies (hers involved a part-whole relationship between these two stimuli, whereas the current one did not), the involvement of both the sensory and memory processing levels was the same in both studies.

(Note. In her case, both the target and test stimuli constituted the current stimulus, and the target constituted the template stimulus; the value of the template frequency, however, was not specified in her study.)

In contrast, Previc's identification task involved grating orientation discrimination judgements and, hence, did not tap the memory level. Consequently, hemispheric advantages in his study represented the processing of current, not template, frequencies.

In sum, (a) the presence of a target stimulus and (b) its placement in relation to the test stimuli may have contributed to the different results in these three studies. A single asymmetry pattern in the two studies involving memory processing reflected the processing of a low or high frequency plus an intermediate one (in the current case) and an unspecified one (in the Sergent case); in contrast, such a pattern in the study involving sensory processing measured that of low or high frequencies only.

Stimulus Luminance

Next, luminance levels differed among these three studies: The fixation and test field values were roughly 9 and 30 cd/square meter, respectively, in Sergent's experiment; the stimuli and background fields measured 1.5 and 3 cd/square meter, respectively, in Previc's; and the interstimulus and test fields were both 80 cd/square meter in the current study.

The Effect of Luminance on Spatial Frequency Processing

Viewed from an overall perspective, these luminances did not significantly differ from one another in that they all fell within the photopic range (0.05-50,000 cd/square meter).

Viewed from a more molecular perspective, however, they were significantly dissimilar in that each level differentially affected the spatial frequency transfer function (Patel, 1966): Low photopic levels shifted the function to lower frequencies, and high levels, to higher frequencies, that is, under relatively dim conditions, optimal responses occurred to lower frequencies, and under brighter conditions, to higher frequencies.

This dependence of spatial frequency sensitivity on luminance affects lateralized processing in the following manner: (a) If hemispheric advantage varies with spatial frequency sensitivity, and (b) if spatial frequency sensitivity varies with luminance, then (c) hemispheric advantage varies with luminance.

In the case-at-hand, the 1.5 cd/square meter luminance level, roughly one log unit lower than the 30 and 80 cd/square meter levels, tuned the spatial frequency channels in the visual systems of subjects in the first study to a significantly lower frequency range than that to which channels in the second and third studies were tuned. Hence, the between-study variation in asymmetry patterns partially reflected the different luminance levels at which the stimuli were presented.

The Effects of Luminance Fluctuations on Visual Processing

Next, Sergent's and Previc's Methods sections did not state that (a) their subjects were light adapted and (b) their test stimuli were flashed from a background field of equal luminance. The changing light conditions due to (a) the shift in luminance levels from pretest to test conditions in the first case and (b) the alternation of dim interstimulus fields and brighter test stimuli in the second result in less-than-optimal photopic responding for the following reason.

Visual receptors do not operate to their fullest capacity until they are adapted to a particular luminance level. When light and, hence, adaptation state fluctuate, receptors engage primarily in readjusting to each new luminance level rather than in higher order processing. The consequences of this receptor activity for visual processing include continuous shifts of the spatial frequency transfer function and vacillations in acuity, that is, a significantly reduced ability to see patterns.

Hence, a blurring effect, the functional equivalent of extracting high spatial frequencies, results from inconstant luminance conditions. If such conditions were, in fact, present in these two studies, then the patterns of asymmetry revealed therein reflected not the processing of the frequencies constituting the stimuli, but rather that of the output frequencies transformed by luminance fluctuations.

Implications for Between-Study Differences in Direction of Advantage

In sum, the net effect of (a) low and high luminance levels and (b) variations in luminance is a discrepancy between the physical frequencies (in the stimuli) and the perceived frequencies (in the subjects). The between-study differences in direction of hemispheric advantage for a given frequency range cannot be attributed to differences in physical stimulus range because, as stated above, that range was similar in these studies. These differences in asymmetry patterns, however, can be attributed to between-study differences in perceived stimulus range that varied with luminance.

For example, the perceived stimulus range of Previc's subjects was lower than that of Sergent's and the author's, and whereas the latter two found significant Frequency x

Field effects, the former did not. Previc conjectured that his negative finding was due to too low a frequency range, but the fact that similar ranges yielded significant effects in the other two studies undermines his account.

When, however, his account is viewed in terms of the current discussion, and his referent for "frequency range" is interpreted to be perceived rather than physical, his explanation appears to be valid: Previc's use of a dim light level may have caused the perceived range of frequencies to be too low to differentially engage the cerebral hemispheres. Conversely, Sergent's and the author's use of brighter light levels apparently yielded perceived frequencies that were high enough to differentially activate the cerebral hemispheres.

Stimulus Contrast

Both Sergent and the author held contrast constant at a high level (nearly 1), whereas Previc manipulated contrast at three different levels (.1, .4, and .6). Even the highest contrast level used by the latter was substantially lower than those used by the former two; hence, the visibility of the spatial frequencies in Previc's study was lower than that in Sergent's and the current studies.

Thus, Previc's use of low luminance and contrast levels resulted in (a) a downward shift of the transfer function so that the visual system optimally responded to lower frequencies and (b) the subjects' difficulty in seeing the patterns, that is, they did not clearly perceive the high frequencies presented.

Because the net result of Previc's stimulus presentation conditions was that primarily low frequencies were processed, it is not surprising that a Frequency x Field effect did not emerge. Conversely, when higher luminance and contrast conditions were used (by Sergent and the author), then (a) high frequencies were clearly visible, (b) both the low and high frequencies presented were processed, and (c) significant Frequency x Field effects did emerge.

Stimulus Duration

Previc used 100-ms stimulus durations, whereas Sergent and the author used 150-ms durations. Sergent (1982d) showed that during facial processing, predominantly low spatial frequencies are extracted from 40-ms presentations; low and some high, from 120-ms displays; and probably all low and all high, from 200-ms exposures. These data hence suggest that Previc's presentations may have been too brief to permit the complete extraction of the high-frequency constituents from his stimuli, whereas Sergent's and the author's presentations were sufficiently long to permit such extraction.

(*Note*. With respect to the 150-ms duration used by the latter two investigators, as mentioned in the Methodological Approach subsection, durations much higher than this one cannot be safely used in a lateralization study because eye movements and, hence, bilateral activation occur at roughly 200 ms.)

Thus, the duration factor provides yet another account of Previc's negative finding: His lack of Frequency x Field effect may have resulted from the fact that although high frequencies were present in the stimuli, their brief exposure precluded their availablity to the visual system. As a result, the hemisphere putatively tuned to high frequencies did not receive sufficient input to activate it.

Site of Retinal Stimulation and Stimulus Size

The site of retinal stimulation was practically identical in all three studies being compared, namely, 0.5 degrees to either side of the fovea in Previc's study and almost 0.8 degrees to either side in Sergent's and the author's.

The sizes of the stimuli as imaged on the retina, however, did differ: Sergent's (1.3 degrees wide x 1.9 degrees high) and Previc's (2 degrees wide x 2 degrees high) were substantially smaller than the author's (6.23 degrees wide x 9.3 degrees high).

Stimulus size primarily affects the processing of low spatial frequencies. To review, these frequencies contain few cycles per degree. Hence, the larger the stimuli, the more complete cycles are included therein; conversely, the smaller the stimuli, the fewer complete cycles are included. In the latter case, minimal information concerning the parameters of the low frequency-at-hand is transmitted; as a consequence, aspects of visual processing are impaired. For example, too few cycles may be included for spatial summation to occur (Robson & Graham, 1981).

Hence, the different results yielded by these studies may have been partially due to differences in stimulus size, that is, low frequencies may have been incompletely processed in Sergent's and Previc's studies. Concerning Sergent, her use of small stimuli may have caused too little low-frequency information to be transmitted to optimally stimulate the low-frequency channels; it is thus difficult to assess what her finding of a RH advantage for the processing of 0.65 cpd frequencies actually reflects.

Concerning Previc, in addition to the less-than-optimal processing of high frequencies in his study due to stimulus luminance, contrast, and duration, impaired processing of low frequencies also occurred in his study due to stimulus size.

Again, his finding of a nonsignificant Frequency x Field effect is not surprising: Not only did his conditions effectively create a low-pass filter for his stimuli and, hence, result in the lack of activation of the hemisphere putatively specialized for high-frequency processing; they also resulted in the impaired processing of those low frequencies, and perhaps, the decreased activation of the hemisphere controlling low-frequency processing.

3/ Task Parameters

Both task and level of task difficulty appear to be critical determinants of asymmetry patterns during spatial frequency processing. Concerning task, the types of processes tapped during the current same/different recognition task engage the hemispheres differently (as specified below) than those tapped during Sergent's visual search recognition, and Previc's line orientation discrimination, tasks; such differences almost certainly contributed to the different net hemispheric effects found in these three studies.

Concerning task difficulty, Sergent and Previc did not examine their data with respect to this variable, but the current study showed that hemispheric advantage during pattern recognition varied with level of task difficulty. What were interpreted to be two-way interactions (Frequency x Field) in the first two studies may, in fact, have been three-way interactions (Frequency x Field x Task Difficulty).

Thus, the directions of asymmetry vis-à-vis low and high spatial frequencies found by Sergent and the lack of asymmetry during spatial frequency processing found by Previc may have been true for the processing of their respective frequency values at particular levels of task difficulty, rather than for those frequencies per se.

The reader is reminded that task difficulty was not an independent variable in the current study. Rather, during data analysis, this factor was defined with respect to (a) distance between the TES and TAR stimuli (the closer the stimuli, the more difficult the task) and (b) absolute accuracy rates (the lower the rate, the more difficult the task).

Hence, because spatial frequency and task difficulty were confounded in the current study, the validity of the above hypothesis cannot be evaluated at present; such an evaluation requires data yielded by a study in which these two factors are independently manipulated.

The current subsection discusses the effects of (a) same/different recognition judgements and (b) task difficulty on hemispheric activity.

Same/Different Recognition and Lateralization

First, the categorizing and labelling of one stimulus as the same as or different from another are conceptual and linguistic processes. Although early data suggest that linguistic processing involves greater LH than RH activity, more recent data suggest that certain aspects are controlled by the LH, and others, by the RH (see subsection 1.1/3). Until these aspects are specified, it remains unknown whether this task biases the LH.

Second, Smith and Nielson (1970) investigated the memory-related aspects of same/different processing during a facial recognition task: They varied (a) the number of features differing between the two (line drawing) faces being compared and (b) the length of the retention interval. They found that, in a sample of 144 college-aged males and females, the RTs of different (D) judgements correlated with the number of features differing between a given stimulus pair at all retention intervals; in contrast, the

RTs of same (S) judgements did not vary in this manner.

These investigators concluded that D judgements involved an exhaustive, self-terminating, serial type of retrieval, whereas S judgements entailed a parallel type. If serial processing is primarily LH-controlled, and parallel processing, primarily RH-controlled, then these data suggest that D judgements engage the LH more than the RH, and conversely, S judgements, the RH more than the LH.

Task Difficulty and Lateralization

Table 10 lists (a) the stimuli in the current study ordered from easiest to most difficult to recognize (as measured by performance; accuracy and sensitivity scores corroborated one another), (b) the hemispheric advantages found at each of these frequencies, and (c) the correlations between size of advantage and proficiency.

As Table 10 shows, the following effects were found:

1. The two tasks labelled by the experimenter to be easy (respectively comparing the low and high frequencies furthest from TAR with TAR) and the two labelled by the experimenter to be difficult (respectively comparing the low and high frequencies closest to TAR with TAR) were neither equally easy nor equally difficult.

2. Within each of the low- and high-frequency ranges, hemispheric advantage differed between the easy and difficult tasks (as categorized by the experimenter).

3. Within each of the easy and difficult levels of task difficulty (as categorized by the experimenter), hemispheric

Table 10

Hemispheric Advantage and Effect of Advantage on Proficiency as a Function of Task Difficulty (Entire Sample)

Task difficulty level	Stimulus no.	Hemispheric advantage: Direction[a] and Size[b]	Size of advantage-Proficiency Correlation
easiest	F1 (easy low)	RH (larger in d' than % correct); second largest	negative
second easiest	F4 (easy high)	none (d') slight LH (% correct and VFAI); smallest	N.S.[c]
third easiest	F2 (difficult low)	LH; largest	positive
most difficult	F3 (difficult high)	RH; third largest	positive

[a] according to all three measures. [b] according to the visual field advantage index. [c] N.S. = not significant.

advantage at the low frequency differed from that at the high.

(Note. The fact that these effects varied with degree of stimulus familiarization is omitted from these data; this issue is addressed in the following subsection.)

Level of Task Difficulty

The first effect may have occurred for two reasons. First, stimulus generation may have been imperfect, that is, the actual frequency values may have slightly deviated from the theoretical values; hence, each low- and high-frequency pair putatively falling at equal distances around the target may, in fact, have been asymmetrically placed around it.

Second, even if the stimuli were perfectly generated, each subject probably perceived each task to be at a slightly different level of difficulty than it was based solely on physical factors.

Asymmetry as a Function of Spatial Frequency and Task Difficulty

As the second and third points show, a Frequency x Task Difficulty interaction emerged; hence, as suggested in the introduction to this subsection, the direction and magnitude of asymmetry found for each frequency in the current study were actually for that frequency at a particular level of task difficulty. Speculative accounts of the current findings follow.

Direction of asymmetry. The within-range shifts in direction of asymmetry ([a] from a RH advantage at "easy" F1 to a LH advantage at "difficult" F2 in the low-frequency range and [b] from a no/LH advantage at "easy" F4 to a RH advantage at "difficult" F3 in the high range) with changes from easy to difficult tasks may have occurred for reasons suggested by the following concordant electrophysiological and psychophysical data.

1. <u>The RH to LH shift in advantage</u>. Concerning the shift pattern in the current low-frequency range, Ornstein, Johnstone, Herron, and Swencionis (1980) found the same pattern during visuospatial tasks other than that currently used, namely, a mean RH advantage changed to a mean LH advantage (as measured by alpha activity at parietal and central sites in 10 male and 10 female dextral 18- to 37-year-olds) when the levels of difficulty of circle-matching and mental rotation tasks increased.

These investigators attributed this shift to their subjects' using a synthetic strategy for simpler tasks and an analytic strategy for difficult ones. They concluded that hemispheric advantage depended on processing mode used to meet task requirements rather than on stimulus material (see Nebes, 1978, cited in Ornstein et al., Ibid., for discussion of the processing mode model of hemispheric specialization).

Galin (1978, cited in Ornstein et al., Ibid.), De Renzi (1978), Patterson and Bradshaw (1975), and Yin (1970) corroborated Ornstein et al.'s finding with respect to other visuospatial tasks, namely, the first, for Kohs Blocks tests; the second, for spatial orientation; and the last two, for facial processing. De Renzi concluded from his review of his lab's 12 years of research on spatial processing that

> "whenever the processing of perceptual data goes beyond the level of `pure' detection of spatial orientation and involves intellectual analysis (such as deduction of relationships . . .), the contribution of the LH to performance increases and tends to attenuate the RH's superiority." (p. 67)

When viewed in relation to the above-cited data, De Renzi's account suggests that processing levels may be characterized in terms of the difficulty dimension: Low-level (sensory) processing is easier than high-level (cognitive). Consequently, the hemispheric advantage that emerges during the sensory processing of visuospatial stimuli (RH) likewise reflects lateral activity during an easy task; the advantage appearing during cognitive processing (LH) reflects that during a difficult task.

In sum, the above-cited findings suggest that a single approach to problem solving is not used for a given task; rather, different approaches, reflected in shifts in direction of hemispheric advantage, are used at different levels of difficulty (and, perhaps, corresponding levels of processing).

It is simplistic, however, to generalize from these data and to assume that problem-solving approaches are limited to RH-based synthetic processing for easy tasks and LH-based analytic processing for difficult tasks for all individuals and for all tasks.

On the contrary, a high degree of individual variability in processing mode used to solve identical tasks, possibly related to cultural and occupational influences, has been demonstrated (Springer & Deutsch, 1985, chap. 11). Also, the opposite pattern, namely, a no/LH advantage during easy tasks and a RH advantage during difficult tasks, has been demonstrated in several studies described immediately below.

2. The no/LH to RH shift in advantage. First, this shift pattern emerged in the high-frequency range in the current study. Also, Umilta et al. (1978, cited in Koss, 1981) found that subjects displayed a LH advantage (in speed) when they discriminated among relatively less complex geometric figures and nonsense patterns; in contrast, they showed a RH advantage for more complex figures (e.g., polygons).

Fontenot (1973, cited in Koss, Ibid.) likewise presented random shape stimuli of varying degrees of complexity, but he used a recognition, rather than discrimination, task. He, too, found a RH advantage vis-à-vis highly complex shapes, but, unlike Umilta et al., observed no significant advantage for the low-complexity shapes.

Koss (Ibid.) found the same pattern of results as Fontenot with respect to a different visuospatial task: Her subjects demonstrated a RH advantage during a difficult line orientation task and no advantage during an easy version of the same task.

One hypothesis concerning the emergence of a RH advantage during the processing of complex visuospatial stimuli is that such stimuli are not easily verbally encoded and, hence, do not engage the LH for linguistic processing (Koss, Ibid.). Buffery (1974, cited in McQ.Reynolds & Jeeves, 1978) provided supportive data for this hypothesis. He found that stimuli that he had designated as "easy to verbalize" were better matched when presented in the RVF than in the LVF; "difficult to verbalize" stimuli, on the other hand, were better matched when presented in the LVF than in the RVF.

3. Conclusion. In sum, two opposing shift patterns in hemispheric advantage have been demonstrated with shifts in levels of task difficulty, namely, (a) a RH to LH shift and (b) a no/LH to RH shift. These changes have been attributed to (a) processing mode (synthetic/analytic), (b) processing level (sensory/cognitive), and/or (c) stimulus material (verbal/nonverbal). The current data suggest that stimulus spatial frequency range may be another determinant of these changes.

For example, just as the current study showed a RH to LH shift during low-frequency processing (when an easy checkerboard recognition task was changed to a difficult one), so did the RH to LH shift found in Ornstein et al.'s study occur during low-frequency processing (i.e., when an easy whole-whole [circle-circle] matching task was changed to a difficult part-whole matching task [arc-circle]).

Conversely, just as the current study showed a no/LH to

RH shift during high-frequency processing (also when an easy checkerboard recognition task was changed to a difficult one), so did the LH to RH shift found in Umilta et al.'s study occur during high-frequency processing (i.e., when an easy task involving discrimination among relatively less complex patterns was changed to a difficult task entailing complex polygon discrimination).

Further, this shift in hemispheric advantage with task difficulty as a function of frequency range provides a possible account of the different pattern of results in Sergent's and the current studies.

Within each frequency range, (a) the directions of hemisphere advantage during the easy tasks in the current study were identical with the directions of advantage in Sergent's (viz., a RH advantage for low frequencies and a LH for high), and (b) the directions of advantage during the difficult tasks in the current study were opposite to the directions of advantage in Sergent's (viz., [a] a LH advantage for difficult low frequencies [current] vs. a RH advantage for low frequencies [Sergent] and [b] a RH advantage for difficult high frequencies [current] vs. a LH advantage for high frequencies [Sergent]).

Hence, this comparison implies that Sergent's pattern may not have reflected the processing of low and high frequencies, but rather, that of low and high frequencies during an easy task (and possibly a lower level task; Sergent's visual search task and the easy checkerboard recognition task may have been less cognitively demanding than the difficult checkerboard recognition task). Further, the results of these two studies appear discrepant only if task difficulty is not taken into account; on the contrary, they are compatible when this factor is considered.

The reader is reminded that Sergent's spatial frequency model of hemispheric specialization proposes that direction of advantage varies with frequencies required by task demands. Hence, if the different directions of advantage for frequency found in Sergent's and the author's studies were shown to be due to task difficulty, then the current results would not be incompatible with the model.

Finally, a general consideration to keep in mind while evaluating data on this topic is that when different studies use identical stimulus parameters and procedural conditions except for level of task difficulty, then one should expect that their asymmetry patterns will differ. Rather than being contradictory, however, such differences are complementary: Each pattern represents spatial frequency processing at the particular level of difficulty tested; viewed as an ensemble, they reflect the different patterns of asymmetry that emerge during spatial frequency processing across a wide range of task difficulty.

<u>Magnitude of asymmetry</u>. Just as within-range shifts in direction of advantage may have been due to increasing task requirements, so may increases in magnitude of advantage have reflected increasing task demands (larger advantages

appeared during the more difficult than easier tasks [percent correct data]).

Three points should be noted in this regard. First, advantages were larger to the low (1.4-2 cpd) than to the high (2-2.8 cpd) frequencies, hence demonstrating that size of asymmetry also varies with frequency range. Thus, not surprisingly, a moderately sized, rather than small, advantage (VFAI data) emerged at the easy low frequency (F1), reflecting, not increasing asymmetry with decreasing difficulty, but rather increasing asymmetry as a function of the Range x Task Difficulty interaction (see Table 10).

Second, it was also not surprising that the magnitude of advantage was larger during the second most difficult task (F2) than during the most difficult one (F3). Whereas a large degree of unilateral activity may suffice for the solution of moderately difficult tasks, bilateral activity (due to the utilization of more than one strategy) may be required for the solution of exceedingly difficult tasks. When measured behaviorally, rather than electrophysiologically, such a "dual hemispheric advantage" appears as a small hemispheric advantage like the one found (in the VFAI measure) at F3 (see subsections 1.1/6 and 1.5/6).

Third, some electrophysiological data also support the "increasing asymmetry with increasing difficulty" hypothesis. Kok and Rooijakkers (1985) showed that the Slow Wave (SW) component of the ERP (i.e., the late endogenous component that emerges during a highly difficult task [Kok & Looren de Jong, 1980a, 1980b; Ruchkin et al., 1980, all cited in Ruchkin & Sutton, 1983]), was asymmetrically distributed over temporal (T3 and T4 sites) and parietal (P3 and P4 sites) cortex during word recognition in 20- to 32-year-old males and females. They further commented that lateral functional asymmetries in adults are reliably obtained when subjects perform difficult tasks.

In sum, both the current psychophysical data and some electrophysiological data suggest that increases in size of asymmetry may accompany increases in task requirements.

4/ Stimulus Familiarization (Hypothesis 5)

Direction of hemispheric advantage during spatial frequency processing varies not only with level of task difficulty and stimulus frequency range, but also with the subjects' degree of stimulus familiarization, that is, functional asymmetry during pattern-processing is a task-, range-, and time-dependent function.

The Experimental Manipulation of Stimulus Familiarization: Number of Trials

Degree of stimulus familiarization is determined by total number of trials (both practice and experimental). This number differed among Sergent's, Previc's, and the current studies; differences in degree of familiarization almost certainly contributed to their discrepant results. Rather than being contradictory, their variant asymmetry patterns reflected processing at different stages of the subjects' familiarization with the stimuli.

(Note. Sergent administered 54 practice, and 270 experimental, trials in one session; Previc did not specify whether practice trials were given and administered 1,536 experimental trials plus a replication of that amount over a four-session period; and the author administered no practice, and 360 experimental, trials in one session.)

Since number of practice trials affects total number of trials (and hence, degree of familiarization), differences in this factor alone can contribute to differences in direction of advantage at any point in time over the course of the session.

For example, at the onset of a given test session, advantage reflects (a) the processing of somewhat familiar stimuli if practice trials had been administered and (b) that of novel stimuli if they had not. Facial recognition studies have shown that the hemispheric advantage which tends to occur to moderately familiar stimuli (LH) emerges at the onset of testing when practice trials had been given, whereas the opposite advantage (RH) appears when they had not (see subsection 1.1/9).

Current Familiarization Effects

Direction of Advantage: A Tripartite Shift at F4

In the current study, the major time-related effect occurred at the easy high-frequency (F4) stimulus. An initial trend toward a RH advantage in the first block changed to a large LH advantage in the second and returned to the initial small RH trend in the third and fourth blocks. (The direction of asymmetry in the second half of the session prevented a significant cubic trend for frequency from being reached at that time.)

Because initial processing may reflect more about individual differences in hemisphericity than responses to the stimulus-at-hand, the Block 1 "novel stimulus" response is not analyzed herein.

The Blocks 2 and 3 responses are indicative of hemispheric activity during learning; these data showed that during the early phases of learning, direction of advantage during an easy spatial frequency recognition task varied with frequency range (i.e,. a RH advantage emerged in the low-frequency range, and a LH advantage, in the high). In contrast, as learning progressed, the former was independent of the latter (i.e., a trend toward a RH advantage appeared in both the low- and high-frequency ranges).

Finally, the Block 4 response, indicative either of continued learning effects or of a characteristic response to this stimulus, was the same as that in the Block 3.

Hence, the above-described tripartite sequence corroborated that found in other visual and auditory pattern discrimination and recognition studies, namely, (a) an initially variable advantage; (b) then a LH advantage; and finally, (c) a RH advantage (again, see subsection 1.1/9). Here, as in the literature, this particular sequence may reflect the utilization of an analytic processing strategy while becoming familiar with the stimulus followed by that of a synthetic strategy once the stimulus is known (Ross & Turkewitz, 1982; Ross-Kossak & Turkewitz, 1986; Turkewitz & Ross, 1983).

Magnitude of Advantage: An Increase During Early Learning

It is of interest to note that in addition to a directional change in advantage during the initial stages of familiarization, a change in degree occurred: Not only was the Block 2 advantage in the hemisphere opposite to those in the other three blocks, but also it was substantially larger. These two findings combined with one cited above, namely, magnitude of advantage increases with task difficulty, suggest that early learning may be the most difficult phase of stimulus familiarization; consequently, it may require a substantial amount of analytic processing.

Concluding Remarks

Because task difficulty is one determinant of direction and magnitude of asymmetry, changes in difficulty through time as a function of learning (i.e., one way of viewing changes in degree of stimulus familiarization) cause pattern and degree of functional asymmetry to be dynamic effects.

5/ Subject Characteristics: Gender

(Hypothesis 2)

Comparison Between Sergent's and the Current Methodological Factors Affecting Gender Data

Whereas Sergent's study revealed no significant gender differences, the current study reported gender differences in (a) the pattern of shifts in hemispheric advantage during stimulus familiarization and (c) performance. (Note. Previc is not included in this comparison because his sample was all-male.)

Since the precise respects in which males and females differ vis-à-vis visuospatial processing are not definitively known at the anatomical, physiological, or behavioral levels, it is difficult to specify why these two researchers found different gender effects. Possible reasons include the following:

1. Different sample sizes: Sergent's sample (6 subjects of each gender) may have been too small to reveal what may be a small effect, whereas the current sample (10 subjects of each gender) was apparently large enough to do so.

2. Different stimulus parameters: The intergender differences may have been related to the processing of the nonverbal and nonconfigurational dimensions of spatial frequencies present in the current stimuli and not present in Sergent's. Further, Sergent's stimulus presentation conditions (e.g., fluctuations in luminance level and small stimulus size) that resulted in less-than-optimal spatial frequency processing may have masked gender differences that, in fact, exist, but that require optimal stimulation of the visual system to be manifested.

3. Different tasks: The sources of these gender differences may have included the component processes of the same/different recognition judgements tapped in the current

task and not tapped in Sergents's visual search task.

4. Different dependent variables: The processes tapped by Sergent's speed and accuracy measures may not have differed between males and females, whereas those tapped by the current accuracy and sensitivity measures apparently did differ between the genders.

5. Different data analyses: The current study indicated that gender differences may be related to task difficulty and learning, and Sergent's data were not analyzed with respect to these two factors.

Current Gender Effects in Pattern of Asymmetry

The gender differences that emerged in the current study in pattern of asymmetry are as follows:

1. Females alone demonstrated the same familiarization effect as the total sample, namely, a RH advantage during the easiest recognition tasks independent of frequency (at F1 and F4) to highly familiar stimuli (in Block 4).

2. In the high-frequency range, the females showed the same shift pattern as the total group at the easy high frequency (F4), namely, (a) a LH advantage during stimulus familiarization (for females, this advantage was largest in Block 2 and almost nonexistent in Block 3) and (b) a RH advantage once the stimuli were familiar (Block 4).

Further, one point at which the gender difference was most apparent was Block 2. At this time, at the difficult high frequency (F3), females used a LH strategy, and males, a RH one; this dissimilarity resulted in a statistically significant difference between genders in the quadratic trend in frequency (females alone showed this trend).

Turkewitz and Ross-Kossak's Account of the LH to RH Shift in Advantage with Increasing Stimulus Familiarization

This pattern of results is consistent with those of Turkewitz and Ross-Kossak (1984); they likewise observed that relatively mature females show a LH advantage while becoming familiar with patterned (facial) stimuli and a RH advantage when familiar with those stimuli (see subsection 1.1/6). These investigators proposed that these advantages reflect (a) the utilization of an analytic strategy during the challenging learning phase and (b) that of an advanced synthetic strategy (the use of both external and internal cues as the basis for recognition judgements) during the easier phase (recognizing familiar patterned stimuli).

The task difficulty account of changes in advantage with increasing stimulus familiarization. This model suggests that the current results may have been due to changes in task difficulty inherent in the stimulus familiarization process, that is, this process represents a progressive reduction in task difficulty over the course of the session; shifts in hemispheric advantage reflect strategy changes required by these diminishing task demands.

Hence, in the current example, the large LH advantage (in Block 2) that decreased in magnitude (in "transitional" Block 3) and changed to a RH advantage (in Block 4) may have reflected decreasing task demands, that is, recognizing practically novel stimuli and becoming familiar with those stimuli (Blocks 2 and 3) are more difficult than recognizing known stimuli (Block 4).

Implications for Female Superiority in Facial Recognition

Although this model was formulated to account for females' facial recognition patterns, the current data suggest that it holds specifically for females' recognition of a narrow band of spatial frequencies (roughly 2-3 cpd). This latter result is not surprising in that Tieger and Ganz (1979) demonstrated that "2.2 cpd . . . appear to be relatively more important than other frequencies in the face recognition task" (p. 165).

(Note. These researchers found that grid masks of this value disrupted facial recognition more than grid masks composed of 0.54, 0.82, 1.1, and 3.9 cpd. This finding occurred under foveal stimulation conditions; hence, the 2.2 cpd value is slightly shifted from the most salient spatial frequency for facial recognition under parafoveal stimulation conditions, those required for lateralization research.)

Gender Differences in Performance (as Measured by Accuracy and Sensitivity)

The second gender effect, a trend which did not reach statistical significance, concerned performance during the entire session: (a) Males were more accurate than females, particularly at the difficult frequencies (F2 and F3), and (b) males demonstrated slightly greater sensitivity in the

RH than females at these same two frequencies. Females, on the other hand, displayed greater sensitivity in the LH than males at all frequencies.

Possible Underlying Processing Mechanism

The source of this gender reversal in superiority as a function of dependent variable was a gender difference in hit rates due to a gender difference in criterion placement (see Results section for description and numerical example; also see subsection 1.5/4 to review TSD paradigm).

The female pattern. Their inferior performance in both hemispheres in accuracy and superior LH performance in sensitivity occurred because, to RVF presentations, they set lower criteria than males; they therefore reported "Different" less frequently and "Same" more frequently than males.

This response pattern resulted in females' yielding (a) a smaller number of correct rejections (reporting "Different" when TES and TAR were different), that is, a lower accuracy rate; (b) a greater number of hits (reporting "Same" when TES and TAR were the same); and (c) a larger d' than males.

The male pattern. The inverse situation describes their pattern, namely, superiority in both hemispheres in accuracy and inferiority in LH sensitivity. It appears that, to RVF presentations, males set higher criteria than females; they therefore reported "Different" more often and "Same" less often than females. Consequently, males yielded (a) more correct rejections, that is, a higher accuracy rate; (b) fewer hits; and (c) a smaller d' than females.

Theoretically, a greater male than female false alarm rate (reporting "Same" when TES and TAR were different) to RVF presentations could also underlie the smaller male LH d' score; in actuality, however, this situation could not have occurred. Because the male correct rejection (accuracy) rate exceeded that of the females, the male false alarm rate (unity less the number of correct rejections) was necessarily smaller than the females'.

Summary. Thus, higher male than female accuracy and lower male than female LH sensitivity were due to the males' maintenance of a higher criterion, with respect to RVF stimulus presentations, than the females'. This pattern of criterion placement resulted in the males' maintaining their superior accuracy rate while simultaneously yielding a lower hit rate and a lower d' score than the females.

Relationship Between Current and Past Findings

Male visuospatial superiority. Next, concerning the relationship between the current data and the gender differences reported in the information-processing literature, the current finding of a trend towards greater male than female accuracy supports the hypothesis that males are superior to females in visuospatial processing.

Further, because visuospatial processing is putatively mediated in the RH, the other finding of a trend toward higher male than female sensitivity in the RH suggests that the processes reflected in d' contribute to this male visuospatial superiority. (Note. The reader is reminded that d' in a recognition task measures the capacities [a] to discriminate and [b] to compare present with past stimuli, i.e., perform a template match.)

Smaller degree of lateralization in females. Next, the trend toward higher sensitivity in the LH than in the RH in females supports the hypothesis that females' brains are less lateralized than males'. This result, demonstrating that the processes reflected in d' during the current visuospatial task are slightly more efficiently performed in the LH than in the RH, undermines the classical functional asymmetry model (RH mediation of visuospatial, and LH mediation of verbal, processing) for females.

Concluding Comments

It is important to remember that although some gender differences were found in the current study, they were extremely small effects. First, differences in pattern of asymmetry emerged only in one instance, namely, during stimulus familiarization. In contrast, no gender differences occurred in pattern of asymmetry for the total session. (The reader is reminded that, as in the total sample, [a] accuracy and sensitivity for both genders were greater at F1 and F4 than at F2 and F3, and [b] accuracy and sensitivity for both genders were greater in the LH than in the RH at F2 and in the RH than in the LH at F3.)

Second, the gender differences which emerged in performance (as measured by percent correct and d') were trends that did not reach statistical significance. Third, no significant differences in magnitude of asymmetry were found.

Both the size and types of gender effects found herein were not surprising. As Springer and Deutsch (1985) noted, gender differences in functional asymmetry may be "small in magnitude and easily masked by individual variability" (p. 183); they therefore require large samples to be detected.

Other reasons the current results were not surprising are listed in the Expected Results subsection; the reader is referred to that discussion.

4.2] RECOGNITION PROFICIENCY: DETERMINANTS OF THE EFFECTS OF DEGREE OF ASYMMETRY AND FREQUENCY RANGE ON PERFORMANCE

1/ The Effect of Lateralized Processing on Performance Depends on Task Difficulty (Hypothesis 4)

To review the results concerning Hypothesis 4 (lateralized processing during pattern recognition correlates with improved accuracy), (a) strong positive correlations were found for the two most difficult tasks, (b) no correlation existed for the second easiest task (recognition at F4), and (c) a negative correlation emerged for the easiest task (recognition of F1).

Hence, the current study found that unilateral processing helped performance during spatial frequency recognition, just as it did during (a) facial and shape recognition and (b) line orientation discrimination (see subsection 1.1/6), but it did so as a function of task difficulty.

Familiarization Effects

Second, to review the familiarization effects relevant to this hypothesis, the above-described pattern was relatively invariant throughout the session: (a) It emerged in each block (except Block 3 in which the positive correlation at F2 was the only significant correlation), and (b) the correlations were of approximately the same value in each block.

The Block 3 pattern was not surprising because this period was a transitional one between relatively difficult (Block 2) and easy (Block 4) phases of stimulus familiarization. Because F2 was the only stimulus for which a substantial advantage existed, it follows that F2 was the only stimulus at which hemispheric advantage improved performance. (Almost no advantages existed at the other three frequencies because, at F3 and F4 at least, they were in the process of shifting to the opposite hemisphere.)

(_Note_. [a] Because Previc found no significant lateralization effects during spatial frequency processing and Sergent did not analyze her data with respect to the correlation between degree of lateralization and performance, comparisons between the current findings and theirs are not made herein.

[b] The reader is referred to subsection 1.1/6 to review the rationale and evidence for the hypothesis addressed

herein; subsection 1.5/6 to note the ways in which these findings are consistent with the predicted ones, and Table 10 to review [a] the direction and magnitude of advantage and [b] the effect of magnitude of advantage on proficiency as a function of task difficulty.)

Task Difficulty Effects

Both the ANOVA (see subsection 4.1/3) and Pearson-r data suggest that more difficult spatial frequency recognition tasks require relatively large asymmetries for their solution (see subsection 4.1/3 for an account of the larger asymmetry during moderately difficult than maximally difficult tasks). Further, the directions of these asymmetries were shown to vary with spatial frequency range: A LH bias emerged during difficult low-frequency recognition tasks, and a RH bias, during difficult high-frequency ones.

In contrast, the solution of easier spatial frequency recognition tasks does not seem to require strong unilateral activity (see subsection 4.1/3 for an account of the moderately sized F1 advantage [VFAI measure]).

Further, the ANOVA and Pearson-r data suggest that the high accuracy rates at the easy frequencies (F1 and F4) were due, not to the utilization of the range-specific cognitive strategies (viz., a RH-based strategy at the easy low frequency [F1] and a no/LH-based strategy at the easy high frequency [F4]), but rather to the high sensitivity levels that the subjects displayed at these frequencies.

Summary

Thus, when examined together, the data yielded by the ANOVAs and correlation analyses suggest that the successful solution of difficult tasks requires processing of a quantitatively and qualitatively different order from that required by easy ones: The former demands (a) a greater amount of the processing mode being used than the latter and (b) the use of the processing mode opposite to that used by the latter in the same frequency range.

The current data thus suggest that the effect of asymmetrical processing on performance varies not only between tasks (Kimura [1985]; Springer & Deutsch [1985, chap. 7]; see subsections 1.1/4 and 1.1/6), but also between levels of difficulty within the same task.

2/ The Effect of Frequency Range on Performance Depends on Task Difficulty (Hypothesis 3)

The demonstration that accuracy to low spatial frequencies exceeds that to high would support Hypothesis 3 (low spatial frequencies are sufficient for accurate pattern recognition [Harmon, 1973]). As can be seen in Table 10, the current study did show this pattern of results under a particular condition, namely, when the tasks involving the low and high frequencies were of roughly the same level of difficulty.

Conversely, accuracy to high frequencies exceeded that to low when the task involving the former was easier than that involving the latter. Hence, as predicted, the current study showed that proficiency was a function of the

Frequency x Task Difficulty interaction as follows: Easier tasks yielded higher accuracy rates than difficult ones; within each of those pairs, accuracy to the lower frequencies surpassed that to the higher ones.

These data thus showed the task difficulty dimension to be of greater salience than that of spatial frequency range in the determinination of recognition accuracy. Hence, differences in task difficulty in the various studies concerning the effect of frequency range on proficiency (see subsection 1.2/5) probably contributed to their contradictory findings.

(*Note*. Because Sergent and Previc did not analyze their data with respect to this hypothesis, their studies are not compared with the current one herein.)

4.3] CONCLUSIONS CONCERNING LATERALIZATION AND PATTERN RECOGNITION PROCESSING AND PROFICIENCY

1/ Analysis of the Effects Found in the Current Study

Examination of the methodological factors influencing hemispheric specialization for spatial frequency recognition has revealed the following:

Dependent Variable Effects (Hypothesis 1)

Various types of speed and accuracy measures "are not necessarily equivalent expressions of lateral differences," that is, hemispheric advantage varies with dependent variable. A given advantage reflects, not overall hemispheric superiority, but superiority only with respect to the aspect(s) of processing measured by the particular dependent variable(s) used.

The Sensitivity Component of Hemispheric Advantage and Gender Effects on Sensitivity (Hypotheses 1 and 2)

Hemispheric advantage was attributed in large part to sensitivity (the level of responsivity at the sensory and/or template match processing levels).

Further, pattern of asymmetry with respect to sensitivity was found to be gender-specific: Sensitivity in the RH exceeded that in the LH in males, whereas the reverse pattern emerged for females. These data suggest that (a) male superiority in visuospatial processing is partially due to greater sensitivity in the hemisphere mediating such processing, and (b) degree of functional asymmetry in females may be smaller than that in males because the LH may be more involved in visuospatial processing in females than in males.

Hemispheric advantage was also found to depend on gender-specific criterion placement: Males maintained a higher criterion with respect to RVF presentations than females; consequently, LH performance in males was characterized by a higher accuracy rate, lower hit rate, and lower d' score than in females.

Frequency and Task Difficulty Effects on Hemispheric Advantage, the Asymmetry-Proficiency Relationship, and Proficiency (Hypotheses 1, 3, and 4)

The direction and magnitude of hemispheric advantage; its effect on recognition performance; and recognition performance itself may be a function of the Spatial Frequency x Task Difficulty interaction. (*Note*. Although the current data suggest this hypothesis, it must be tested by a study in which each of these factors is independently manipulated).

Task Difficulty and Cerebral Asymmetry

The Frequency x Task Difficulty interaction effect was expected because more difficult tasks make significantly different processing demands and, consequently, engage the hemispheres in different ways than easier ones.

Relatively difficult tasks may require (a) cognitive processing (e.g., conceptual, linguistic, and memory processing), (b) use of the analytic approach to problem solving, and/or (c) nonverbal processing (when task difficulty is due to the stimuli's being difficult to verbalize). In contrast, easier tasks may primarily involve (a) sensory processing, (b) use of the synthetic approach to problem solving, and/or (c) verbal processing (when a given task is easy because the stimuli are easy to verbalize).

Memory processing provides a straightforward example of hemispheric involvement as a function of task difficulty. Because recognition memory processing putatively entails template matching, the hemisphere that mediates the processing of the template frequencies is involved in recognizing (as opposed to detecting or discriminating) the stimulus frequencies. Hence, as Sergent's, Previc's, and the author's data suggest, hemispheric advantages during spatial frequency recognition differ from those during spatial frequency discrimination. Their data further suggest that within each of those tasks, advantages during more difficult problems differ from those during easier ones.

The current study suggests that difficult spatial frequency recognition tasks may require processing of a qualitatively and quantitatively different order than easier ones:

1. Hemispheric advantages found during the former were opposite to those found during the latter in the same frequency range (viz., a LH advantage was found for the difficult recognition task in the low-frequency range, and a RH advantage, for the difficult high-frequency task; the advantage opposite to each of these was found for the easy task in each frequency range).

2. Hemispheric advantages during the difficult tasks were found to be larger than those during the easy ones (i.e., magnitude of advantage covaried with task difficulty).

Task Difficulty, Cerebral Asymmetry, and Proficiency

Next, lateralized processing may be beneficial to recognition accuracy during more difficult tasks. Hence, the effect of this type of processing on proficiency may vary not only between tasks, but also between levels of difficulty within the same task.

Task Difficulty and Proficiency

Finally, concerning recognition accuracy itself, task difficulty was of greater salience than spatial frequency range in determining accuracy rate: Accuracy was greater to easy than to difficult tasks; within each of those pairs, accuracy to lower frequencies surpassed that to higher ones.

Familiarization Effects and Gender Effects Therein (Hypotheses 2 and 5)

Direction and magnitude of hemispheric advantage are dynamic: Between 2 and 3 cpd, at least, they were shown to shift from a large LH advantage to a small RH advantage as stimulus familiarization increased, and task difficulty decreased, throughout the session. Greater difficulty during the early phase of learning may have required a LH-based analytic strategy, whereas lesser difficulty after the stimuli were familiar may have elicited a RH-based synthetic strategy.

This pattern emerged for (a) the total and female samples in the current checkerboard recognition task and (b) female adolescents during a facial recognition task (Turkewitz & Ross-Kossak, 1984). Because 2-3 cpd are the salient frequencies in facial recognition (Tieger & Ganz, 1979), the current finding suggests that the stimulus familiarization effect observed by Turkewitz and Ross-Kossak was due to familiarization with respect to the spatial frequency dimension of their facial stimuli.

2/ Considerations Regarding Future Research on Hemispheric Specialization During Spatial Frequency Recognition

The current analysis of the procedural conditions affecting asymmetries during spatial frequency recognition has also revealed that the following factors need be considered in the design of future studies on this topic:

1. To assure that the entire range of spatial frequencies presented is processed and, hence, that the respective lateral sites underlying that processing are activated, (a) luminance must be kept constant at a moderate photopic level, (b) contrast must be held constant at a relatively high level, (c) stimulus duration must range betweeen 150-200 ms, and (d) the retinal site stimulated must be relatively large.

2. The following factors must be independently manipulated to specify the determinants of pattern and degree of functional asymmetry during spatial frequency processing: (a) verbal and nonverbal stimuli, (b) sensory (detection and discrimination) and cognitive (recognition and identification) tasks, and (c) nonconfigurational and configurational stimuli.

Each element in each of these pairs makes specific processing demands and, consequently, engages the hemispheres in ways specific to that type of processing. The first two factors were mentioned earlier in this subsection.

Stimulus Configuration and Direction of Advantage

Regarding the third factor, cognitive strategy utilization and, hence, hemispheric advantage, vary with stimulus configuration: A RH-based synthetic strategy is often used to process the structural dimension of a given stimulus, and a LH-based analytic strategy, its nonstructural aspects (e.g., internal details).

Further, hemispheric mediation of particular frequencies may depend on the interfrequency relationship, rather than the frequencies per se, inherent in a given configuration; hence, direction of advantage may vary between patterns. For example, at least 5.5 cpd were required to engage the LH during the processing of a facial pattern (Ginsburg, 1978, cited in Previc, 1982), whereas 1.7 cpd yielded a LH advantage during the processing of a checkerboard pattern (current study).

(Note. The effect of stimulus configuration on direction of hemispheric advantage is further discussed in subsection 4.4/1.)

4.4] CRITIQUE OF THE CURRENT FORMULATION OF THE SPATIAL FREQUENCY MODEL OF HEMISPHERIC SPECIALIZATION

In addition to the strengths of Hypothesis 1 (see Expected Results subsection), its major weaknesses are:

1. It is incorrect with respect to the argument that hemispheric specialization for spatial frequency underlies hemispheric specialization for cognitive functions.

2. It is ambiguous concerning the issue of whether hemispheric specialization is for (a) spatial frequencies relative to one another, that is, the global/local structural levels of a patterned stimulus, or for (b)

spatial frequencies per se, that is, different-sized stimuli.

3. It is ambiguous regarding the processing level at which hemispheric specialization for spatial frequency emerges.

4. It does not specify the neural mechanism underlying such specialization.

Regarding the first point, psychophysical data (see subsections 1.2/5, 4.2/2, 4.3, and 4.4/1) have disproved the argument that the RH mediates nonverbal processing because low frequencies, more efficiently processed in the RH than in the LH, are sufficient for the discrimination and recognition of nonverbal stimuli. Low frequencies are not always sufficient for these types of tasks vis-à-vis nonverbal stimuli. On the contrary, the frequency range required to recognize and identify nonverbal stimuli probably varies with stimulus and task parameters.

Also regarding the first point, psychophysical data (see subsection 4.4/1) have also disproved the argument that the RH mediates holistic processing because low frequencies, more efficiently processed in the RH than in the LH, are sufficient for form processing. Low spatial frequencies do not necessarily carry form information; hence, a RH superiority in low-frequency processing does not necessarily assure a RH superiority in holistic processing. This confounding of size and form, referred to in logic as a category mistake, is discussed in the following subsection.

(Note. Of course, for the cases in which low frequencies do carry form information, this argument is correct.)

Concerning the second point, Sergent's model implies that the hemispheres are differentially sensitive to low and high frequencies per se, but her experiments test the asymmetrical processing of low and high frequencies organized into a configuration. As mentioned in the Expected Results and Stimulus Parameters subsections, the latter involves both sensory (spatial frequency) and cognitive (figure-ground, embedded figure, and structural level [part-whole relationships]) processing, whereas the former entails sensory (spatial frequency) processing alone.

With respect to the third point, specification of processing level at which hemispheric specialization for spatial frequency emerges is critical because such specialization is for the frequencies constituting the neural representations at that level, not for the input frequencies. As mentioned in the Stimulus Parameters subsection, the frequencies at the two levels differ due to convolution during visual processing.

Regarding the closely related third and fourth points, the current hypothesis is meaningless unless a neural mechanism (at a particular processing level) for the differential lateral processing of spatial frequency exists. Subsection 4.5 reviews the anatomical, physiological, and behavioral literatures regarding where the asymmetrical processing of spatial frequency might emerge in the brain.

Other asymmetries that might affect the net asymmetry for spatial frequency are included herein. Finally, hypothetical neural mechanisms underlying the asymmetrical processing of spatial frequency, both in terms of structural levels (global/local) and size (large/small), are suggested.

The net effect of the above-described ambiguities is that researchers are testing different hypotheses (without acknowledging the differences and the rationale for their being tested). For example, Sergent tested hemispheric specialization for global/local processing where global and local differed along the structural dimension; in contrast, Previc tested such specialization for global/local processing where global and local differed along the size dimension. Hence, the four issues listed above should be clarified before further experiments are designed.

1/ RH Superiority in Low-Frequency Processing Does Not Unconditionally Assure RH Superiority in Holistic Processing

> "If one considers that the cerebral hemispheres diverge in the degree of sensory resolution of the incoming information to which they are preferentially sensitive, it would appear that analytic processing is more probable in the LH and holistic processing is more likely in the RH. This does not require basically different processes in each hemisphere, but rather may imply similar processing applied to different neural representations." (Sergent, 1982a, pp. 267-268)

The current susbection critiques the above argument that differential hemispheric sensitivity to spatial frequency underlies hemispheric specialization for cognitive strategy. Defining the major concepts in this argument is required prior to evaluating it.

Definitions of Important Terms

To briefly review, low and high spatial frequencies refer to the sinusoidal constituents of large and small sizes, respectively (see subsection 1.2). Holistic and analytic processing refer to the use of different units (levels of structure) of a stimulus as cues for the solution of a given problem concerning that stimulus.

The unit used during holistic processing is the stimulus configuration (relative disposition or arrangement of parts) or gestalt (a unified whole; an organized field having specific properties that cannot be derived from the summation of its component parts); that used during analytic processing is the stimulus feature or part (a portion or division of a whole that is separate; piece; fragment, fraction or section; constituent) (definitions are cited from The Random House Dictionary [Urdang, 1968]).

Hence, holistic processing operates on the structure (gestalt) formed by the nonlinear spatial integration of its components (Embree, 1981; Hughes, 1982; Husserl, cited in Edie, 1981; Pedelty et al., 1985), that is, on a whole that is qualitatively different from its constituent parts and size-independent:

> "A gestalt is a whole (ensemble) which . . . has parts . . . within it such that if all the parts are, say, doubled in size, there is the same gestalt, but if one part is changed, there is a different gestalt." (Embree, 1981, p. 93)

Evaluation of the Argument for the Sensory Foundation of Cognitive Strategies

Reiteration of the Argument

Now that cognitive strategies have been defined, Sergent's suggestion that low-frequency and holistic processing occur in the RH, and high-frequency and analytic processing occur in the LH, can be examined. The fundamental logic of this argument is as follows:

1. If large representations are most efficiently processed at the sensory level in the RH (and small representations, in the LH); and

2. if large representations carry configurational information (and small representations, feature information), then

3. configurational information is most efficiently processed at the cognitive level in the RH (and feature information, in the LH).

This argument thus proposes that the mode and lateral location of cognitive strategies have sensory determinants, namely, (a) the sizes of the stimulus representations upon which they operate and (b) the cerebral region in which those sizes are most efficiently processed.

Hence, holistic processing is RH-based because large representations, putatively conveying configuration (form) information, are more proficiently processed in the RH; conversely, analytic processing is LH-based because small representations, putatively carrying stimulus feature information, are more efficiently processed in the LH.

Critique of the Argument

The weaknesses of this argument include the following. Whether the low frequencies, putatively describing form, and the high frequencies, putatively representing features, are low and high in an absolute sense or low and high relative to one another, is not explicitly stated.

1. If they are used in an absolute sense, then (a) the respective ranges need be stated, and (b) the argument need be modified because holistic strategies may be used to process absolutely small representations, and analytic strategies, absolutely large ones.

2. If they are used in either an absolute or relative sense, then the argument requires modification because low frequencies, in either case, do not unconditionally carry form information. Conflicting data exist concerning the sinusoidal components of form.

Some data report that low frequencies define form (see Previc, 1982, for citations); others, that either low or high may define stimulus "unity" (Moore, 1985); others, that relatively high define it (Klymenko & Weisstein, 1985; Wong & Weisstein, 1985); and yet others, that the relation between frequencies defines it (see definitions immediately above). Whatever the case, form, rather than size, may determine selective cognitive strategy utilization.

<u>Cognitive strategy and stimulus size</u>. Concerning point (1b), holistic strategies may be used to process small representations, and conversely, analytic processes may operate on large ones. Configuration is not synonomous with

large (i.e., the shape created by the spatial relationship among features may be small), and feature is not synomonous with small (i.e., the elements of a given form may be large). Both holistic and analytic strategies may be used to recognize a visual stimulus characterized by very large features (e.g., windows in a skyscraper) or by a very small form (e.g., a picture postcard).

As is suggested in the discussion of the second point below, the selective utilization of these strategies may be structure-dependent rather than size-dependent. For example, a holistic strategy is often used to recognize an upright face, that is, one with a familiar configuration, whereas an analytic strategy is used to recognize an inverted face, that is, one without a familiar configuration, of the same size.

The sinusoidal components of form.

1. Psychophysical data. Concerning the second point, as mentioned in subsection 1.2/5, Moore (1985) found that low frequencies do not necessarily convey unity information. Rather, Moore found the relationship between frequency range and unity to be stimulus-specific: In fragmented paintings, low frequencies convey a sense of unity, whereas in unified paintings, high frequencies carry unity information.

Also concerning the second point, Weisstein and her colleagues showed psychophysically that the relatively high spatial frequencies in a given pattern are perceived as figure, and the low frequencies, as ground.

For example, when a disc-and-annulus pattern in which the disc was composed of higher frequencies than the annulus was presented, the disc was perceived as the figure; conversely, when the annulus was composed of higher frequencies than the disc, the annulus was perceived as figure (Wong & Weisstein, 1985). The presentation of an ambiguous figure (the Rubin face/goblet pattern) yielded the same results (Klymenko & Weisstein, 1985).

These findings suggest that form information is carried by relatively high frequencies rather than by absolutely or relatively low frequencies as is purported in the current argument.

<u>2. The configuration-frequency relationship</u>. A final issue regarding the second point listed above is raised by the definitions listed at the beginning of this subsection, namely, stimulus configuration is not necessarily synonomous with low spatial frequency: It may be synonomous with the interrelationship between frequencies of any value. How configuration and frequency are related is currently unknown, as was conveyed by Hughes' (1982) recent inquiry as to whether the perception of global pattern configuration relates to spatial frequency-specific channels.

It is probable that the processing of configuration (the relationship between features) differs from that of low frequencies (large features). Whereas the former involves nonlinear summation, the processing of spatial (positional) information, and that of integral properties of a given stimulus, the latter entails linear summation, no spatial processing, and the processing of separable stimulus properties.

In addition, the former may engage a different "functional stream" of the visual system (Ungerleider & Mishkin, 1982, cited in Gattas et al., 1985, p. 16; see subsection 1.2/3) than the latter. Form perception (and the closely related process of figure-ground differentiation) entails localization processing, whereas feature perception involves pattern discrimination.

The neural substrates of localization (and hence, form perception) and discrimination (and hence, feature perception) in the visual system may differ at the cellular, regional, and hemispheric levels (see subsection 1.2/3) (e.g., the Y-cell system may be relatively more involved in form perception, and the X-cell system, in feature perception).

Confounding of "Gestalt" and "Large" is a Category Mistake

This confounding of global structure (interfrequency processing) and global size (low-frequency processing) is referred to in logic as a category mistake, that is, the representation of X as if it belongs to one logical type (category) when it actually belongs to another.

If, while reading the following anecdote, the reader imagines that the university symbolizes global structure and the institutions, global size, he/she will better understand the way in which the confusion of global structure and size constitutes a category mistake:

> "[A visitor is shown colleges, libraries, playing fields, museums, scientific departments and administrative offices.] `But I have not yet seen the University.' `The University is not another collateral institution . . . . [It] is just the way in which all that he has already seen is organized. When they are seen and when their coordination is understood, the University has been seen. His mistake lay in his innocent assumption that it was correct to speak . . . as if `the University' stood for an extra member of the class of which these other units are members. He was mistakenly allocating the University to the same category as that to which the other institutions belong.'" (Ryle, 1949, p. 16)

The origin of this category mistake in the current context (both the Sergent [1982a] study, in particular, and the global/local literature-at-large assume that large is synonomous with gestalt) is thoroughly understandable for the following two reasons:

1. The term configuration, one of the English translations of the German term gestalt, has a definition besides the one cited above. This second definition is "external form" (The Random House Dictionary [Urdang, 1968]), a notion that connotes shape and outline (composed of low spatial frequencies) as opposed to the interrelationship of parts (composed of a wide range of frequencies).

2. A substantial amount of psychophysical data (see subsection 1.2/5) have suggested that low frequencies convey form information.

Different connotations of the holistic unit. Hence, the first point suggests that the unit used during holistic processing is ambiguous. Although, historically, the organized whole, not the outline, was initially considered to be the holistic unit (Kohler, 1940), the outline has been deemed the object of holistic processing by some more recent researchers.

To further complicate this issue, a third connotation of this unit, namely, pattern constituents with "configurational properties" (Pedalty et al., 1985, p. 434), is sometimes used. Examples of this third type of unit are face width and nose-lip distance in a facial pattern. These features have "configurational properties since they involve spatial relations among several parts of the face" (Ibid.). (Note. This third connotation was used by Carey, 1978, and defined by Carey & Diamond, 1980, both cited in Pedelty et al., 1985).

Local precedence and form information. Concerning the second point, the fact that limits to the global precedence model (Navon, 1977) have been shown (viz., global aspects of a stimulus are not recognized prior to local ones when the former are larger than an optimal angular size [Kinchla & Wolfe, 1979], distorted [J. Hoffman, 1980], or presented for long durations [Paquet & Merikle, 1984]; see subsection 1.2/4) may have the following implications for form perception:

1. If low frequencies carry form information partially because low frequencies are processed faster than high; and

2. if, under certain conditions (e.g., the three stated above), high frequencies are processed as fast as or faster

than low, then

3. under those conditions, high frequencies may carry form information.

Complementary relationships among the holistic units. Identifying (a) the unit of holistic processing and (b) the spatial frequencies constituting that unit are empirical issues; thus, studies should be designed to resolve this problem. What may be found is that the above three holistic units are complementary rather than contradictory, that is, each type of unit is used during holistic processing in a different situation.

For example, Ross-Kossak and Turkewitz (1986; Turkewitz & Ross, 1983; Turkewitz & Ross-Kossak, 1984) have suggested that during facial recognition, more than one type of holistic strategy, the utilization of which depends on degree of stimulus familiarization, may exist: The first type, the primitive synthetic strategy, used to process unfamiliar stimuli, uses the "configuration-as-outline" unit; the second type, the advanced synthetic strategy, used to process familiar stimuli, uses the "configuration-as-gestalt" unit.

Conclusion

In sum, "it is necessary to clarify what is meant by `configurational'. The term has been used differently by various investigators" (Pedelty et al., Ibid., p. 434). Such clarification could be derived from studies designed to specify the conditions under which (a) different spatial frequency ranges and (b) the interrelationship between frequencies define stimulus form (and hence, constitute the units used during holistic processing).

Once these data are known, Sergent's argument that the RH mediates holistic processing because low frequencies, more efficiently processed in the RH than in the LH, are sufficient for form processing, can be appropriately modified, that is, the conditions under which it is true can be specified.

4.5] EMERGENT LEVEL OF HEMISPHERIC SPECIALIZATION FOR SPATIAL FREQUENCY RECOGNITION

At present, the processing level during which, the cerebral locus in which, and the cerebral mechanism by which the asymmetrical processing of spatial frequency during recognition might occur are unknown.

The current subsection (a) presents anatomical, physiological, and psychophysical data concerning asymmetries in the resting EEG and at the sensory-perceptual and cognitive levels of information-processing that may influence the direction and/or magnitude of the net asymmetry yielded during spatial frequency recognition; and (b) suggests hypothetical neural mechanisms of asymmetrical spatial frequency processing.

The following points regarding the content of this subsection should be noted at the outset:

1. Although motor asymmetries might influence the net spatial frequency asymmetry, they are not discussed herein;

this dissertation discusses the processing of input spatial frequencies from detection through recognition, but does not discuss output production.

2. The anatomical, physiological, and psychophysical literatures are being examined because an asymmetry may be present in one type and not in another. For example, a given cerebral region involved in spatial frequency recognition may be symmetrically organized, but asymmetrically activated; hence, a physiological, but not an anatomical, measure would detect this source of asymmetry.

3. The anatomical data are categorized into sensory-perceptual or cognitive level on the basis of cerebral region: Striate and peristriate cortex is the site of sensory-perceptual processing; PTO cortex, of intermodal association processing; and IT cortex, of visual recognition processing.

In contrast, the physiological and psychophysical data are categorized into sensory-perceptual or cognitve level on the basis of task. For example, passive viewing during VEP recording and discrimination during a psychophysical study represent sensory-perceptual processing, whereas problem-solving during VEP recording and recognition during a psychophysical study represent cognitive processing.

4. To the best of the author's knowledge, no pharmacological asymmetries exist within cerebral regions involved in visual pattern recognition processing; hence, their omission from subsections 4.5/1-3.

1/ Intrinsic Asymmetries: The Resting EEG

Definitions of Terms

As mentioned above, EEG represents spontaneous cerebral electrical activity, putatively driven and coordinated by the subcortical "pacemaker," the thalamus in the brain stem. In normals at rest, overall EEG is bilaterally synchronous or mildly desynchronous (Jasper, 1937, cited in Glanville & Antonitis, 1955) with respect to amplitude, latency, and waveform. Marked EEG asymmetries may indicate (a) such state changes as arousal and sleep in normals (Bremer, 1958; Diamond, 1972) and (b) such abnormalities as lesions (Rossi, 1963, cited in Dimond, 1972).

Spectral analyses of EEG have revealed normal asymmetries in two component frequencies predominant in visual sensory and/or association cortex. Brief descriptions of these components followed by the precedent data concerning their lateralized distributions are presented immediately below.

The Alpha Rhythm

The alpha (Berger) rhythm (α) (6-14 Hz), predominant in occipital cortex (primary [sensory] and secondary [intramodal association area] visual cortex), is the dominant EEG rhythm in relaxed, awake adults.

Unlike other EEG components, a decrease in α activity reflects its involvement in a particular function. Such activity is maximal in an organism not engaged in visual processing (e.g., with closed eyes) and decreases during visual stimulation; it is associated with such aspects of cognitive processing as attention and problem-solving (Adrian & Matthews, 1934; Aird & Gastaut, 1959; Galin & Ellis, 1975; Ray & Cole, 1985).

Occasional α asymmetries are considered normal, but persistent amplitude asymmetries of this component may be clinically significant (Katz & Cracco, 1971).

The Slow Posterior Rhythm Predominant in Youth

As its name implies, this rhythm (3-4 Hz) decreases in incidence with age (it is found in normal 6- to 26-year-olds). It is prevalent in the PTO region (tertiary [intermodal] visual association cortex), and, in normals, is sometimes asymmetrically distributed such that its amplitude in the RH exceeds that in the LH (Katz & Cracco, 1971).

Precedent Data Concerning Asymmetries in Two Components of the Resting EEG

The slow posterior and α rhythms were analyzed in clinical experimental (8,000 6- to 25-year-old males and females with primarily neurogenic abnormalities) and normal control (500 19- to 22-year old males) populations (Aird & Gastaut, 1959).

The α Rhythm

Occipital α was found to be symmetrical in 82% of both populations; slightly asymmetric in 17% (75% showed a RH predominance, and 25%, a LH predominance); and markedly asymmetric in 1%. Clinical abnormalites were also found in subjects in the third group listed herein. The investigators concluded that

> "marked differences of potential, if consistent, and especially if associated with homologous asynchronism, as well as asymmetries of form and frequency, probably reflect . . . focal (epileptic) processes." (p. 641)

This finding of α symmetry in the majority of humans replicates that of Adrian and Matthews (1934). When they recorded over homologous occipital sites in each hemisphere, they found that

> "the waves are now almost identical, the potentials at either side rising and falling simultaneously with reference to the occiput. This result (from four subjects) makes it unlikely that there is much difference in the phase or extent of the beat in the right and left hemipheres, though occasionally the waves are found to increase in size for a few beats on one side and decrease correspondingly on the other." (p. 366)

Adrian and Yamigawa (1935) and Raney (1939) found a similar "alternating dominance" pattern in normal α activity.

<u>The Slow Posterior Rhythm</u>

Aird and Gastaut also found that the slow posterior rhythm, which appeared in 17% of the 6- to 25-year-old abnormal subjects, 10% of the 16- to 25-year-old abnormals, and 10% of the 19- to 22-year-old normals, was symmetrical in half of the cases and asymmetrical (with a RH predominance) in almost the entire other half.

Finally, since this rhythm did not significantly correlate with any clinical factor in abnormals, occurred equally often for the same-aged subjects in both the experimental and control groups, and appeared more frequently in younger than in older subjects, it was interpreted to reflect normal EEG maturation.

Summary

Both symmetry and slight asymmetry are considered normal patterns for occipital α and slow posterior rhythms, with symmetry being far more common. Within normals, (a) α symmetry is four times more frequent than α asymmetry, with the majority of asymmetries showing a RH bias; and (b) slow posterior symmetry occurs equally often as slow posterior asymmetry, also with a RH bias. Finally, the incidence of the latter wave decreases with age.

(Note. If and how this variability correlates with handedness is unknown, as handedness data were not systematically collected for these subjects. These researchers noted, however, that LH predominance correlated with sinistrality in several cases.)

In sum, these data show that prior to the onset of a subject's engaging in a visual pattern recognition task, EEG activity in visual cortical regions may intrinsically prime the RH in a small group of normals, the LH in an even smaller group, and contribute equally to both hemispheres (with occasional asymmetries) in a larger number of normals.

Such activity is not constant throughout the lifespan, however, as one of these EEG components disappears during adolescence or early adulthood, the particular time varying between individuals, in normals.

2/ Asymmetries at the Sensory-Perceptual Processing Level

"One can assume that sensory function is symmetrical and

> that the neural output from the visual sensory areas to other cortical structures is similar in both hemispheres. This implies that qualitatively similar processing can be achieved at the same time in the right or the left field, and one may wonder what purpose it would serve to have differential sensitivity to the visual world on our left and our right." (Sergent, 1983a, p. 491)

Anatomical Data

Comparative studies have revealed anatomical asymmetries in (a) the retina and (b) striate and/or peristriate regions of mammalian cortex.

The Retinal Level

Perry, Oehler, and Cowey (1984) reported nasal/temporal asymmetries in retinal ganglion cell densities in monkey: In each eye, cells in the nasal retina were more densely packed than those in the temporal retina. A likely functional consequence of this anatomical organization is better acuity in the nasal than temporal retina.

Under monocular viewing conditions, this retinal asymmetry could contribute to a hemispheric asymmetry: During RE stimulation, a LH advantage would result because the "better acuity" nasal retina projects to the LH, and the "poorer acuity" temporal retina, to the RH. Conversely, during LE stimulation, a RH advantage would result because the "better acuity" nasal retina projects to the RH, and the "poorer acuity" temporal retina, to the LH.

In contrast, during binocular viewing, this retinal asymmetry could not lead to hemispheric asymmetry because the above-described hemispheric asymmetries are mirror-reversed; hence, the combined effect of the LH advantage (due to the RE retinal asymmetry) and the RH advantage (due to the LE retinal asymmetry) is hemispheric symmetry.

The Cortical Level

Rosen, Aboitiz, Sherman, and Galaburda (1985) found that in 19 male and female rat cerebra, the number of cells in area 17 significantly differed between hemispheres.

Second, as mentioned in subsection 1.1/7, de Lacoste and her colleagues (de Lacoste & Woodward, 1985; de Lacoste et al., 1986) reported (a) significant volumetric asymmetries in retrocalcarine cortex "in species at all phylogenetic levels within the primate order" (de Lacoste et al., 1986, p. 719) and (b) an increase in degree of such asymmetries with increasing status on the phylogenetic scale.

Physiological Data

(*Note*. Although some of the following data represent processing outside of striate cortex, they all represent processing during sensory tasks; hence, their inclusion in this subsection on asymmetries at the sensory-perceptual level.)

Photic Driving Data

RH superiority for luminance. Freedman (1963) monitored EEG activity in parietal-occipital cortex (bipolar recordings between these two regions) in each hemisphere in 4 dextral subjects under three conditions: (a) control: no stimulation (resting with eyes open in the presence of a steady full-field light source), (b) control: full-field binocular stimulation, and (c) experimental: differential driving (binocular stimulation of either the left or right hemiretinas (and hence, the LH or RH, respectively). Stimulation consisted of strobe flashes at the rate of 8 per second.

Freedman found that (a) in the first and third conditions, EEG (8 cycle per second) activity in the RH exceeded that in the LH (and occurred 1.5-2.5 times as much in the driven than resting condition); and (b) in the second condition, activity did not significantly differ between the hemispheres. He concluded that, in humans, an electrophysiological asymmetry favoring the RH for photic stimulation exists:

> "The RH showed greater following no matter which hemisphere had been stimulated . . . . The greater following of the RH, or the lack of symmetry of the unilateral driving effect, suggests a classical dominance interpretation." (p. 599)

VEP Data

RH superiority for luminance. VEP data also indicate that hemispheric asymmetry for visual processing may exist at a level more fundamental than that of pattern recognition. A. Davis and Wada (1974) found that in 75% of 12 19- to 28-year-old normal dextral males and females, the coherence (degree of waveform similarity) of VEPs recorded over PTO regions in both hemispheres to "simple, unstructured flash stimuli" (p. 1) was greater in the RH than in the LH. Since coherence suggests "similar processes" (p. 7), these data indicate greater organization of electrophysiological activity in the right than left tertiary visual association cortex to unpatterned photic stimulation in right-handers.

Like Freedman's photic driving data, these VEP data also point to the asymmetrical processing of light in a cortical region that mediates visual pattern recognition. They hence suggest a source of asymmetry at a lower level than spatial frequency processing that may bias such processing.

Factors affecting cerebral asymmetry for luminance. Differential hemispheric sensitivity to luminance was further investigated in a study involving the spectral analysis of flash EPs (Jutai, Gruzelier, & Connolly, 1984). This study showed that power (squared amplitude values) varied as a function of the recording site and frequency range of the potential, and the stimulus luminance value.

Power in the three lowest ranges (0-10 Hz, including delta [δ], theta [θ], and alpha-1 [α-1]) increased linearly with stimulus luminance at midline central, and lateral occipital and temporal, sites. In contrast, power in the three highest ranges (10-22 Hz, including alpha-2 [α-2], beta-1 [β-1] and beta-2 [β-2]) increased linearly with luminance at occipital sites only. There, it was greater in the LH than in the RH in the beta-2 (18-22 Hz) frequency range only.

Power in the α-1 and α-2 ranges (6-14 Hz) in the RH exceeded that in the LH at the temporal locations. Also in this region, a significant Hemisphere x Luminance interaction effect for power in the α-2 range (10-14 Hz) was found. Within the RH only, power in respose to 2.5 and 5 ft-L was larger than to 0.65 ft-L, and power was greater in the RH than in the LH in response to 1.25, 2.5, and 5 ft-L flashes.

Hence, Jutai et al.'s data also show electrophysiological asymmetries in occipital and temporal cortex to nonpatterned visual information. The additional information they provide is the specification of the intrahemispheric locations and luminance values at which, and the EEG frequency ranges in which, these asymmetries emerge.

Pattern EP data. The pattern EP data demonstrate functional symmetry during sensory-perceptual processing when (a) the direct pathways alone are monocularly stimulated and (b) both the direct and indirect pathways are monocularly stimulated.

In the first case, although the responses within the contralaterally and ipsilaterally stimulated hemispheres differ from one another, the same effect occurs (these responses occur in these respective hemispheres) whether the right or left eye is stimulated (Blumhardt & A. Halliday, 1979).

In the second case, although the responses within the directly and indirectly stimulated hemispheres differ from one another, the same effect occurs whether the RH or the LH is directly stimulated (Ladenheim, 1983). Descriptions of the evoked responses found in each of these studies follow.

1. Symmetrical pattern EPs in normals. Blumhardt and Halliday found that when they monocularly presented pattern-reversed checkerboard stimuli to 50 normal adults, the occipital and parietal potentials in the ipsilaterally stimulated hemisphere differed in amplitude and polarity from those in the contralaterally stimulated one.

For example, with respect to polatrity, the 75-ms, 100-ms, and 145-ms components of the response in the ipsilaterally stimulated hemisphere were negative-going (N), positive-going (P), and negative-going (N), respectively; those same three components of the response in the contralaterally stimulated one were P, N, and P. This pattern occurred whether the right or left eye was stimulated.

Ladenheim bilaterally recorded steady-state potentials at occipital sites (in 2 dextral females and 2 males [1 dextral and 1 sinistral]) to monocularly presented checkerboard stimuli varied with respect to temporal frequency. She found the following effects, whether the RH or the LH was directly stimulated:

1. Evoked responses over the directly stimulated hemisphere significantly differed from those over the indirectly stimulated one with respect to both latency and waveform. She attributed (a) the longer latency in the indirectly stimulated hemisphere to callosal transfer time required for information transmission and (b) the different

waveforms to the additional processing and filtering that takes place during that interhemispheric transfer of information.

2. The latency of the ipsilateral projection equalled that of the contralateral projection. For example, when the LH was directly stimulated, the latency of the pathway between the left hemiretina of the left eye and the LH was the same as the latency of the pathway between the left hemiretina of the right eye and the LH.

3. Latencies of evoked responses over the RH when it was directly stimulated did not significantly differ from those recorded over the LH when it was directly stimulated.

Like Blumhardt and Halliday as well as Ladenheim, Jeffreys and Axford (1972a) found symmetrical pattern EPs. These investigators presented checkerboard stimuli (by the pattern onset/offset procedure) to 12 subjects; they observed that, on the average, the earliest pattern-related component (CI occurring at 65-80 ms poststimulus) of the evoked response was of opposite polarity in each hemisphere whether the RH or the LH was stimulated.

An interesting additional finding was a high degree of individual variability in the degree of positivity and negativity of that component. Jeffreys and Axford attributed this variability to

> "the considerable interindividual variability in the layout of striate in and around the calcarine fissures and the layout of the fissures themselves." (p. 18)

They cited Polyak's (1957, cited in Jeffreys & Axford, Ibid.) observation of this anatomical variability:

> "The configuration of the calcarine fissures shows almost an infinity of individual variation of essentially the same gyral pattern." (p. 18)

2. _Asymmetrical pattern EPs in abnormals_. Hence, normative data indicate symmetrical electrophysiological activity to patterned stimulation during sensory-perceptual processing. A. M. Halliday, E. Halliday, Kriss, McDonald, and Mushin (1976) corroborated this conclusion by demonstrating asymmetrical responses in a clinical population.

These investigators monocularly presented pattern-reversed checkerboard stimuli to 19 subjects with optic compression at different points along the visual pathway and recorded responses at lateral and midline occipital and frontal sites. They found significantly greater electrical activity in the LH pattern-related components than in the RH ones when either eye was stimulated.

They attributed this asymmetry to a visual field defect (viz., right homonymous hemianopia [no input travelled to the RH via the right hemiretinas of either eye]). They concluded that the only true cases of sensory asymmetry are pathological ones.

Cerebral Metabolism Data

Phelps et al. (1981) used local cerebral metabolic rate for glucose utilization (see subsection 1.1/3) to measure regional cerebral activity level during visual processing.

These investigators instructed 20- to 25-year-old normal subjects to passively view three monocularly and binocularly presented visual stimuli of increasing complexity (white light, alternating black-and-white checkerboards, and a photograph of a park scene) while their rates of glucose utilization in visual cortex were measured.

Phelps et al. found that (a) these rates were symmetrical in both sensory and association cortex; (b) these rates increased with increasing stimulus complexity; and (c) these rate increases were faster in association than sensory cortex, hence suggesting the relatively greater involvement of the former in complex visual processing.

Summary of Physiological Data

Thus, the electrophysiological data suggest the following:

1. Slight asymmetries, primarily favoring the RH, may exist in the occipital alpha and slow posterior rhythms of the resting EEG in a minority of the normal population, but such asymmetries decrease with age (the slow posterior rhythm exists only in the undeveloped EEG).

2. Normal asymmetries, favoring the RH, may exist during sensory processing of nonpatterned visual stimulation (in the sensory and/or association areas of parietal, occipital, and temporal cortex, including the PTO region).

3. The sensory-perceptual processing of patterned stimuli is characterized by symmetrical activity in normals (in occipital and parietal cortex).

The metabolic data suggest symmetrical activity (in visual sensory and association cortex) during sensory-perceptual processing of both nonpatterned and patterned visual stimuli in normals.

Psychophysical Data

Sergent (1983a) reviewed and critiqued the psychophysical literature concerning hemispheric differences in visual processing at the sensory level. Some of those studies as well as Sergent's evaluations of them are mentioned herein, but the reader is referred to that paper for an exhaustive treatment of this topic.

Light Stimulation

Contradictory RT data. First, with respect to hemispheric specialization for light stimulation, contradictory findings resulting from the same RT paradigm (the presentation of laterally presented light flashes to subjects instructed to manually report their responses) have emerged: Both (a) faster RTs to flashes presented in the LVF (Jeeves & Dixon, 1970) and (b) no differences in RTs to flashes presented in either visual field (Di Stefano et al., 1980, cited in Sergent, Ibid.) have been found.

Sergent noted that the interval between the warning signal and stimulus onset varied randomly in this task; she concluded that the asymmetrical responses might reflect the greater transient vigilance capacities (Dimond, 1972), rather than the greater visuosensory capacities, of the RH.

RH superiority for light perception. Another experiment concerning lateralized processing of photic stimulation was performed by Davidoff (1975). He presented, to 12 dextral and 12 sinistral undergraduates (with 6 males and 6 females in each group), stimuli consisting of two gray squares. In half of the stimuli (the experimental set), one square was situated to the left, and the other, to the right, of a central fixation point (a number). In the other half of the stimuli (the control set), one square was situated above, and the other, below, central fixation. The subjects' task was to report whether the pair of grays was the same lightness or, if not, which was the lighter.

The rationale behind this design was the following: If hemispheric differences with respect to lightness perception exist, then the grays in the experimental set (that projected to one hemisphere only) would be perceived to differ from one another, whereas the grays in the control set (that projected to both hemispheres) would be perceived as the same.

Davidoff found that lightness perception correlated with handedness such that dextral subjects saw the stimuli presented in the LVF as lighter than those presented in the RVF. He concluded that the RH was more important than the LH for perceptual functions.

1. Critique of Davidoff's method. Sergent noted several aspects of Davidoff's procedure that confounded his results (i.e., interfered with this study's being a pure measure of sensory-perceptual processing). First, the

subjects' judgement involved cognitive processing.

Second, to monitor fixation, Davidoff required the subjects to name the "fixation digit" prior to performing the task. In keeping with Moscovitch and Klein's (1980, cited in Sergent, 1983a) finding that LH involvement in one type of processing frees the RH to gain a relative advantage in another type of processing, Sergent suggested that, here, LH involvement in digit-naming (speech production) may have left the RH processing resources free to engage in the perceptual task.

Pattern Stimulation

Next, with respect to differential hemispheric sensitivity to patterned stimulation during sensory processing, Bryden (1976, cited in Sergent, 1983a) found no significant visual field differences when subjects were required to respond "Yes" or "No" to indicate whether or not a dot had been presented. Kimura (1969, cited in Sergent, Ibid.), in contrast, did find a LVF advantage in a dot localization task. Sergent pointed out that the latter task was a less pure measure of sensory processing than the former.

Few divided visual field psychophysical studies involving the binocular presentation of nonverbal spatial frequency stimuli in a sensory-perceptual task have been performed. One study that did meet these criteria (Previc, 1982) (see subsection 1.4/3) reported a lack of hemispheric specialization for spatial frequency in a go/no go orientation identification task involving a manual response.

Summary

Although some investigators have reported asymmetries for light and pattern perception, their studies measured cognitive in addition to sensory-perceptual processing.

Current data suggest that hemispheric specialization during visual processing emerges at a level higher than the sensory one. Divided visual field studies involving pure detection and discrimination tasks vis-à-vis stimuli in which either luminance or spatial frequency alone is manipulated need be performed to test this hypothesis.

Conclusions: Hemispheric Differences in the Visual System at Rest and During Sensory Processing

Anatomical and Electrophysiological Asymmetries

Asymmetries in mammalian visual cortex have been suggested by anatomical (cell count and regional volume techniques) and some electrophysiological data. The latter showed, for example, a RH predominance in (a) the occipital alpha and slow posterior components of the resting EEG in a small percentage of normals and (b) EEG (in parietal-occipital cortex) driven by flash stimuli.

Also, (a) the organization of electrical activity within PTO cortex may be greater in the RH than in the LH; and (b) hemispheric advantage varies with cerebral region (occipital and temporal cortex), EEG frequency range, and stimulus luminance value.

Finally, the regional volume and resting EEG data suggest a greater amount of asymmetry in visual cortical regions in immature than mature organisms.

Anatomical, Physiological, and Psychophysical Symmetries

Other electrophysiological data have shown symmetrical responses during the sensory-perceptual processing of patterned stimuli (in occipital and parietal cortex). Another physiological measure, that of regional metabolic rate (in visual sensory and association cortex), and psychophysical studies, have demonstrated symmetrical responses to both flash and patterned stimuli. (*Note*. Those psychophysical data showing asymmetrical processing were probably measuring a combination of sensory and cognitive processes.)

Finally, to the author's knowledge, no published data exist showing either anatomical or physiological asymmetries in the transient and sustained visual systems (i.e., the neural substrates of low and high frequency processing, respectively). For example, no one has reported that the retinocortical pathways or spatiotemporal response characteristics of these systems differ between the right and left sides of the brain in any mammalian species.

Concluding Remarks

In sum, the bulk of physiological and psychophysical data point to symmetrical processing at the sensory level; hence, the relationship between structural asymmetries in retrocalcarine cortex and functional symmetries during visual processing requires examination.

Finally, (a) anatomical studies in which subject characteristics (e.g., sex, age, hand preference, pathological condition) are carefully documented and (b) electrophysiological and psychophysical studies in which subject characteristics, stimulus composition and presentation, and task requirements are carefully controlled need be performed to specify under what conditions, if any, asymmetries occur in the mature human organism at rest and/or when engaged in visuosensory tasks.

3/ Asymmetries at the Cognitive Processing Level

> "If the output from the visual sensory areas is similar in both hemispheres, functional asymmetries must then arise beyond that level, resulting from different kinds of processing in the left and right `association' areas underlying cognition." (Sergent, 1983a, p. 492)

Anatomical Data

The PTO region (intermodal association cortex) is larger in the RH than in the LH (Cummings, 1985). How the degree of asymmetry in this area compares with that in areas 17-19 requires further investigation.

For example, Springer and Deutsch (1985, Appendix) concluded from their reveiw of the lateralization literature that tertiary association cortex is the level at which hemispheric asymmetry emerges. Similarly, Luria (1973, cited in Kolb & Whishaw, 1985, chap. 7) concluded from his review of the data in this field that lateralization develops progressively and first appears at higher cortical levels. For example, it is minimal in area 17 and maximal in the PTO region.

In contrast, recent comparative data (de Lacoste et al., 1986) suggest that the magnitude of asymmetry in areas 17-19 exceeds that in PTO cortex in primates.

Physiological Data

(*Note*. See subsection 4.5/2 for data concerning asymmetries in the association areas of occipital, parietal, and temporal cortex, including the PTO region, during sensory tasks.)

Electrophysiological Data

Asymmetries in EEG components correlated with attention, cognitive processing, task difficulty, and processing mode have been shown. For example, Ray and Cole (1985) recorded parietal and temporal α (6-14 Hz) and β (16-24 Hz) potentials from 18 dextral college-aged males and females engaged in four types of tasks: (a) Intake-LH (counting verbs in a passage and finding errors in math problems), (b) Intake-RH (paper-folding and Mooney facial closure tasks), (c) Rejection-LH (mental arithmetic and creating sentences beginning with a certain letter), (d) Rejection-RH (mental rotation of a geometric figure and visualization of an imaginary walk).

These investigators found that parietal α reflected the attentional dimension, and parietal β, the cognitive one. Regarding α, more of this rhythm occurred during rejection than during intake in both hemispheres; during rejection, more α occurred in the RH than in the LH. Regarding β, a significant Task x Hemisphere interaction effect was found: This rhythm was greater in the RH during the visuospatial-synthetic tasks and greater in the LH during the verbal-analytic ones. Hence, a RH predominance of parietal α occurred while subjects internally attended to either a typical RH or LH cognitive task, that is, these data showed a RH bias for attention to internal processing.

Other electrophysiological evidence for differential hemispheric engagement during attentional processing was provided by Marsh and Thompson, 1973 (cited in W. S. Brown et al., 1985). They found that the type of EP associated with expectancy, orientation, and attention prior to stimulus presentation (the contingent negative variation [CNV]) was present only in the LH prior to subjects' involvement in linguistic tasks.

Concerning the effect of task difficulty on the lateral distribution of EEG activity, as mentioned in subsection 4.1/3, Ornstein et al. (1980) recorded α activity at parietal and central sites in 10 males and 10 females engaged in either a spatial or verbal task. They found that EEG activity was significantly greater in the RH than in the LH for all spatial tasks except the more difficult ones (mental rotation and part-whole matching).

These investigators concluded that the simpler visuospatial tasks were able to be solved by a RH-based synthetic strategy, whereas the more difficult ones required a LH-based analytic strategy for their solutions. These results support the hypothesis that a cognitive factor, (viz., processing mode) rather than a sensory factor (viz., sensory modality [stimulus material]) differentially engages the cerebral hemispheres (see Bever, 1975, pp. 254-256 for discussion).

Regional Cerebral Blood Flow (rCBF) Data

Functional differences between the hemispheres during attentional processing were demonstrated by the physiological measure, rCBF (see subsection 1.1/3). Melamed and Larsen (1977, cited in Drake, 1985) found that when subjects were instructed to look to either their left or their right, the amount of blood flow in the cerebral hemisphere contralateral to their direction of gaze significantly increased (12-25%). (Note. To what degree this study measured sensory or attentional processing is unclear).

Psychophysical Data

Attentional Effects

In addition to the physiological evidence mentioned above, some behavioral evidence for functional asymmetry during attentional processing exists. First, Kinsbourne (1970) found that when 32 dextral adults performed a visual detection task (viz., gap detection in the perimeter of a square), they were equally accurate when the stimuli were presented in the left and right visual fields (with a trend toward superior performance to LVF presentations). In contrast, when they undertook a concurrent LH task (viz., subvocal rehearsal of six one-syllable words prior to presentation of the square stimuli), their degree of accuracy to RVF presentations exceeded that to LVF presentations.

Kinsbourne described this situation as follows:

> "Concurrent verbal activity, in the form of subvocal rehearsal while awaiting the stimulus presentation, introduced an asymmetry into what was without that verbal activity symmetrical performance." (p. 199)

He viewed these data as supportive of his attentional bias hypothesis. This model proposes that the type of processing in which a subject is involved prior to engagement in a second task predisposes him/her to orient toward the visual field contralateral to the active hemisphere. This predisposition places that hemisphere in a greater state of readiness than the active one to respond to stimulus material to be presented in the attended location.

Hence, this view purports that a mental set and consequent lateral orientation, established prior to stimulus presentation by task demands or expectancy, interact with the processing resulting from stimulus presentation. This prior activity thus affects the direction of asymmetry during engagement in the second task.

Klein et al. (1976) provided additional evidence for Kinsbourne's model. These researchers found that the respective RH and LH advantages in face and word recognition tasks demonstrated by 20 dextral undergraduates decreased when these subjects were "LH-primed" (engaged in word recognition tasks prior to those of face recogntion) or

"RH-primed" (undertook face recognition prior to word recognition).

(Note. Whether purely attentional effects, rather than attentional, stimulus material, and/or processing mode effects, caused the results in both Kinsbourne's and Klein et al.'s studies is ambiguous.)

Memory Effects

If asymmetrical processing exists during memory processing, Di Lollo's (1981) findings suggest that it occurs at either the short- or long-term levels. In his study, 9 dextral males and females were required to report the location of a missing dot in an array of dots successively presented (the duration of interarray intervals were varied) in either the RVF or LVF. Because accurate performance required the simultaneous visibility of successively displayed pattern comonents, subjects had to remember and perceptually integrate the stimulus presentations; hence, the interstimulus intervals (ISIs) measured duration of visible persistence (iconic representation).

Subjects performed equally to stimuli presented in both visual fields at all ISI durations. (Also, as expected, they performed best to short ISI durations and worst to long ones.) Di Lollo suggested that asymmetries in visual processing must arise at a level higher than that of iconic storage:

"Visible persistence is produced at an initial stage of

> processing, and early stages of information processing are handled similarly and with equal efficiency by both hemispheres." (p. 25)

Smith and Nielson (1970) (see subsection 4.1/3) provided data supporting Di Lollo's notion that asymmetries during memory processing occur at either the short- or long-term level. Their data suggest that during facial recognition, "same" judgements entail parallel, and "different" judgements, serial, retrieval processes. These differences imply RH engagement during the formulation of "same", and LH involvement during that of "different", judgements.

Finally, Moscovitch (1979, cited in Di Lollo, 1981) agreed with Di Lollo that asymmetries arise at levels higher than the iconic one, but he suggested a different level than Smith and Nielson:

> "Hemispheric asymmetries emerge only at the level of a central processor that integrates information from the peripheral channels and represents it in terms of configural, relational, or categorical properties that reflect the mode of operation peculiar to the processor in each hemisphere." (Di Lollo, Ibid., p. 24)

As the following subsection shows, single units in IT cortex might provide the neural mechanism underlying the cognitively based asymmetry hypothesized by Moscovitch.

Summary: Cognitive Asymmetries

Both structural and functional asymmetries have been demonstrated at the cognitive level:

1. The right PTO region is larger than the left one.

2. Attentional processing may bias the hemispheres in several ways: (a) RH involvement in attention to "mental events," (b) RH superiority in sustained vigilance and LH

predominance in transient vigilance (see subection 1.1/6), (c) anticipatory activation in the hemisphere that typically processes the type of stimulus expected by a given subject, (d) activity in the hemisphere contralateral to the visual field of stimulation to which a subject is attending, and (e) activation in a given hemisphere and correlative orientation toward the contralateral visual field due to the subject's attending to a previous task.

3. The RH may be selectively engaged by a relatively simple task requiring synthetic processing, and the LH, by a relatively difficult task requiring analytic processing.

4. The RH may be involved in the retrieval processes underlying "same," and the LH, in those underlying "different," facial recognition judgements.

5. At a high cognitive level, perhaps in IT cortex, inputs may be integrated differently by each hemisphere.

In contrast to the above-listed asymmetries, iconic representations of patterned stimuli were shown to be processed symmetrically, that is, equally efficiently by both hemispheres.

4/ Hypothetical Neural Mechanisms of the Asymmetrical Processing of Spatial Frequency

As mentioned above, (a) "sufficient data have not yet been accumulated to discuss the neural mechanisms of pattern vision from the neuron level" (Iwai, 1985, p. 435), and (b) the relationship between the perception of global pattern configuration and spatial frequency-specific channels is not well-understood (Hughes, 1982). Hence, the mechanisms underlying the asymmetrical processing of spatial frequency suggested herein are purely speculative.

(*Note*. For argument's sake, the assumed directions of asymmetry herein are those postulated by the spatial frequency model of hemispheric specialization, namely, a RH advantage for low frequencies and a LH advantage for high.)

Global Versus Local Contour Sensitivity of IT Cells

> "The topographical representation of the distribution of sensory neurons is preserved in [retinotopic] maps, but neurons with different functional properties at different levels introduce qualitative changes in the functional operations that are performed at successive levels of the projection." (Jacobson, 1978, p. 371)

Electrophysiological (single-unit) and psychophysical data have suggested that one type of neuron in IT cortex might introduce a qualitative functional change in visual processing of the sort described by Jacobson (Desimone et al., 1985; C. Gross et al., 1985; Iwai, 1985; Perrett et al., 1982, Rolls, 1983, Schwartz et al., 1983, all three cited in C. Gross et al, 1985). Whereas other neurons encode local stimulus information (i.e., different parts of stimuli), this type of neuron seems to encode global information (i.e., overall stimulus form [shape]).

(*Note*. See subsection 1.3/7 for (a) descriptions of above-listed studies and findings, and (b) discussion of relationship between large receptive field size and capacity for global analysis. Also see Hughes [1985] for model concerning striate mediation of detail, and extrastriate control of *figural*, analysis [in cat].)

To the author's knowledge, no data exist concerning the relative densities of this type of cell as a function of hemisphere. Were this cell-type found to be differentially laterally distributed such that more existed in the RH than in the LH, it would provide an anatomical mechanism underlying greater RH sensitivity to the global (in the configuration-as-outline sense) dimension of visual stimuli.

Global Versus Local Types of Integration

The hypothetical asymmetrical distribution of this "single-unit global processor" would be consistent with the behavioral and anatomical data implicating the RH temporal lobe, in particular, and the RH, in general, in synthetic processing.

To review, humans with RH temporal lobe damage demonstrate impaired abilities in such synthetic tasks as: (a) combining individual visual impressions into a single picture (*Note*. These subjects had occipitotemporal damage [Kolb & Whishaw, 1985, chap. 10]), (b) forming spatial relationships among separate features (Milner, 1954), (c) performing a closure task (Landsell, 1968), and (d) recognizing overlapping nonsense figures (Kimura, 1963, cited in Fedio & Buchsbaum, 1971; see subsection 1.3/7).

Diffuse Versus Focal Organization of the Respective Right Versus Left Hemispheres

Concerning the RH in general, Semmes (1968) concluded from the differential pattern of behavioral deficits associated with different-sized unilateral lesions in humans that the RH was diffusely organized, and the LH, focally organized (see subsection 1.1/3). Semmes' data lay the foundation for the model of the RH-as-synthetic, and LH-as-analytic, processor because her data implied that the integration of global information was superior in the RH, and that of local information, in the LH.

Superior Long-Distance Versus Short-Distance Communication in the Respective Right Versus Left Hemispheres

More recent normative anatomical data provided support for this model, namely, the ratio of white (myelinated fibers) to gray (nonmyelinated fibers) matter in the RH was found to exceed that in the LH; conversely, the ratio of gray to white matter in the LH was shown to be greater than that in the RH (Gur et al., 1980; McHenry et al., 1978 and Meyer et al., 1978, both cited in Gur et al., Ibid.). These data imply that long-distance neural communication and the integration of global information in the RH supercede these functions in the LH; conversely, short-distance neural communication and the integration of local information in the LH are more proficient than these functions in the RH (again, see subsection 1.1/3).

Summary

Hence, (a) a diffuse overall pattern of neural organization and (a) a high white-to-gray-matter ratio, resulting in relatively greater RH proficiency in the integration of information on a global scale, might provide mechanisms other than the shape-sensitive IT cells underlying RH specialization for the global structural level of a given patterned stimulus. The converse pattern and ratio, yielding greater LH efficiency in the integration of local information, might underlie LH specialization for the local level of a patterned stimulus.

Narrow versus Broad Tuning Curves of V4 Cells

Hemispheric differences in the breadth of tuning curves to spatial frequency stimuli might provide another mechanism of the asymmetrical processing of this stimulus dimension. (Note. Broadly tuned channels respond to a wide range of frequencies, i.e., are nonspecific with respect to spatial frequency; narrowly tuned channels respond to only one or very few frequencies, i.e., are highly selective with respect to frequency.)

The relationship between tuning breadth and global/local processing is unclear. One might argue that either (a) broadly tuned channels "see" a greater amount, that is, a global picture of a given stimulus, whereas the narrowly tuned ones see a smaller amount, that is, particular parts; or (b) the opposite argument: The narrowly tuned channels are highly specific, not for stimulus parts, but rather for stimulus configurations. This second argument is consistent with the single-unit data showing that higher level visual neurons are more selective for particular complex stimuli and have narrower tuning curves than lower level ones (see subsection 1.2/3).

Whichever of the above two situations represents the real relationship between breadth of tuning and stimulus structural level, the fact remains that, in either case, the differential lateral tuning of spatial frequency channels would result in the asymmetrical processing of the global and local levels of a given stimulus. Although the single-unit and psychophysical data suggest the symmetrical lateral tuning of these channels (again, see subsection 1.2/3), one single-unit study revealed a finding which might relate to their asymmetrical tuning.

Attentional Effects on Tuning Curve Breadth

Hochstein and Maunsell (1985) showed that tuning curve breadth varies with selective attention: In one-third of the cells studied in area V4 (provides direct input to IT cortex) of Rhesus monkey, the tuning curves to the attended stimulus dimension were narrower than those to the irrelevant one (see subsection 1.3/7).

Because attentional processing may result in (a) the sharpening of spatial frequency tuning curves and (b) the activation of a given hemisphere due to such factors as task demands (prior or concurrent) or expectancy (see subsection 4.5/3), it may therefore result in the sharpening of tuning curves within the activated hemisphere.

Small Versus Large Acetylcholine (ACh) Concentrations in Temporal Cortex

Cholinergic involvement in spatial frequency processing has been indicated by anatomical and psychophysical studies, although the exact range(s) with which it is involved in humans is unknown. (Its involvement in both high- and low-frequency processing has been suggested in cat and monkey; see subsection 1.2/3.)

With whichever range the cholinergic system is involved, the fact remains that its differential lateral concentration would result in the asymmetrical processing of (absolutely) low and high spatial frequencies.

Thus far, its asymmetrical distribution, favoring the LH, has been demonstrated in humans (N = 4 postmortem male brains without any signs of neurologic disease): The activity level of the enzyme choline acetyltransferase (ChAT), a marker for the neurotransmitter ACh, was found to be higher in the superior temporal lobe in the LH than that in the RH (Amaducci, Sorbi, Albanese, & Gainotti, 1981). Maximum interhemispheric differences in this activity were shown 3 cm caudal to Brodman's area 22 (sensory association [tertiary] cortex) in the RH and Wernicke's area (a language comprehension area) in the LH.

ACh has been implicated in cognitive and memory functions (Amaducci et al., Ibid.). Whether, however, (a) area 22 is involved in pattern recognition, as is its adjacent area 20 (IT cortex) and possibly 21 (part of MT cortex, putatively involved in memory formation [Deutsch, 1983]) and/or (b) ACh is also asymmetrically distributed in areas 20 and 21 require further investigation.

Since the real data are not currently known, hypothetical data must be used to explain how a pharmacological asymmetry might underlie hemispheric specialization for spatial frequency. If, for argument's sake, one assumes that ACh is (a) involved in high-frequency processing and (b) more densely concentrated in the LH than in the RH in that part of temporal cortex involved in pattern recognition, then the strength of interneural connections and the quality of interneural communication in the parvocellular X-system in the LH would exceed those in the RH; thus, the former system would yield larger responses to high-frequency stimulation than the latter.

Different Types of Nonlinear Interactions Between Spatial Frequency Channels

Finally, the possibility exists that the hemispheres are not differentially tuned to low and high spatial frequencies (as the spatial frequency model of hemispheric specialization proposes), but that the hemispheres differ with respect to the types of nonlinear interactions which occur between spatial frequency channels: Those in the RH may shift stimulus inputs toward lower ranges, whereas those in the LH may shift them toward higher ones.

Hence, neural representations may be asymmetrical "beyond the sensory level" (Sergent, 1982a, p. 265), not as a result of different receptive capacities to low and high inputs in each hemisphere, but as a result of different processing characteristics yielding low and high outputs in the respective hemispheres. This possibility requires further investigation.

4.6] SUGGESTIONS FOR FUTURE RESEARCH CONCERNING CEREBRAL MECHANISMS OF VISUAL PATTERN RECOGNITION

1/ Suggestions Regarding Modification of the Spatial Frequency Model of Hemispheric Specialization

Sergent's model requires modification with respect to the following points:

1. It needs to incorporate the current findings, namely, hemispheric specialization during spatial frequency recognition is a function of dependent variable, gender, task difficulty, and degree of stimulus familiarization in addition to frequency value.

2. It needs to clarify the issues concerning (a) the relationship between spatial frequency and cognitive functions; (b) the stimulus dimension (pattern structure or size) for which the hemispheres are specialized; and (c) the processing level at which, and the neural mechanism by which, asymmetry for spatial frequency emerges (see subsection 4.4).

To clarify point (2a), experiments need be designed to test the conditions under which (a) different spatial frequency ranges and (b) the interrelationship between frequencies define stimulus form.

Stimulus Form and Recognition

Related to this question, and likewise in need of investigation, is the issue regarding the relationship between stimulus form and the recognition process. The data concerning the relationships between (a) spatial frequency and recognition accuracy (see subsection 1.2/5) and (b) spatial frequency and visual perception (Moore, 1985) suggest a hypothesis requiring testing: The capacity to recognize a complex visual stimulus depends on whichever frequencies constitute the underlying structure of that stimulus.

The values of these frequencies are pattern-specific. For example, in faces, low frequencies constitute their structure and, hence, suffice for their accurate recognition (Harmon, 1973; Tieger & Ganz, 1979). In contrast, in "unified" paintings (e.g., those depicted in a realistic style), high frequencies are required for subjects to perceive their unity (Moore, 1985).

2/ General Considerations Regarding Experimental Design

Future studies that investigate hemispheric specialization for spatial frequency must be carefully controlled with respect to subject characteristics (see subsections 1.5/2, 4.1/5, and 4.3); stimulus composition and presentation (see subsections 4.1/2, 4.1/4, 4.3, and 4.4); and task requirements (see subsections 4.1/3, 4.3 and 4.5/2). (Note. Number of trials, which controls a critical determinant of direction of advantage, viz., degree of stimulus familiarization, is included in the stimulus presentation category.)

There is a need for normative divided visual field studies in which high-contrast, black-and-white checkerboard or grating stimuli are presented at a moderate photopic level during a sensory (detection or discrimination) task; spatial frequency and task difficulty should be manipulated, but luminance should be held constant. These "future" data should be compared to the current recognition data to assess the differences between asymmetry during sensory and cognitive processing.

Further, the current study should be replicated, not only with normative samples, but also with clinical ones. For example, to the author's knowledge, no divided visual field studies in which the spatial frequency constituents of nonverbal stimuli were controlled have been administered to RH and LH temporal lobe-lesioned subjects. The correlations between (a) performance deficits with respect to a particular frequency range and (b) side of damage yielded by such a study could help understand the relationship between direction of advantage and frequency values during recognition.

Finally, the current study should be replicated with younger subjects (middle childhood); a comparison between those and the current data would reveal developmental changes in hemispheric specialization for visual pattern recognition.

3/The Effect of a Dynamic View of Hemispheric Specialization for Spatial Frequency Recognition on Research Methodology

An important perspective to keep in mind when researching the cerebral mechanisms of spatial frequency recognition is that even if the conditions under which a given hemisphere mediates the recognition of a particular frequency range were known, such information would only provide a partial account of spatial frequency recognition. The regional substrates and, hence, the substrates of this behavior along the anterior/posterior meridian of the brain must also be specified.

Courchesne (1977) showed, for example, that different cerebral regions are involved during the recognition of patterned stimuli as a function of stimulus material, luminance, novelty, and/or task difficulty.

This investigator recorded VEPs (over midline frontal [Fz], central [Cz], and parietal [Pz] sites) of 10 6- to 8-year-olds and 10 23- to 25-year-olds while they counted designated target stimuli present among four categories of stimuli: (a) the letter A, the target for half of the subjects; (b) the letter B, the target for the other half of them; (c) the letters C to Z called _the dim stimuli_ due to their significantly lower luminance levels; and (d) quasirandom unrecognizable color patterns called _the novel stimuli_.

Courchesne found that, in adults,

> "easily recognized, nontarget stimuli that were infrequently presented [dim slides] elicited posteriorly distributed P3 waves, while unrecognizable, novel stimuli [novel slides] elicited centrofrontally distributed P3 waves. The scalp distributions of these two types of P3 waves differed significantly." (p. 591)

(_Note_. P3 refers to an endogenous component reflecting information delivery, information value, and stimulus evaluation.)

Hence, as the above study suggests, visual pattern recognition is a complex behavior, that is, a composite of sensory-perceptual and cognitive sub-behaviors mediated by different cerebral regions (primarily in the occipito-temporal-limbic circuit) at different times during a single recognition sequence.

Thus, both pattern and magnitude of hemispheric advantage demonstrated during this behavior should not be expected to be static. On the contrary, a dynamic pattern, reflecting the different advantages as a function of processing stage, should be expected (see subsections 1.1/2, 1.1/5, 1.1/6 and 1.1/10 for theory and data concerning dynamic models of hemispheric specialization).

Further, Friedman et al. (1985) showed electrophysiologically that intergender differences during a recognition task (a continuous performance task in which subjects were instructed to manually respond as quickly as possible to the appearance of a target stimulus) were also a function of processing stage. These researchers found that significant gender differences in ERPs recorded from the midline frontal (Fz), central (Cz), parietal, (Pz) and occipital (Oz) sites of 74 normal adolescents emerged only during the cognitive stage of the task, namely, in the very late endogenous components (the Slow Wave [SW] and P550).

Evoked Potentials: Their Definition and Use in Visual Pattern Recognition Research

The above discussion suggests that such high-resolution measures of visual pattern recognition as ERPs are required to study the cerebral substrates of this behavior. A brief description of this methodology and its application to the problem-at-hand follow.

Definition

EPs are scalp-recorded measures of underlying neural population activity that are time-locked to (triggered by) stimulus presentation. Responses to repetitive stimulation are averaged resulting in a single tracing in which the stimulus-correlated components are relatively large and well-defined against the background noise.

The primary advantages of such measures are the following:

1. They are noninvasive and can therefore provide data from extant, normal humans.

2. They can be recorded (a) during a wide range of tasks, from sensory to cognitive (technically, they are referred to as event-related potentials [ERPs] when recorded during a cognitive task); and (b) in conjunction with other dependent variables, such as discrimination or recognition judgements, during such tasks. Hence, they allow the "direct observation in real-time of the parallel occurrence of psychological and physiological cognitive events" (Beaumont, cited in Young, 1983, p. 129).

3. They can be used, by means of component analysis, to functionally localize a given behavior and its substages.

In one type of EP, namely, the transient potential, response amplitude is measured as a function of time, and particular waveform components correlate with particular stages of processing. For example, in a 1-second recording, the initial 250-ms epoch reflects exogenous (stimulus-related) processing; the remaining 750, endogenous, (cognitive) processing.

The exogenous components. P1 and P2, respectively named for their positively-going peaks at approximately 100 and 200 ms poststimulus presentation, respectively reflect luminance-related (intensity, contrast) and pattern-related (contour density) parameters (MacKay, 1966, cited in Rietveld et al., 1967; Spehlmann, 1965).

The endogenous components. As mentioned earlier in this subsection, P3 is correlated with (a) information delivery (the presentation of a stimulus with a low probability of occurrence [Donchin, 1979; Sutton, 1979; Sutton, Braren, Zubin, & John, 1965]; (b) information value (the presentation of a task-relevant stimulus); and (c) stimulus evaluation (McCarthy & Donchin, 1981; see Pritchard, 1981, for discussion).

P4 is associated with later processing stages during which feedback is utilized (Stuss & Picton, 1978) and additional comparisons required by difficult tasks are made (Kok & Looren de Jong, 1980b, cited in Ruchkin & Sutton, 1983).

These processing functions putatively reflected in the P3 and P4 waves were initially considered to be temporally tied to the 300- and 400-ms ranges, respectively. Recent data, however, have shown that two other endogenous components, the Late Positive Component [LPC] and the Slow Wave [SW], which share many functions with P3 and P4, often extend into the 500-ms to 1-second range (Ruchkin & Sutton, 1983).

EPs and Lateralization Research

Hence, EP components reveal when separate sensory and cognitive processing stages occur. They also reveal where these separate stages take place.

For example, a comparison between the amplitudes and latencies of a selected component recorded over different cerebral sites can specify at which site relatively greater (higher amplitude) and more efficient (shorter latency) activity occurs during the processing stage associated with that component. Thus, recording over laterally homologous sites can reveal relative hemispheric superiority during a given processing stage.

EP analysis can thus show the temporal and spatial parameters of the substages (processing levels) of a given behavior. They can specify, for example, (a) the number of milliseconds poststimulus at which a given sensory or cognitive response occurs and (b) the region within the RH or LH in which a given response is relatively more efficient. These are precisely the data that need be collected to resolve the question postulated in subsection 4.5 regarding level of origin of hemispheric asymmetry during pattern recognition.

An experimental design that might yield particularly enlightening results is one that compares bipolar potentials (recorded by referencing two active electrodes to one another) recorded over laterally homologous sites (an occipital-temporal and central-parietal potential in each hemisphere) during two different tasks, one sensory (the passive viewing of checkerboard stimuli) and the other cognitive (a same/different recognition task to the same stimuli). Differences between components in the viewing set and those in the recognition set would reveal the times and places at which hemispheric asymmetry during visual pattern recognition arises.

Finally, EPs can be used to investigate not only the regional and lateral substrates of the sub-behaviors constituting recognition processing, but also interhemispheric activity during recognition. As discussed in subsection 1.1/5,

> "the important problem is not to parcel out functions on an either/or basis, but to understand how the total output of the human brain is a function of the integration of the two hemispheres." (Dimond, 1972, p. 200)

Summary

Thus, EP methodology can contribute to research concerning the cerebral substrates of spatial frequency recognition by showing (a) shifts in hemispheric advantage as a function of processing stage, (b) the level of emergence of hemispheric asymmetry during recognition, and

(c) interhemispheric activity.

Concerning the second point, EPs provide a powerful method for investigating whether, as psychophysical data suggest, symmetrical processing occurs at the sensory-perceptual level, and asymmetrical processing, at the cognitive one. Although the current study provided some preliminary data in the effort to answer these questions, it did not directly or completely answer them. Future research using high-resolution physiological measures almost certainly will.

4/ The Adaptive Advantage of Hemispheric Specialization for Spatial Frequency Recognition

In conjunction with the continued experimental investigation of the topic-at-hand, further thought should be given to the fundamental question of the adaptive advantage of the asymmetrical processing of spatial frequencies. For example, if one considers that one advantage of the hemispheric specialization type of functional organization is "the separation of incompatible mechanisms which cannot occur in the same place at the same time" (Lashley, cited in Bever, 1975, p. 251), one might wonder why the mechanisms which process large and small sizes would be incompatible and, hence, located in different hemispheres.

One might more readily expect that mechanisms underlying functions which differ qualitatively, rather than quantitatively, would be incompatible. For example, one might expect the separation of the neural substrates of the two different functional streams of the visual system, namely, localization and discrimination (see subsection 1.2/3), rather than the separation of substrates within one of those functional streams, namely, discrimination.

The spatial frequency model of hemispheric specialization, as it is currently stated, suggests the latter case: Asymmetry exists for the processing of different-sized features within a given pattern to expedite the identification of that pattern.

Hemispheric Specialization for Stimulus Location and Identification (The "Where" and "What" Aspects of Vision)

Were future data to show, not size-related asymmetries, but rather those for the processing of global and local structural levels (form [either outline or structure] and internal details), such data would suggest the former case, that is, hemispheric specialization exists with respect to both functional streams such that (a) the lateral half more proficient in form processing is specialized for stimulus localization, and (b) that more efficient in pattern processing, for discrimination.

Harter et al. (1982) found some EP data and cited other references suggesting that the hemispheres might be specialized for these interlocutional and intralocutional functions (Ibid.; see subsection 1.2/3). In contrast, data showing symmetry of the transient and sustained systems undermine such a hypothesis.

What must be kept in mind is that if such specialization is eventually shown, it would not be more fundamental than or instead of other asymmetries, that is, it would not negate the possibility that other asymmetries simultaneously exist for stimulus material, processing mode, and so forth.

5/ Conclusion: Main Contribution and Ultimate Purpose of the Current Study

Asymmetry for Visual Pattern Recognition Reflects Its Complex and Dynamic Characteristics

The primary contribution of this dissertation is the following view, based on both the current data and the literature reviews herein:

1. Visual pattern recognition is a complex behavior, that is, a network of sensory-perceptual and cognitive sub-behaviors controlled by different cerebral regions at different times during a single recognition sequence.

2. Pattern and magnitude of asymmetry during this behavior vary with stimulus, subject, and task characteristics; time (degree of stimulus familiarization, processing stage, and age of subject); and dependent variable.

Hence, the most accurate way of conceptualizing about asymmetry during pattern recognition is not by such general propositions as "a given hemisphere is specialized for recognizing a particular spatial frequency range," but rather by statements specifying the conditions under which such specialization occurs. Further, the most fruitful approach to investigating this behavior is the use of a high-resolution physiological technique sensitive to its dynamic characteristics, for example, one that is capable of revealing shifts in advantage with processing stage.

Theoretical and Clinical Values of the Current Study

Finally, as mentioned at the outset of this study, the author chose to study visual pattern recognition for both theoretical and clinical purposes. Regarding its theoretical purpose, understanding recognition for its own sake is valuable because it is such a fundamental cognitive function, itself a sub-behavior in such critical human intellectual processes as concept formation and language.

Regarding its clinical purpose, the current study provides preliminary data for an ERP study that has been designed to investigate the emergent level issue. That study will yield normative "visual recognition ERPs" that can be used as a standard against which abnormal ones can be measured. Hence, the current data are a first step toward generating a tool to be used to functionally localize visual recognition deficits.

It is the author's intention and hope that the current psychophysical data in combination with the literature reviews and critiques; the presentation of methodological considerations; the examination of the possible emergent level of, and neural mechanisms underlying, hemispheric specialization for spatial frequency; the suggestions for future research; and the EP data to be collected in a subsequent study will be successful in achieving its clinical goal, namely, treating those who examine known "objects as if they were being presented for the first time" (Klüver & Bucy, 1938, p. 39).

Appendix A

Hand Preference Questionnaire: Bryden Test

Instructions. For each of the activities listed below, indicate with a "++" which hand you normally use to perform the activity. If you would only use the other hand when forced to, mark a "+". If you would use both hands equally often, place a "+" in each column.

Activity	Hand	
	Left	Right
1. Writing a message.		
2. Drawing a picture.		
3. Using a toothbrush.		
4. Throwing a ball.		
5. Using a pair of scissors.		

Scoring. Assign 1 point for L++, 2 for L+, 3 for a + in each column, 4 for R+, and 5 for R++. Sum the scores, subtract 15, and divide by 10. This will yield a score ranging from -1 (extremely left-handed) through 1 (extremely right-handed).

Note. From *Laterality: Functional Asymmetry in the Intact Brain* (p. 164) by M. Bryden, 1982, New York: Academic Press.

Appendix B

Table B-1. ANOVA on Number Correct Responses

Source	df	Sum of squares	F	p
G	1	24.025	0.56	
S (G)[a]	18	777.600	--	
VF	1	11.025	2.98	
G x VF	1	0.625	0.17	
S x VF (G)[a]	18	66.600	--	
F	3	3109.425	90.54	.0001
G x F	3	43.125	1.26	
S x F (G)[a]	54	618.200	--	
VF x F	3	151.025	7.64	.0003
G x VF x F	3	5.125	0.26	
S x VF x F (G)[a]	54	355.600	--	

Note. G = gender. S = subject. VF= visual field. F = frequency.

[a] error term.

Appendix C

Table C-1. ANOVA on d' Responses

Source	df	Sum of squares	F	P
G	1	0.4687	0.16	
S (G)[a]	18	53.5122	--	
VF	1	0.2673	0.25	
G x VF	1	1.2567	1.20	
S x VF (G)[a]	18	18.9158	--	
F	3	101.3465	82.66	.0001
G x F	3	0.5662	0.46	
S x F (G)[a]	54	22.0692	--	
VF x F	3	3.8522	6.83	.0006
G x VF x F	3	0.2817	0.50	
S x VF x F (G)[a]	54	10.1589	--	

Note. G = gender. S = subject. VF = visual field. F = frequency.

[a] error term.

Appendix D

ANOVAs on Visual Field Advantage Indices

Table D-1. Entire Session Data

Source	df	Sum of squares	Mean Square	F	P
M	1	0.05859	0.05859	0.31	
G	1	0.15798	0.15798	0.83	
E	18	3.43708	0.19095	--	
F (1)	1	0.11509	0.11509	0.22	
F (1) x G	1	0.40227	0.40227	0.77	
E	18	9.46313	0.52573	--	
F (2)	1	0.83538	0.83538	5.06	.0372
F (2) x G	1	0.55029	0.55029	3.33	
E	18	2.97142	0.16508	--	
F (3)	1	4.32536	4.32536	12.94	.0021
F (3) x G	1	0.04851	0.04851	0.15	
E	18	6.01618	0.33423	--	
F	3	5.27583	1.75861	5.15	.0033
F x G	3	1.00107	0.33369	0.98	
E	54	18.45072	0.34168	--	

Note. M = mean. G = gender. E = error. F = frequency. (1) = linear trend. (2) = quadratic trend. (3) = cubic trend.

Appendix D

ANOVAs on Visual Field Advantage Indices

Table D-2. Block 1 Data

Source	df	Sum of Squares	Mean Square	F	P
M	1	0.03081	0.03081	0.15	
G	1	0.04278	0.04278	0.21	
E	18	3.63883	0.20216	--	
F (1)	1	0.02907	0.02907	0.05	
F (1) x G	1	0.07756	0.07756	0.14	
E	18	10.05219	0.55846	--	
F (2)	1	0.06441	0.06441	0.20	
F (2) x G	1	0.05050	0.05050	0.16	
E	18	5.77311	0.32073	--	
F (3)	1	0.77704	0.77704	5.37	.0325
F (3) x G	1	0.20657	0.20657	1.43	
E	18	2.60541	0.14475	--	
F	3	0.87502	0.29017	0.85	
F x G	3	0.33463	0.11154	0.33	
E	54	18.43072	0.34131	--	

Note. M = mean. G = gender. E = error. F = frequency. (1) = linear trend. (2) = quadratic trend. (3) = cubic trend.

Appendix D

ANOVAs on Visual Field Advantage Indices

Table D-3. Block 2 Data

Source	df	Sum of Squares	Mean Square	F	P
M	1	0.24864	0.24864	1.18	
G	1	0.04418	0.04418	0.21	
E	18	3.79018	0.21057	--	
F (1)	1	1.19684	1.19684	3.22	
F (1) x G	1	0.33062	0.33062	0.89	
E	18	6.69212	6.69212	--	
F (2)	1	0.03960	0.03960	0.18	
F (2) x G	1	0.96800	0.96800	4.37	.0511
E	18	3.98939	3.98939	--	
F (3)	1	1.92654	1.92654	13.27	.0019
F (3) x G	1	0.15602	0.15602	1.07	
E	18	2.61325	0.14518		
F	3	3.16298	1.05433	4.28	.0088
F x G	3	1.45465	1.45465	1.97	
E	54	13.29476	0.24620	--	

Note. M = mean. G = gender. E = error. F = frequency. (1) = linear trend. (2) = quadratic trend. (3) = cubic trend.

Appendix D

ANOVAs on Visual Field Advantage Indices

Table D-4. Block 3 Data

Source	df	Sum of Squares	Mean Square	F	P
M	1	0.17020	0.17020	0.86	
G	1	0.05995	0.05995	0.30	
E	18	3.56637	0.19813	--	
F (1)	1	0.05406	0.05406	0.10	
F (1) x G	1	0.18447	0.18447	0.35	
E	18	9.59626	9.59626	--	
F (2)	1	0.42195	0.42195	1.87	
F (2) x G	1	0.19110	0.19110	0.85	
E	18	4.05967	0.22554	--	
F (3)	1	0.70141	0.70141	3.60	
F (3) x G	1	0.27931	0.27931	1.43	
E	18	3.50935	0.19496	--	
F	3	1.17741	0.39247	1.23	
F x G	3	0.65488	0.21829	0.69	
E	54	17.16528	0.31788	--	

Note. M = mean. G = gender. E = error. F = frequency. (1) = linear trend. (2) = quadratic trend. (3) = cubic trend.

Appendix D

ANOVAs on Visual Field Advantage Indices

Table D-5. Block 4 Data

Source	df	Sum of Squares	Mean Square	F	P
M	1	0.06328	0.06328	0.48	
G	1	0.29890	0.29890	2.25	
E	18	2.39414	0.13301	--	
F (1)	1	0.00016	0.00016	0.00	
F (1) x G	1	0.00021	0.00021	0.00	
E	18	6.47260	0.35959	--	
F (2)	1	0.52650	0.52650	2.60	
F (2) x G	1	0.50721	0.50721	2.50	
E	18	3.64541	0.20252	--	
F (3)	1	1.10776	1.10776	3.05	
F (3) x G	1	0.00081	0.00081	0.00	
E	18	6.53312	0.36295	--	
F	3	1.63441	0.54480	1.77	
F x G	3	0.50823	0.16941	0.55	
E	54	16.65113	0.30835	--	

Note. M = mean. G = gender. E = error. F = frequency. (1) = linear trend. (2) = quadratic trend. (3) = cubic trend.

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