7

Lateralization of Cerebral Functions

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The human brain is clearly divided into hemispheres by a deep longitudinal fissure. Although these hemispheres are similar from a gross anatomical point of view, research over the past century suggests that they have specialized functions. Anatomically, right-handed individuals display asymmetries between the hemispheres of the primary motor cortex (M1), whereas individuals who are left-handed do not show these same asymmetries (Solodkin, Hlustik, Noll, & Small, 2001). The anatomical difference of M1 between left- and right-handed individuals suggests that motor physiology (i.e., sequential movements) may differ between right- and left-handed individuals (Solodkin et al., 2001). Asymmetries are also found in the frontal, temporal, and parietal lobes (Hugdahl, 1996).

Microanatomical and psychophysiological differences in hemispheres of the brain have been observed as early as the 30th week of gestation (Molfese, Freeman, & Palermo, 1975; Wada, Clarke, & Hamm, 1975). Others have argued that lateralization begins as early as 12 weeks gestation (McCartney & Hopper, 1999). While elementary lateralization is measurable in perinatal stages, more complex patterns of hemispheric specialization continue to develop during childhood and into adulthood (Dean & Anderson, 1997; Satz, Bakker, Teunissen, Goebel, & van der Blugt, 1975). Research incorporating functional magnetic resonance imaging (fMRI) and positron emission topography (PET) affirms early evidence that structural differences between hemispheres may lead to functional differences and thus specialization for tasks and activities within each hemisphere (Robichon, Levrier, Farnarier, & Habib, 2000; Xu et al., 2001).This chapter examines aspects of hemispheric lateralization of functions that may hold clinical insights. Following a review of a number of critical issues in the assessment and understanding of hemispheric differences, the clinical significance of a lack of secure hemispheric lateralization will be examined for language disorders.

HISTORICAL ANTECEDENTS

Early in the nineteenth century a number of papers were published that began to link complex psychological functions to specific areas of the brain. Although efforts in the specific localization of functions to microstructures of the brain have not fared well, broad organizational principles of the relationship between anatomical features of the brain and behavior remain the focus of neuropsychology (Dean, 1985a). It is now well recognized that an individual's developmental history and normal differences in both the structure and the chemistry of the brain interact in such a way that highly specific structural localization of functions is a tenuous pursuit. Thus, although hemispheric differences are acknowledged, highly specific localization of function does not appear as robust as once portrayed. Parallel increases in neuropsychological instruments and neuroimaging have shifted the foci of neuropsychology toward examination of the relationship between behaviors and the structural functioning of the brain (Dean & Anderson, 1997).

Serious consideration of functional asymmetry of hemispheres may be traced to Broca's (1861) and Dax's (1865) clinical observations of brain-damaged subjects. Moreover, patients with damage to the left hemisphere were reported to have compromised linguistic processes. Specifically, Broca (1861) concluded that with damage to the third convolution of the left cerebral cortex, many aspects of the patient's speech were impaired. Jackson's seminal work in the late nineteenth century began to articulate more fully the idea of two different yet coexisting modes of cognitive processing that followed hemispheric lines of the brain (1932). Summarizing his clinical observations, Jackson argued that "in most people, the left side of the brain is the leading side—the side of the so-called will, and the right is the automatic side" (1932, p. 141). Although Jackson also described the left hemisphere as serving functions of sensation and perception.

These conclusions extended Dax's (1865) and Broca's (1861) observations and provided the underpinnings of what has been referred to as the bimodal theory of hemispheric processing. The evolving notion of hemispheric dominance was originally articulated to distinguish the hemisphere that most clearly served language functions and has only recently taken on more global connotations associated with control functions. The luxury of retrospect allows criticisms of reports that offered conclusions on normal function based on the study of diseased brains. However, these early papers are the antecedents of continued research efforts.

Congruent with increased experimental sophistication of recent investigations has come debate as to the nature of the lateralization process. Thus, although consistent hemispheric differences are acknowledged by more neuroscientists, debate continues as to whether hemispheric differences in processing (e.g., Geschwind & Levitsky, 1968; Petersen, Fox, Posner, Mintun, & Raichle, 1989), attention (e.g., Kinsbourne, 1975), or storage (e.g., Hardyck, Tzeng, & Wang, 1978) are responsible. Although most investigators have found the arguments favoring processing differences to be more heuristic, Hardyck and colleagues' (1978) data concerning hemispheric lateralization in memory storage and Kinsbourne's (1970) reports regarding the direction of attention between hemispheres need to be seriously addressed when attempting conclusions concerning the underlying neurological mechanism.

LATERALIZATION OF FUNCTIONS

The notion that hemispheres of the brain selectively serve rather different psychological functions has gained scientific credence (Dean, 1985b). Although acknowledging interhemispheric communication, laboratory and clinical researchers portray distinct hemispheric differences for more complex cognitive functions. As may be gathered from Table 7.1, investigations of patients who have undergone surgical section of the corpus callosum and those with localized brain damage to one hemisphere indicate rather clear differences in the functional efficiency between hemispheres. As suggested early on by Dax, Broca, Wernicke, and Jackson, the left hemisphere has been more closely linked to processing involving speech, language, and calculation (Reitan, 1955; Sperry, 1969) than has the right. Poizner, Bellugi, and Klima (1990) have offered similar data with deaf individuals who have had either a right or a left hemispheric lesion. Furthermore, Jackson implicated that lateralization of speech to the left hemisphere and thus localization of speech ability to this area of the brain does not imply that all damage that impacts speech is inherently within such areas. Brain injury resulting in speech impairments could occur in processes

TABLE 7.1 Lateralized Functions of the Right and Left Hemispheres

Function	Reference
	Right hemisphere
Processing modes	
Simultaneous	Sperry (1974)
Holistic	Sperry (1969); Dimond & Beaumont (1974)
Visual/nonverbal	Sperry (1974); Savage & Thomas (1993)
Imagery	Seamon & Gazzaniga (1973)
Spatial Reasoning	Sperry (1974); Poizner, Bellugi, & Klima (1990)
Nonverbal functions	
Depth perception	Carmon & Bechtoldt (1969)
Melodic perception	Shankweiler (1966)
Tactile perception (integration)	Boll (1974b)
Haptic perception	Witelson (1974)
Nonverbal sound recognition	Milner (1962)
Motor integration	Kimura (1967)
Visual constructive performance	Parsons, Vega, & Burn (1969)
Pattern recognition	Eccles (1973)
Memory/learning	
Nonverbal memory	Stark (1961)
Face recognition	Milner (1967); Hecaen & Angelergues (1962)
	Left hemisphere
Processing modes	
Sequential	Sperry, Gazzaniga, & Bogen (1969)
Temporal	Mills (1977); Efron (1963)
Analytic	Morgan, McDonald, & McDonald (1971); Eccles (1973)
Verbal functions	
Speech	Wada (1949); Reitan (1955); Posner, Petersen, Fox, & Raichle (1988)
General language/verbal abilities	Gazzaniga (1970); Smith (1974)
Calculation/arithmetic	Reitan (1955); Eccles (1973); Gerstmann (1957)
Abstract verbal thought	Gazzaniga & Sperry (1962)
Writing (composition)	Sperry (1974); Hecaen & Marcie (1974)
Complex motor functions	Dimond & Beaumont (1974)
Body orientation	Gerstmann (1957)
Vigilance	Dimond & Beaumont (1974)
Learning/memory	
Verbal paired-associates	Dimond & Beaumont (1974)
Short-term verbal recall	Kimura (1961)
Abstract and concrete words	McFarland, McFarland, Bain, & Ashton (1978); Seamon & Gazzaniga (1973)
Verbal mediation/rehearsal	Dean (1983); Seamon & Gazzaniga (1973)
Learning complex motor functions	Dimond & Beaumont (1974)

necessary to create speech within either hemisphere. Thus, localizing function or damage is independent of the localization of speech (Zillmer & Spiers, 2001).

The study of sign language with brain-damaged individuals allows another perspective of hemispheric specialization, as it is a combination of visual-spatial elements and language. These differences seem more heuristically attributed to the mode in which information is processed than to the specific stimuli or modality of presentation (Brown & Hecaen, 1976). That is to say, the left hemisphere has been shown to be better prepared to process information in a more analytical, logical, or sequential fashion; as such, language is an excellent tool for such processing (Kimura, 1961). Research that has examined the electrical activity of the brain (electroencephalographic studies) and relies on perceptual asymmetries reinforces the duality of cerebral processing (Gordon, 1978; Kimura, 1967; Morgan, McDonald, & McDonald, 1971).

Studies of autism also demonstrate the effects of lateralization upon language. Recent evidence concerning autism has implicated abnormal lateralization as a cause of language deficits (Escalante-Mead, Minshew, & Sweeney, 2003). The authors suggested that language disturbances in autism may be associated with the left hemisphere not developing as a specialized area for language skills. For example, patients diagnosed with autism, characterized by delayed language development, exhibited reduced rates of established lateral hand preference (Escalante-Mead et al., 2003). Alternatively, patients with high-functioning autism with normal language development were more likely to demonstrate an established lateral hand preference.

Generally, the linguistic dependence of the left hemisphere is not seen in tasks shown to be typically served by the right hemisphere. As shown in Table 7.1, the right hemisphere is more closely linked to a direct representation of visual-spatial reality. Indeed, the right hemisphere is shown to be prepotent (Sperry, 1969) in the presence of nonverbal-spatial task requirements. The frequent inference that this verbal–nonverbal distinction follows hemispheric lines seems something of an overstatement (Dean, 1985b). Moreover, research indicates that one must closely examine the requirements of and cognitive processes involved in the individual task before assuming hemispheric differences. Examination of the requirements associated with the task rather than the stimuli involved in the task provides greater insight into hemispheric specialization as confirmed through fMRI studies (Stephan et al., 2003). Such research supports assessment of the hemispheres through the information-processing model rather than discrete localization or task approaches and gives way to assessment implications (Springer & Deutsch, 1998).

Research findings with patients who have suffered right hemispheric damage contrasts, in many ways, with the research findings for patients with damage to the left hemisphere. In general, it seems that the right hemisphere more efficiently serves tasks that require the holistic, or simultaneous, processing of nonverbal gestalts and the complex transformations of complex visual patterns (e.g., Milner, 1962). As such, incoming information of a parallel or spatial nature that requires cognitive manipulation has been shown to be closely linked to processing in the right hemisphere (e.g., Gordon, 1970). It also seems that information that does not lend itself to verbal mediation, such as diffuse representation of the environment, is most efficiently served by the right cortical hemisphere (Levy, Trevarthen, & Sperry, 1972). Recent research has expanded the commonly assumed nonverbal functions of the right hemisphere to include aspects of memory, depth perception, and motor integration (see Table 7.1). More recently, visual-half field techniques demonstrate a right-field preference for word recognition in regards to laterality while visuospatial tasks and face processing demonstrate a left-field preference, which supports the notion that the right hemisphere more efficiently processes simultaneous processing of nonverbal gestalts and complex visual patterns (Hugdahl, 1996). However, some crossover in functions may exist. Indeed, hearing-impaired subjects with right hemispheric lesions have been found to have visual-spatial deficits, although they possessed the ability to sign and comprehend sign language. Conversely, left-hemispheric signers showed signing or interpreting deprivation but retained nonlanguage spatial functions (Poizner et al., 1990).

Apparently, individuals have some control over the mode of processing that will be utilized and thus the specific hemisphere. Dean and Hua (1982) have offered data portraying hemispheric specialization as an active constructive process, with the specific form of encoding dependent on constraints of attention and individual differences in the lateralization of functions. Hemispheric specialization is also often used to denote differences between hemispheres when processing sensory information (Hugdahl, 1996). Evidence for this position also comes from investigations showing that visual-spatial stimuli may be encoded semantically (Conrad, 1964) and that verbal material can be represented as visual traces (Paivio, 1971). Apparently, individuals can process and encode information in at least two qualitatively distinct but interconnected systems (see Bower, 1970; Paivio, Clark, Digdon, & Bons, 1989). These processing modes have been shown to follow in part the left–right functional distinction. In essence, learners can readily generate nonverbal or verbal processing strategies regardless of the form of the original stimulus. These rather different modes of processing correspond to function ordinarily seen as hemisphere-specific (Bower, 1970; Dean, 1985a; Paivio et al., 1989).

A corollary view, in concert with Luria's (1966) theory, has been articulated by Das (1973). These researchers have characterized differences in hemispheric processes as complementary and coexisting modes. Research seems consistent with cortical functions of the right and left cerebral hemispheres (e.g., Luria, 1966), spoken of as simultaneous and successive modes of information processing. While Luria acknowledged discrete cortical zones, equipotentiality theory proposes that all parts of the cortex contribute to cortical processing of complex functions. Thus, research relevant to hemispheric specialization and cerebral dominance remains conflicted as to the functional roles of each hemisphere in cortical processing (Dronkers, 2001; Rains, 2002).

Hemispheric Functional Similarities

Despite compelling evidence favoring hemispheric lateralization of functions, a good deal of symmetrical processing occurs. Research with normal individuals and patients who have suffered unilateral lesions indicates equal proficiency of hemispheres in registering and storing sensory information (Milner, 1962). The magnitude of functional lateralization would seem to increase in direct proportion to the amount of conceptual reformulation or, if you will, cognitive processing necessary for interpretation and encoding (Gordon, 1974).

Patients with unilateral lesions to either hemisphere generally show deficit performance in the extraction of stimulus features (e.g., brightness, color, pitch, and elements of somatosensory perception) compared with normal controls (e.g., Gordon, 1974; Milner, 1962; Scotti & Spinnler, 1970). In contrast to higher-order differences in function between groups of patients with unilateral left and right hemispheric lesions, lower-level sensory discrimination differences between patients with localized lesions lack robustness (e.g., Gordon, 1974; McKeever & Gill, 1972). Apparently, specific performance deficits that correspond to the hemisphere in which the patient has suffered damage occur only when patients are required to reorder, categorize, integrate, or abstract stimulus elements. It would seem that as the degree of cognitive processing necessary for a task increases, so too does the extent to which that function is asymmetrically lateralized.

Using split visual field (e.g., McKeever & Gill, 1972), auditory evoked potentials (Gordon, 1974), and dichotic listening (Darwin, 1974, 1975) techniques with normal subjects, a number of investigators have shown hemispheric symmetry in the extraction of low-order visual, auditory, and tactile elements with normal adults. Such findings seem robust and have been found even in cases in which the target stimuli are embedded in a verbal or nonverbal context (e.g., Rabinowicz, 1976; Wood, 1975). Apparently, then, when normal subjects must discriminate simple sensory elements such as brightness, pitch, color, pressure, sensitivity, sharpness, or contour, few hemispheric differences in processing are evident. However, when the task requires higher-order cognitive processing beyond that found in such simple discrimination, rather clear hemispheric differences become evident.

Evidence indicates that hemispheric asymmetries are also related to the amount of previously encoded information that must be used to interpret incoming sensory information (e.g. Goodglass & Peck, 1972; Moscovitch, 1976). Moscovitch (1979) argues elegantly that accentuated hemispheric asymmetries occur after a delay in the recognition or recall of incoming stimuli (e.g., Goodglass & Peck, 1972; Milner, 1968). Functional lateralization varies in proportion to the degree of transformation that has occurred prior to encoding. In sum, then, it appears that hemispheric asymmetries in function are more clearly evidenced in tasks requiring higher-order processing or when incoming information must be interpreted in light of prior knowledge.

Subcortical structures also show a left–right asymmetry. Hugdahl, Wester, and Asbjornsen (1990) studied patients with Parkinson's disease who were undergoing stereotactic thalamotomy surgery in an attempt to reduce tremors and rigidity. Using a dichotic listening technique, the authors compared patients operated either in the left or right thalamus. The results demonstrated that patients with operations in the left thalamus demonstrated cognitive dysfunction, while those patients with right side thalamus surgery did not demonstrate the same cognitive dysfunction (Hugdahl, 1996). The authors determined that a subcortical activating gating mechanism in the left ventrolateral thalamic nucleus controlled the flow of auditory language information to the corresponding cortical area. More importantly, the study revealed the importance of the subcortical structures for functional asymmetry in cognition (Hugdahl, 1996). Wittling (1995) also supported the notion that brain asymmetry involves the entire nervous system, not just the cortical hemispheres.

Developmental Aspects

Structural differences in the hemispheres of the brain exist prior to birth (Geschwind & Levitsky, 1968). Left hemispheric structures (left temporale planum), most often considered to serve speech, language, and reading functions, are significantly larger than temporal structures of the right hemisphere early in gestation (Geschwind & Levitsky, 1968; Robichon et al., 2000; Witelson & Pallie, 1973). Rather clear structural differences have also been noted in the rate at which the pyramidal tract develops projections to hemispheres of the brain. Yakovlev and Rakic (1966) have shown consistently earlier crossing of projections from the left hemisphere than seen for the right hemisphere. Such research has begun to outline early structural differences between hemispheres that may be the precursors of functional differences in cerebral hemispheres.

Equipotentiality, most clearly attributed to Lenneberg (1967), portrays the cerebral hemispheres of the brain as having equal potential in the development of functional specialization for language. Although this is an appealing notion, neurophysiological differences between hemispheres (Molfese et al., 1975; Wada et al., 1975) and early neuroanatomical differences limit its explanatory power. Of course, rejection of the notion of early equal potential of hemispheres does not rule out the possibility that functional lateralization is a progressive, developmental process.

The extent to which functions are progressively lateralized to cerebral hemispheres is still a matter of controversy (Kinsbourne, 1975; Satz, 1976). Cerebral lateralization has been portrayed to follow patterns similar to that for the development of numerous psychological functions (Bruner, 1974; Piaget, 1952). From this point of view, the functional lateralization of hemispheres is seen to follow a progressive pattern of consolidation of functions corresponding to the child's neurological development (e.g., Dean, 1985a; Satz et al., 1975). Although arguments favoring early specific specialization continue (Kinsbourne, 1975), a large corpus of data exists supporting developmental progression in the lateralization of functions (see Dean, 1985a). While left hemispheric asymmetries related to language are present at birth, further research has demonstrated that language may still develop normally in children who sustain a unilateral lesion in the left hemisphere (Dean & Anderson, 1997). Neuroimaging studies have postulated two sides to the development or presence of functional lateralization such that language is either bilaterally organized at birth and becomes specialized to the left hemisphere or language is localized to the left hemisphere at birth (Balsamo et al., 2002; Booth et al., 2001).

The lateralization of language of the left hemisphere has been argued to correspond to the continuing maturation of secondary association areas, which begins some time after the 5th year of life (Peiper, 1963). Indeed, we find a decrease in the role played by the right hemisphere in language, which covaries with the child's neurological development (see Krashen, 1973). Sperry (1968, 1969) has suggested that this progressive lateralization of function may well relate to the rather slow maturation of the commissure-associative cortex. In this regard, numerous reports suggest that the rate of lateralization varies with the specific function being examined (Molfese, 1977; Waber, 1977). Clearly, it would seem that although hemispheric asymmetries for certain functions are observable in the neonate, patterns of functional lateralization continue to develop in an orderly fashion throughout the early childhood years (see Satz et al., 1975).

Related to developmental aspects of hemispheric specialization is the notion of functional plasticity. Plasticity here refers to the degree to which functions of a damaged hemisphere are preempted by the other. As early as the nineteenth century, clinical reports suggested that the effects of damage to the left hemisphere before adolescence were less severe and language disturbances more transient than those from similar lesions occurring in adults (Dax, 1865). Since these early reports, numerous investigators have presented data favoring what amounts to a "critical period" occurring between 5 and 7 years of age. Prior to this critical period, functions normally served by the left hemisphere may more completely be subserved by the right cerebral hemisphere following damage to the language center (Chelune & Edwards, 1981; Dikman, Matthews, & Harley, 1975; Pirozzolo, Campanella, Christensen, & Lawson-Kerr, 1981). In contrast, damage to similar areas occurring after this critical period is more severe and less transient (e.g., Dikman et al., 1975). These conclusions are consistent with Krashen's (1973) data suggesting a decreasing role of the right hemisphere for language with age. Neuroimaging studies have demonstrated that by 8 years of age language is no longer bilaterally evident (Balsamo et al., 2002).

The completeness of the transfer of functions between hemispheres is also positively related to the severity with which the brain is damaged (e.g., Pirozzolo et al., 1981). This conclusion is evidenced in patients who have undergone a left hemispherectomy before this critical period. In such cases, the behavioral effects are less devastating in terms of later language function than disabilities that occur with relatively minor damage to the left hemisphere (Dikman et al., 1975; Pirozzolo et al., 1981; Springer & Deutsch, 1998). Smith and Sugar (1975) have hypothesized that, with the removal of the left hemisphere, "competition for language" functions is less likely to occur than is true when more localized damage has occured. The heuristic value of plasticity as an explanatory term has begun to be questioned. Research suggests the process of plasticity and ability of the right hemisphere to subsume language functions occurs over time and is most evident in children under 5 years of age (Springer & Deutsch, 1998; Zillmer & Spiers, 2001). The interested reader is directed to Fletcher and Satz (1983) for the subtleties of the counterargument.

Sex Differences in Lateralization

Subtle structural neurological differences have been observed between males and females (see MacLusky & Naftolin, 1981). However, neuropsychological dissimilarity between adult males and females is more heuristically attributed to functional-organizational factors than to an obvious central nervous system disparity (Dean, 1985a; Kolata, 1979). Although genetic and morphological differences exist between males and females from conception, sex hormones have been shown to have more striking effects on the structure and function of the central nervous system (Baum, 1979; MacLusky & Naftolin, 1981; Weintraub, 1981). These sex steroids have a dramatic effect on the function and development of the nervous system because they are permeable to the blood-brain barrier. Hence, rapid changes in some sex-related brain functions may be due in part to the structure of androgens, which enable rapid access to the brain (Schmeck, 1980). Importantly, these sex hormones have privileged access to the brain early in gestation, when rates of development heighten their sensitivity (Baum, 1979; Gur, Gunning-Dixon, Bilker, & Gur, 2002).

The extent to which genetic-hormonal sex differences are responsible for hemispheric lateralization remains in dispute (see Maccoby, 1966). Of course, one must be careful not to attribute differences in neuropsychological functioning to gender when behavior could heuristically be attributed to social-cultural variables. With this caveat in mind, numerous neuropsychological differences between normal males and females have been reported that relate directly to an appreciation of the lateralization of brain functions. For example, the superior spatial ability of males and relatively greater verbal facility of females have been attributed to sex differences in hemispheric specialization arising from sex-specific steroids (Dean, 1985a; Levy & Levy, 1978). Several studies suggest that certain sex hormones (e.g., testosterone) stimulate growth in right hemispheric regions or delay development in left hemispheric regions (de Lacoste, Horvath, & Woodward, 1991; Tan, 1991). Indeed Reinisch and Sanders (1992) concluded that prenatal exposure to diethylstilbestrol (DES), a synthetic estrogen, reduced hemispheric laterality and lowered spatial ability.

Conversely, several studies argue that females with high androgen levels possess spatial abilities comparable to males (Kolb & Whishaw, 1990; Shute, Pelligrino, Hubert, & Reynolds, 1983). In this regard, Witelson (1976) offers data favoring earlier right hemispheric specialization for spatial processing in males than is found for females, who more often exhibit bilateral representation of these functions until early adolescent years. Hemispheric specialization for language has also been observed earlier in males than in females, who show less consistent lateralization throughout the life span (Levy, 1973). MacLusky and Naftolin (1981) argue convincingly that such findings may more heuristically be attributed to genetic-hormonal differences than to developmental rates in general. Goy and McEwen (1980) have presented data suggesting that sex hormonal differences also result in a proclivity to rely on specific cues (e.g., verbal, spatial) in learning and differences in the rate of acquisition for verbal and spatial stimuli.

Findings of less secure hemispheric specialization for females stand in contrast to the consistent report of more coherent lateral preference (handedness, eye preference, etc.) for females (Annett, 1976; Dean, 1986; Levy, 1973). In fact, a study by Cappa et al. (1988) suggested that the role of gonadal hormones and lateralization have little significance on the establishment of asymmetries. With the frequently drawn association between lateral preference and the functional lateralization of hemispheres, such findings seem rather paradoxical. Although lateral preference will be examined in greater depth later in this chapter, it suffices to say at this point that the one-to-one relationship between hand preference and hemispheric specialization for language may be rather naïve.

Although males evidence more consistent hemispheric lateralization of verbal and nonverbal functions, this consistency does not seem to occur without a consequence (Dean, 1985a; Nottebohm, 1979). The consequence here seems to be exhibited in a higher risk of specific expressive and receptive language disorders for males (Benton, 1975; Brain, 1965; Dean, 1981). Benton (1975) has reported a risk of language disorders for males 10 times greater than that for female cohorts. Assessment of demographic data reflects a greater percentage of males referred for assessment and special education services as well as a higher percentage of males with reading problems (D'Amato, Dean, Rattan, & Nickell, 1988; Share & Silva, 2003).

INFERRING FUNCTIONAL LATERALIZATION

Undoubtedly, the most predominant difficulty in the measurement and study of functional lateralization is the inaccessibility of the human brain. Indeed, the vast majority of our knowledge of human neuropsychology and the study of functional lateralization has come about as the result of inferential methods. Neuropsychological assessment grew out of a need to objectively describe the behavioral effects of known brain damage. Thus, until quite recently, functions of specific areas of the brain were inferred from behavioral deficits that correspond to localized lesions. Correlational in nature, these data have been the basis of the quantitative-actuarial approach that has dominated neuropsychology in North America. Clearly, attempts to link structure and function from this database often become a tautological pursuit.

With this limitation in mind, one can state that damage to the left hemisphere of the brain in most right-handed individuals corresponds to deficits in speech, language, and calculation (Boll, 1974a, 1974b; Reed & Reitan, 1963; Reitan, 1955), whereas damage to the right hemisphere correlates with functional deficits of a more nonverbal nature (Reitan, 1955). Although handedness will be examined in greater detail later in this chapter, it suffices to say that language disturbances for left-handed individuals after left hemispheric damage are less severe and more transient than those for right-handers (Hecaen, 1962). These results are often cited as the basis for inferring less secure left hemispheric lateralization of language for most left-handed individuals. Such data have been cited as the basis for making inferences from scores on neuropsychological test batteries (Reitan, 1969).

Sperry and his associates (Gazzaniga & Sperry, 1962; Sperry, 1968; Sperry, Gazzaniga, & Bogen, 1969) have confirmed and extended the neuropsychological findings for patients with localized lesions in research involving surgical section of the corpus callosum as a treatment for intractable seizures. The amount of communication between hemispheres is drastically reduced with this procedure, and functions of individual hemispheres can be more completely examined. Although difficulties exist in drawing conclusions about normal hemispheric functioning from such patients, the contribution of Sperry and his associates to our understanding of hemispheric function has been seminal. In general, research with split-brain subjects has refined our understanding of functional lateralization and confirmed that, in most right-handed and many left-handed individuals, complex linguistic functions are served by the left hemisphere (Dean & Hua, 1982; Kimura, 1961; Sperry, 1968; Springer & Deutsch, 1998) and visual-spatial reality is more closely linked to the right hemisphere (Milner, 1962).

In addition to the research concerning functions that are compromised with lateralized lesions, most neuropsychological batteries utilize tasks that allow comparison of right side performance with left side performance. This is possible, of course, because simple unimanual performance and sensory perception to one side of the body are served by the contralateral hemisphere. Thus, left versus right differences in strength of grip, finger tapping, and finger localization are compared against normal values. With larger than expected differences, inferences can be made concerning lateralized impairment. In turn, these results are interpreted in conjunction with functions (e.g., language) most often associated with either left or right hemisphere impairment. Although less useful in making diagnostic statements, most neuropsychology batteries include a measure of lateral preference for motor tasks (e.g., Halstead-Reitan Lateral Dominance examination, Dean-Woodcock Sensory Motor Battery Lateral Preference subtest) as an indicator of the degree to which functions ordinarily ascribed to one hemisphere or the other can be applied to a given patient. Lateral preference percentages match distributions for planum temporale asymmetries in the general population and thus provide additional evidence for assessment of language processing (Richardson, 1995).

Normal Perceptual Asymmetry

The Wada Test (Wada, 1949), which involves the intracarotid injection of amytal to one hemisphere or the other, has been considered to be the most emphatic measure of hemispheric functional specialization. Obviously, the use of this method with basically normal subjects is questionable. However, recent advances in neural imaging technology employing positron emission tomography (PET) and magnetic resonance imaging (MRI) have allowed more precise anatomical-functional correlations in the primary and secondary sensory and motor areas of the human brain (Damasio & Damasio, 1992; Petersen et al., 1989). Nevertheless, because these are rather new techniques, expense and accessibility can be somewhat problematic. Short of these techniques, the use of perceptual asymmetry techniques to infer functional lateralization based on a left–right difference in performance remains the most extensively used procedure with normal subjects (Dean, 1983).

In the dichotic listening technique, which was first introduced by Broadbent (1954) and refined by Kimura (1961), auditory asymmetries for various verbal and nonverbal stimuli are assessed. Specifically, the ear advantage is measured when different stimuli are presented simultaneously to each ear. In this way, hemispheric differences are inferred because there are a greater number of contralateral than ipsilateral ear-to-hemisphere "nerve connections"; and ipsilateral input from one ear is "blocked" by simultaneous stimuli presented to the contralateral ear. Thus, the dominant hemisphere for a particular stimuli (e.g., consonant-vowel letter groups) is inferred from more consistent recall or recognition of specific stimuli presented to the ear opposite that hemisphere. Therefore, if a given subject reports more correctly or reacts more quickly for a specific signal to one ear than the other (ear advantage), the contralateral hemisphere to the ear is considered to be specialized for that function (Kimura, 1961).

Although any simple comparison of individual studies is difficult due to differences in specific stimuli and subtleties in procedures, it may safely be concluded that for normal adults (Dean & Hua, 1982; Kimura, 1961) and children (Dean, 1983; Hynd & Obrzut, 1977; Summers & Taylor, 1972) a right-ear advantage exists for linguistic stimuli when presented in a dichotic fashion. Thus, data with normals support a left hemisphere specialization for language often inferred from clinical studies of brain-damaged patients (e.g., Reitan, 1955). In contrast, dichotic presentation of nonverbal tones most often has been shown to produce a left-ear advantage for most normal right-handed subjects (Kimura, 1967). While results obtained from dichotic listening tests tend to align with Wada Test findings, other results may prove contradictory especially for non–right-handed subjects (Bryden, 1988; Hugdahl, Carlsson, Uvebrant, & Lundervold, 1997; Segalowitz, 1986). Although distinct methodological difficulties exist (Berlin & Cullen, 1977; Birkett, 1977; Bryden, 1978; Satz, 1976), the dichotic listening technique is considered by many to be the most valid noninvasive indicator for inferring functional hemispheric lateralization for language.

The split visual field technique is similar to the dichotic listening paradigm in terms of neurological assumptions. Because the visual half fields in humans are contralaterally served by the hemispheres of the brain, stimuli presented to one visual field (e.g., right) have privileged access to the opposite hemisphere (e.g., left). The presentation of stimuli is most often accomplished with a tachistoscope, which allows exposure to different stimuli by both visual fields simultaneously. Very brief exposure periods reduce the methodological difficulties that would be attributed to the possibility of eye movements during presentation. Early on, research utilizing the visual half field technique employed unilateral presentations (e.g., Heron, 1957). Recent research has been more sensitive to the methodological difficulties associated with unilateral presentations and has focused on simultaneous bilateral exposures. In this research, we would expect and indeed we find an advantage to the right visual half (left hemispheric) for linguistically related material (Kershner, 1977; Marcel & Rajan, 1975).

Because of the possibility of post-exposure attentional scanning (Witelson, 1977) and other difficulties related to the visual mode of presentation (Dean, 1981), methodological difficulties continue in the use of this technique with linguistic stimuli. A left-field advantage has consistently been reported when tasks involve more nonverbal spatial stimuli (Kimura & Durnford, 1974). Indeed, McLaren and Bryson (1987) demonstrated similar findings when nonverbal emotional stimuli (pairs of expressive and neutral faces) presented in the left visual field (i.e., right hemisphere) enhanced subjects' emotional responses. However, a recent study by Gainotti, Caltagirone, and Zoccolotti (1993) argued that there may be some interconnection between the left/right and cortical/subcortical structures, because the right hemisphere is dominant for basic levels of emotional arousal and response, whereas the left hemisphere may be more involved in the cortical aspects of inhibition and may dominate the subcortical emotional functions.

Kinsbourne and Cook (1971) have reported data favoring hemispheric lateralization when subjects are required to perform different tasks, both of which are lateralized in a single hemisphere simultaneously. The consistent finding using this paradigm has been significantly greater interference for verbal tasks in the right-hand performance of motor tasks than that found for the left hand. Comparing left- and right-hand performance on dowel-balancing and finger-tapping tasks, researchers have inferred greater lateralization of language functions in the left hemisphere because of greater interference in the performance of the right hand (e.g., Hiscock, Antoniuk, & Prisciak, 1985; Kinsbourne & Cook, 1971).

Research that has examined the electrical activity of the brain also reinforces the hemispheric lateralization of functions. When utilizing electroencephalographic (EEG) leads, decreased activity is inferred from the presence of alpha waves. The majority of studies that employ this technique have shown increased alpha activity in the right hemisphere (post-central area) when normal right-handed subjects are involved in verbal analytic tasks (Morgan et al., 1971). Conversely, greater alpha activity has been noted in the left hemisphere of normal individuals when they have been required to perform spatial or musical tasks (Davidson & Schwartz, 1977; Morgan et al., 1971). Thus, in concert with research involving other research paradigms, EEG studies indicate a verbal-analytical versus spatial-holistic processing difference that corresponds to the left and right hemispheres of the brain.

Recently, Savage and Thomas's (1993) data of visual evoked potentials (VEP; i.e., subjects pressed a button when a stimulus appeared), measured by EEG, showed that reaction time was faster and right hemisphere activity was more prevalent for right-handers, whereas hemispheric asymmetries were less consistent for left-handers. Moreover, PET studies of normal right-handed subjects have indicated that specific processing differences do indeed exist (e.g., Petersen et al., 1989; Posner et al., 1988). These studies identified specific brain areas related to lexical (i.e., single word) processing. However, it is the underlying process requirements of the task that are localized rather than the actual task itself (Posner et al., 1988).

Lateral Preference

The performance of unimanual activities on one side of the body is served by the contralateral hemisphere of the brain. Consistent with the rather antiquated notion of cerebral dominance, it has long been inferred that lateral preference may be a behavioral expression of the degree of functional specialization of the left hemisphere for language and other control functions. Indeed, most clinical examinations and neuropsychological batteries have incorporated some measure of lateral preference (handedness, eye preference, etc.) as an indicator of the underlying functional organization of cortical hemispheres. A corollary to the notion of hemispheric dominance is the long-held hypothesis that anomalous preference patterns may underlie many functional disorders (e.g., Orton, 1937). The relationship between atypical patterns of lateral preference and cortical functioning remains one of the most studied and controversial issues in neuropsychology (Dean, 1985a).

The implicit assumption has been that observable patterns of preference would reflect functional lateralization of cortical hemispheres (Harris, 1947). Although measures have varied from direction of eye gaze (Reynolds, 1978) to left or right turning of the individual's hair whorl (Tjossen, Hansen, & Ripley, 1961), research has concentrated on hand preference (Dean, 1983). This concentration probably relates to the deceptive ease in assessment and various reports of a higher incidence rate of mixed-hand preference for individuals with a number of expressive and receptive language disorders (e.g., Orton, 1937).

Population estimates based on large samples suggest that some 90% of normal individuals may be considered as right-handed. The remaining 10% consists of individuals who are either consistently left-handed or without a clear hand preference (Annett, 1976; Oldfield, 1971). Although a number of clinical reports have stressed the importance of assessing hand preference, it has become obvious that simple handedness does not relate directly to functional lateralization for language (Dean, 1982; Kinsbourne & Hiscock, 1977).

Inconsistent findings in the study of lateral preference seem understandable when in many cases simple hand preference for writing is the only measure of laterality. Dean (1982) has argued that confusion in past research that has used lateral preference as a measure of hemispheric lateralization may well be related to the specific index of preference used. Indeed, it seems that the relationship between simple hand preference and cerebral lateralization is less than robust (Dean, 1978, 1982). In fact, conclusions concerning hemispheric specialization based on hand preference are more likely to be in error than if the assumption is made that language is served by the left hemisphere in all subjects regardless of handedness (Dean, 1986). This conclusion is reflected in research showing that for most right- and left-handed individuals, complex linguistic functions are served by the left hemisphere (Lake & Bryden, 1976). Milner (1974) reported that some 95% of right-handed and 70% of left-handed individuals have secure left hemispheric specialization for language. For some 30% of left-handed individuals, language has been shown to be served by the right hemisphere, or symmetrically organized.

These data stand in contrast to early speculations of right hemispheric language dominance for all left-handed individuals. Other than the social learning that occurs, differences between left-handers in language lateralization may be attributed to differences in the etiology of left-hand preference (Satz, 1976). Moreover, although there has been shown to be a distinct genetic factor in left-handedness (Levy & Nagylaki, 1972), a number of researchers have argued in favor of a form of left-handedness that arises out of pathological factors relating to early brain damage or a developmental anomaly in the left hemisphere. Specifically, Lucas, Rosenstein, and Bigler (1989) suggested that mentally retarded left-handed subjects had a higher incidence of impairment. Furthermore, there was a greater degree of expressive and receptive language impairment for females than for males.

Satz (1976) has argued convincingly against measures of lateral preference based on simple handedness as an index of cerebral dominance for language. This seems reasonable when the degree of social learning and environmental constraints are considered in the establishment of hand preference. Clearly, early theoretical notions that offered handedness as a definitive indicator of cortical specialization appear naïve in light of our present research base (Dean, 1981). It seems then, that although preference for peripheral activities may reflect cortical organization, the relationship is not a simple one.

Measures of lateral preference have often been used to classify respondents in a rather arbitrary, nominal fashion (left, right, mixed) (e.g., Annett, 1976; Harris, 1947; Jasper & Raney, 1937; Oldfield, 1971). Like other individual difference variables, lateral preference seems more heuristically considered as a continuous variable, and one would expect individuals to show various degrees of preference (see Dean, 1978; Shankweiler & Studdert-Kennedy, 1975; Whitaker & Ojemann, 1977). From this point of view, it is not surprising to find confusion between studies that have relied on methodologies that portray lateral preference as an all-or-nothing variable.

Dunlop, Dunlop, and Fenelon (1973) presented data showing little reliable variance associated with simple hand preference as a predictor of language. However, these authors showed a clear association between inconsistent eye/hand use and confused hemispheric lateralization for language. This finding seems consistent with other research showing discrepancies in ear/hand preference (e.g., Bryden, 1967) and more confused hand preference for fine motor activities requiring visual guidance (Dean, Schwartz, & Smith, 1981; Kaufman, Zalma, & Kaufman, 1978), which may be more sensitive indicators of language confusion. Examining preference for a large number of items in a continuous fashion, Dean (1982) offered data favoring lateral preference as a factorial complex variable that is best represented on a continuum from entirely right to entirely left. Given that hand preference falls along such a continuum, lateral preference is most appropriately assessed through this fashion (Dean, 1982). Dean (1982) argued that the neurological significance of lateral preference may well have been masked in methodologies that summed across subjects' preferences for individual activities with little more than intuitive support.

Dean et al. (1981) hypothesized that much of the inconsistency in results of studies on lateral preference may well vary as a function of the specific tasks chosen to infer lateral dominance. Using factor analysis, Dean (1982) isolated six distinct dimensions that accounted for some 90% of the variability in subjects' preferences for activities involving the hands, arms, eyes, ears, and feet. Research comparing individual factors with sophisticated measures of hemispheric language lateralization indicates a more robust relationship with that factor, which involves preference for visually guided motor tasks (Dean, 1985b). These data suggest that the choice of preference items (writing, etc.) in past research may have played an interactive role with other neuropsychological variables (Dean & Hua, 1982). Thus, lateral preference patterns would seem not only to vary from individual to individual but, more important to the present discussion, for each individual as a function of the cerebral system under study. For example, assessment of lateral preference data indicates that the percentage breakdown of handedness in the general population reflects the distribution of planum temporale asymmetry and thus contributes to the assessment of language processing disorders (Richardson, 1995).

Using a multifactor measure of lateral preference, Dean (1981) has offered data favoring a greater mixed tendency for males than for females. Although these results are consistent with Oldfield's (1971) data, sex differences in lateral preference are not as simplistic as once proposed (Oldfield, 1971). Moreover, Dean (1979, 1982) showed males to present a significantly more mixed pattern in lateralization for factors involving strength and those requiring visual guidance in their performance. Although genetic factors that would predict such differences have been proposed (Levy & Levy, 1978), sex steroids and specific social learning cannot be dismissed (see McGlone, 1980).

ATYPICAL LATERALIZATION AND LANGUAGE DISORDERS

INCOMPLETE HEMISPHERIC LATERALIZATION of language has long been hypothesized as a predisposing factor for a number of disorders. The most often articulated view speculates that language-related disorders may result from the bilateral representation of language functions in the brain and thus some form of competition between hemispheres (e.g., Arnett, 1976; Orton, 1937). Orton's (1937) early hypothesis of confused lateralization for severe reading disorders was based on his clinical observations of a higher incidence of confused lateral preference (hand and/or hand/eye preference) for children referred for reading problems. As outlined previously because purposeful unimanual activities are served by the contralateral hemisphere of the brain, observed confusion for such behaviors was seen to reflect confused lateralization of cortical functions (Annett, 1976; Orton, 1937; Zangwill, 1962). In support of this notion, Zangwill (1960) offers data showing that some 88% of "congenital dyslexics" present with some form of confused lateral preference. Although over a half century has passed since Orton's (1937) hypothesis, cerebral dominance as an etiological factor in reading disorders remains one of the most controversial issues in neuropsychology.

As mentioned previously, measures of hemispheric specialization based on simple handedness do not relate to language lateralization in a one-to-one fashion. In the Dunlop et al. (1973) study, little relationship between handedness in isolation and language-related disorders was found. However, when crossed eye-hand preference was examined, this index was shown to be clearly associated with such disorders. Similarly, Dean et al. (1981) have offered data favoring less coherently lateralized systems of lateral preference for children diagnosed as learning-disabled. Interestingly, when summed across systems of lateral preference, learning-disabled children differed little from normal controls.

Inconsistencies in this area exist not only in how lateral preference is measured but also in a lack of a consistent rationale for inclusion of individuals in nosological categories. Moreover, classifications such as reading disabilities, dyslexia, and the like are both overlapping and confounded. Using a more descriptive approach to reading disorders, Dean (1978, 1979) has reported significantly greater mixed systems of lateralization for children with adequate decoding skills who experience problems in reading comprehension. However, in the same investigation, poor readers deficient in decoding also were similar to good readers in their lateral preference patterns. Thus, refined diagnostic specificity in considering language disorders is as important as the measure of lateralization used. A good deal of research indicates a consistent right-ear advantage for language-disabled patients when verbal stimuli are presented in a dichotic fashion (Dean & Hua, 1982; Hynd, Obrzut, Weed, & Hynd, 1979; Satz et al., 1975), a pattern similar to that found for normals. Thus, these data would suggest that language lateralization for language-disabled patients, when measured in an auditory fashion, is similar to that reported for normals (Dean & Hua, 1982). However, when language lateralization is inferred from a visual presentation (split visual field), the majority of studies show a smaller right visual field superiority as well as differential neuronal size of the visual pathway for linguistic material in language-disabled patients than that found for normal controls (Kershner, 1977; Marcel, Katz, & Smith, 1974; Marcel & Rajan, 1975).

Interestingly then, it appears that although evidence of normal language lateralization exists when measured in an auditory fashion, many language-disabled individuals show less secure visual language lateralization. The etiology of such deficits has been attributed to developmental aberrations (Satz, 1976), early insult (Geschwind, 1974), genetic factors (Levy & Reid, 1976), and the interaction of these factors. Evidence of left-right symmetry or reversed right asymmetry on measures of temporal lobe size has been demonstrated in individuals with dyslexia (Dalby, Elbro, & Stodkilde-Jorgensen, 1998; Duara et al., 1991; Leonard et al., 1993). Indeed, professional controversy persists concerning neuropsychological aspects of reading disorders in general and the heuristic value of Orton's (1937) original hypothesis of inconsistent cerebral dominance for many linguistically disabled patients. In one study, dysphasic and autistic subjects demonstrated reversed direction of hemispheric asymmetry (Dawson, Finley, Phillips, & Lewy, 1989). However, when language ability was analyzed, the autistic subjects demonstrated more right hemispheric activity, whereas the dysphasic subjects appeared to have more left hemispheric activity (Dawson et al., 1989).

Beaumont and Rugg (1978) have offered an interesting hypothesis that attempts to reconcile findings of normal auditory (right-ear advantage) and less secure visual (split visual field) language asymmetries for patients who present with severe reading disorders. In concert with Pizzamiglio's (1976) and Geschwind's (1974) conceptualizations, Beaumont and Rugg (1978) have hypothesized a functional disassociation in the lateralization of auditory and visual language systems. The deficit here is seen as integration of visual-verbal systems in the presence of normal auditory-verbal functioning. From this point of view, functional lateralization for language may vary for an individual as a function of the specific system (i.e., visual-verbal) examined (Beaumont & Rugg, 1978; Dean & Rothlisberg, 1983; Luria, 1966).

Although empirical attempts to subtype linguistic disorders in the selection of subjects is encouraging (Boder, 1970; Pirozzolo, 1979), the lack of relevant diagnostic criteria represents a major difficulty in drawing conclusions in this area of research (Dean, 1986). The reader should be particularly alert to the myriad of practical assessment and complex theoretical issues when drawing clinical inferences of functional lateralization as part of a comprehensive neuropsychological evaluation. Moreover, although inconsistent patterns of functional lateralization may be viewed as having potential clinical implications, there is little robust evidence that atypical lateralization should be considered pathogenic in isolation.

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