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Neuropsychological Assessment
of Cerebral Interhemispheric Relations
in Early Childhood.

James K. Maxwell]

This Dissertation is submitted to the School of Graduate Studies of
Carleton University as partial fulfillment of the requirements for the
degree of Doctor of Philosophy in Psychology, July, 1981.

The undersigned recommend to the Faculty
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"Neuropsychological Assessment of Cerebral
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in partial fulfilment of the requirements for
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September 1981

This paper is dedicated to Josie,
my wife and best friend, who has
encouraged and supported me from
the beginning of my interest in
neuropsychology.

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Abstract

Developmental changes in intermanual transfer and lateral asymmetry were postulated on the basis of studies of maturational changes in structure and function of the human cerebral commissures and association cortex during early childhood. In the present study, 32 3-year-olds and 32 5-year-olds, all right-handed, were given a battery of five tests modified from existing neuropsychological tests sensitive to a variety of brain functions in children. The tests included measures of motor, visual-motor, tactual-motor, tactile naming and matching speeds, as well as picture vocabulary. On some tests, lateral asymmetries were present at 3 years of age, suggesting an early appearance of hemispheric functional specialization in human development. Most tests showed lateral asymmetries were the same size or smaller at 5 than at 3 years of age, implying that lateral asymmetry can be modified by normal developmental increases in interhemispheric communication. Intermanual transfer was present by 3 years of age and appeared to be greater at 5 years, possibly reflecting an increase in interhemispheric communication during early childhood. Positive correlations between magnitude of intermanual transfer and degree of lateral asymmetry on two tasks suggested a temporal correlation between developing interhemispheric communication and hemispheric functional specialization. These results were consistent with hypotheses that the two phenomena work together to facilitate learning and performance on specific tasks. Overall, the test results appeared to follow a developmental trend in which lateral asymmetry, intermanual transfer, and a relationship between the two are present depending on chronological age and on the nature of the task.

Table of Contents

I. Abstract	1
Table of Contents	2
List of Tables	3
List of Figures	5
List of Appendices	6
II. Literature Review and Statement of the Problem	7
A. Hemispheric Functional Specialization and Lateral Asymmetry	8
B. Interhemispheric Communication and Intermanual Transfer	12
C. Relationships between Hemispheric Functional Specialization and Interhemispheric Communication	15
D. The Developmental Sequence of Cerebral Functioning	16
E. Rationale	18
F. Rationale for Specific Tests	19
III. General Methodology	26
A. Subjects	26
B. Procedure	26
C. Screening Procedures	27
D. Experimental Tasks	30
IV. Results	39
A. Motor Speed: Tapping Speeds	39
B. Visual-motor Speed: Trails R	56
C. Tactuo-motor Speed: Formboard	69
D. Speed of Response Onset: Tactile Naming and Matching	77
E. Lateral Asymmetry of the Pointing Response: Peabody Picture Vocabulary	86
F. Analysis of Lateral Asymmetry and Intermanual Transfer Measures in Combination	95
G. Effects of Early Brain Damage	110
V. General Discussion	121
VI. Suggestions for Future Research	145
VII. Summary and Conclusions	149
VIII. References	152
IX. Appendix Tables	182

List of Tables

Table 1.	Means and Standard Deviations for Summary Characteristics and PPVT Scores of Both Age Groups	29
Table 2.	Means and Standard Deviations in Each Tapping Condition	40
Table 3.	Analysis of Variance Summary Table for Means of Tapping Conditions	44
Table 4.	Pearson Correlation Coefficients (r) for Mean Tapping Speeds	47
Table 5.	Pearson Correlation Coefficients (r) between Lateral Asymmetry and Bimanual Performance on the Tapping Test	49
Table 6.	Means and Standard Deviations for Lateral Asymmetry of Tapping as a Function of Alternate Finger Tapping Speed	51
Table 7.	ANOVA Summary Table for Means of Lateral Asymmetry on Tapping as a Function of Alternate Finger Tapping Speed Group, Age, Sex	52
Table 8.	Means and Standard Deviations of Speed Scores for Both Hands on the Trails R Test	57
Table 9.	Means and Standard Deviations for Intermanual Transfer on the Trails R Test	60
Table 10.	ANOVA Summary Table for Mean Intermanual Transfer on the Trails R Test	61
Table 11.	Pearson Correlation Coefficients between Lateral Asymmetry and Intermanual Transfer on Trails R	63
Table 12.	Pearson Correlation Coefficients (r) between First and Second Trials of Trails R	65
Table 13.	Means and Standard Deviations for Speed of Performance of Both Hands on the Formboard Test	70
Table 14.	Correlation Coefficients between Lateral Asymmetry and Intermanual Transfer on the Formboard Test	73
Table 15.	Means and Standard Deviations for Speed of Response Onset for Items on the Tactile Naming Test	78
Table 16.	Means and Standard Deviations for Speed of Response Onset for Items on the Tactile Matching Test	79
Table 17.	Lateral Asymmetry Frequencies for Tactile Naming Speeds	81

Table 18.	Lateral Asymmetry Frequencies for Tactile Matching Speeds	83
Table 19.	Means and Standard Deviations for Pointing Response on the PPVT	88
Table 20.	Mean Item Numbers for Instructed Use of One Hand by 3-Year-Olds on Modified PPVT	90
Table 21.	Number of 3-Year-Old Children Selecting Each of Four Alternate Pictures of PPVT	92
Table 22.	Spearman Rank Order Correlations between Test Measures for 3-Year-Old Group	96
Table 23.	Spearman Rank Order Correlations between Test Measures for 5-Year-Old Group	98
Table 24.	Spearman Rank Order Correlations between Test Measures for All Children in Study	100
Table 25.	Canonical Correlation Analysis of Lateral Asymmetry and Intermanual Transfer Variables	101
Table 26.	Principal Component Analysis of Lateral Asymmetry and Intermanual Transfer Variables	103
Table 27.	Second Principal Component Analysis of Lateral Asymmetry and Intermanual Transfer Variables	104
Table 28.	Summary Table for Lateral Asymmetry Measures Entering into a Discriminant Function between Age Groups	106
Table 29.	Summary Table of Lateral Asymmetry and Intermanual Transfer Measures Entering into a Discriminant Functions between Age Groups	108
Table 30.	Normative Data for 3- and 5-Year-Olds and Test Results for Two Brain-Damaged Children	112-113

List of Figures

Figure 1. The Four Forms of the Trails R Test	33
Figure 2. The Formboards	35
Figure 3. Right Hand Versus Left Hand Unimanual Index Finger Tapping Speeds for Individual 3-Year-Olds	42
Figure 4. Relative Difference between 3- and 5-Year-Old Tapping Speeds	45

List of Appendices

Table A.	Means and Standard Deviations for Tapping Onset Delays	182
Table B.	Spearman Rank Order Correlation Coefficients between Mean Tapping Speeds and Mean Tapping Onset Delays	183
Table C.	ANOVA Summary Table with Lateral Asymmetry for Finger Tapping as a Function of Alternate Finger Tapping Onset Delay	184
Table D.	Pearson Correlation Coefficients between Tests using Overall Levels of Performance	185

Neuropsychological Assessment of Cerebral Interhemispheric Relations in Early Childhood

Literature Review and Statement of the Problem

The purpose of this study was to investigate lateral asymmetries, intermanual transfer, and the nature of the relationship between these two phenomena as they relate to performance skills in young children. Specifically, three questions were asked concerning: (1) whether lateral asymmetries are present and of the same magnitude and direction at 3 and 5 years of age; (2) whether the magnitude and direction of intermanual transfer is the same at 3 and 5 years of age; and (3) whether there is a relationship between the magnitudes of lateral asymmetry measures and measures of intermanual transfer at both 3 and 5 years of age. Age group differences were evaluated on behavioral tests measuring lateral asymmetry of manual performance and intermanual transfer of learning or bimanual coordination. The five tasks included measures of motor, visual-motor, tactual-motor, tactile naming, and tactile matching performance speeds. Hand preference for pointing to pictures based on vocabulary and the potential effects of early brain damage on task performance were also examined in this study.

The following literature review first examines developmental aspects of lateral asymmetry, intermanual transfer, and their relationship. This is followed by literature reviews for each task introduced in the rationale.

Hemispheric Functional Specialization and Lateral Asymmetry

Hemispheric functional specialization refers to the tendency for physiological activity of one cerebral hemisphere to consistently subserve functions more efficiently than the other hemisphere. Witelson (1974) regarded hemispheric specialization as the asymmetrical contribution of

each of the cerebral hemispheres in processing different kinds of material, e.g., linguistic and nonlinguistic information. Since each cerebral hemisphere tends to control motor and sensory ability of the contralateral body side (Lawrence & Kuypers, 1968), lateral asymmetries in performance are commonly used to make inferences about the magnitude and direction of hemispheric functional specializations. Lateral asymmetries are behaviorally defined as consistent superior performances of one body side over the other. Recently, lateral asymmetries have been tested in children in an effort to answer questions about early ontogenic aspects of hemispheric functional specializations (see Witelson, 1977, for review). Two important questions dealt with in this study concern: (1) when hemispheric functional specializations arise in the developmental process; and (2) whether the degree of specialization varies during the course of postnatal maturation.

Literature concerned with the time of onset of hemispheric functional specializations has not resolved this issue. Several studies have suggested that the specializations continue to arise during childhood because unilateral cerebral damage before 5 years of age does not result in permanent aphasia, as it does in adults (Alajouanine & Lhermitte, 1965; Basser, 1962; Krashinsky, 1973; Lenneberg, 1967). Early left hemisphere damage is also more likely to lead to a right hemispheric specialization for language than damage later in life (Lansdell, 1962, 1969). Some studies have reported that right hemispheric damage in early childhood can result in aphasia, suggesting bilateral speech representation in the cerebral cortex (Basser, 1962; Hecaen, 1976); however, Woods (1980a, b) found this is true only before 1 year of age and that later age estimates may be an artifact of inadequate behavioral tests for aphasia. More evidence for

a late postnatal maturation of hemispheric functional specializations is provided by patients who have had early unilateral hemispheric removals following damage in infancy. These patients acquire both language and visual-spatial skills in the remaining hemisphere (Dennis & Kohn, 1975; Dennis, Lovett, & Wiegel-Crump, 1981; Dennis & Whitaker, 1976; Krunaw, 1950; Verity, Strauss, Moyes, Wada, & Dunn, 1981). However, those patients with left hemisphere removals still do more poorly on verbal tasks than spatial tasks, while the converse is true for patients with right hemisphere removals, suggesting hemispheric functional specializations are present in infancy or earlier (Dennis & Whitaker, 1976; Hecaen, 1976; Smith, 1974; Woods & Teuber, 1973).

A number of studies of the magnitude of lateral asymmetry in normal children have attempted to determine when lateral asymmetries appear during development in an effort to make inferences about the ontogenesis of hemispheric functional specializations. The usual course has been to examine changes or differences in the magnitude of lateral asymmetries across chronological ages (e.g., Finlayson, 1976; Satz, Bakker, Teunissen, Goebel & Van der Vlugt, 1975). At least five studies have reported that the magnitude of lateral asymmetries on perceptual tasks increase during childhood (Bryden, 1970; Flanery & Balling, 1979; Inglis & Sykes, 1967; Reynolds & Jeeves, 1978; Satz et al., 1975). However, the majority report no change in magnitude of lateral asymmetries on sensory and motor tasks during childhood (Annett, 1970; Berlin, Hughes, Lowe-Bell & Berlin, 1973; Cioffi & Kandel, 1979; Finlayson, 1976; Gardner, 1979; Geffen, 1976, 1978; Hiscock & Kinsbourne, 1980a; Peters & Durdin, 1979; Witelson, 1974, 1977; Young & Bion, 1979). Decreases in the magnitude of lateral asymmetries

during childhood have also been found (Ingram, 1975; Knox & Kimura, 1970; Wolff & Hurwitz, 1976). A number of methodological problems have been cited for failures to show developmental increases in lateral asymmetry (Satz et al., 1975), but another possibility is that many of the studies have been conducted with children 5 years of age or older, and perhaps explored changes too late in development to find behavioral indications of postnatal changes in the cerebral cortex. Lateral asymmetries in head turning and hand preference have been found in infants (Cohen, 1966; Lewkowicz, Gardner, & Turkewitz, 1979; Turkewitz & Creighton, 1974; Turkewitz, Gordon, & Birch, 1965), and lateral asymmetries have been reported for dichotic listening with 2- and 3-year-old children (Gilbert, 1976; Ingram, 1975; Nagafuchi, 1970). Sex differences in lateral asymmetries have also been noted as a source of error variance in behavioral studies (Witelson, 1977).

Anatomical studies of postnatal changes in the normal cerebral cortex support both an early development of hemispheric specialization and a postnatal increase in the degree of hemispheric specialization. The cerebral cortex of human infants and fetuses has been found to have morphological asymmetries (Wada, Clark, & Hamm, 1975; Witelson & Pallie, 1973) similar to those of adults (Geschwind & Levitsky, 1968; Hochberg & LeMay, 1975; LeMay & Culebras, 1972; Rubens, 1977; Wada & Clark, 1975). These results are in agreement with studies showing that infants have asymmetries in EEG activation with auditory and visual stimuli (Crowell, Jones, Kopunial, & Nakagawa, 1973; Gardiner & Walter, 1976; Molfese, Freeman, Overman, & Palermo, 1976). Analyses of fine structural changes in the postnatal cerebral cortex, however, show that volumetric expansion and

addition of neural elements near completion in primary motor and sensory cortex during the first two postnatal years, while "association" areas of the frontal, parietal, and temporal lobes continue to make such structural additions well into the second and third decades of life (Blinkov & Glezer, 1965; Conel, 1939-1967; Luria, 1969; Meyer, 1981a,b; E. Milner, 1967, 1976; Rabinowicz, Leuba, & Heumann, 1977; Von Bonin & Bailey, 1961; Yakovlev & Lecours, 1967). Most of these postnatal additions to brain structure occur as microneuronal proliferation, myelination, vascularization, glial-cell proliferation, and increasing numbers of neuronal components, e.g., boutons and synapses (Purpura, 1975; 1977; Rappoport, Fritz, & Yamigami, 1971; Yakovlev, 1962).

The late addition of cerebral microstructures may correspond to an increasing functional efficiency of the cerebral cortex during childhood (Epstein, 1979). Since the latest postnatal changes occur in association cortex, it is important to note that studies of the behavioral effects of brain damage (Critchley, 1953, 1966; Luria, 1969) and electrical stimulation (Ojemann & Mateer, 1979) indicate association areas of the adult cerebral cortex are specialized for verbal and spatial functions in the left and right hemisphere, respectively. In fact, Luria (1972) asserted that the association areas are the most specialized regions for verbal and spatial processing in the adult cerebral cortex. The notion of a gradual postnatal maturation of the human cerebral cortex is the basis of Brown's (1979) hypothesis that functional specialization of the hemispheres is incomplete during infancy and early childhood, and that new skills are acquired as hemispheric specializations arise. The anatomical perspective also lends support to possible sex differences in hemispheric specialization of normal

children, which could be based on the more rapid biological development of females (Tanner, 1970; Townes, Trupin, Martin, & Goldstein, 1980).

Hécaen (1976) expressed perhaps the most cogent synthesis of the literature on development of hemispheric functional specializations. He pointed out that there ~~may~~ be early hemispheric specializations which continue to mature postnatally, and at the same time there may be an early critical period during which damage to one hemisphere can be compensated by changes in neural organization of the other hemisphere. Thus, poor recovery from aphasia after 5 years of age, for example, may be indicative of the time limits for neural plasticity rather than being indicative of the onset of functional specialization for language by the left hemisphere. The only real problem with Hécaen's hypothesis is that it fails to explain why most of the behavioral evidence shows that lateral asymmetries do not increase in magnitude during normal childhood development, as would be predicted.

Interhemispheric Communication and Intermanual Transfer

In this paper, interhemispheric communication refers to the transfer of electrical activity via the cerebral commissures: the corpus callosum and anterior commissure. Behavioral expression of this phenomenon, as inferred from studies of patients with surgical section of the cerebral commissures (commissurotomy) (Sperry, Gazzaniga, & Bogen, 1969) and patients with congenital absence of the corpus callosum (Jeeves, 1965), will be referred to as intermanual transfer, taking into account measures of both intermanual transfer of learning and bimanual asynchronous motor coordination. In this study, differences in the amount of intermanual transfer at two ages in early childhood were examined in order to make

inferences about the development of interhemispheric communication.

The adult corpus callosum interconnects homotopic regions of the two cerebral hemispheres in the primate brain (Pandya, Karol, & Heilbronn, 1971; Schaltenbrand, Spuler, & Wahren, 1972). The frontal lobes are interconnected through the anterior half of the callosum, followed in order by fibers interconnecting the parietal, temporal, and occipital lobes (Karol & Pandya, 1971). The anterior commissure interconnects the anterior and inferior temporal lobes (Joyandet & Gazzaniga, 1979).

The anatomical and physiological literature strongly support a postnatal increase in the amount of interhemispheric communication. Normally, the two cerebral commissures appear between 10 and 12 weeks gestation; however, they are unmyelinated at birth and by 5 postnatal months contain only 66% of the adult number of neural fibers (Blinkov & Glezer, 1968). Both cerebral commissures continue to gain myelin into the second and third decades of life (Yakovlev & Lecours, 1967); the core regions, interconnecting neocortical regions, myelinate last (Locke & Yakovlev, 1965). Although commissural myelination has significance for the maturation of physiological functioning of particular fibers (Katz, 1966), myelination is more importantly seen as a general indicator of maturation in neural systems or subsystems (Norton, 1976; Selnes, 1974). The sequence of myelination in ontogeny is the same for all mammalian species, beginning with the lower, phylogenetically older spinal cord, followed in order by the brain stem, lower cerebral structures, and finally the cerebral commissures, as well as the association cortex (Fox, 1968; Langworthy, 1933; Tilney & Casamajor, 1924; Yakovlev & Lecours, 1967). The order suggests that the cerebral commissures, as well as the association cortex, are among the last structures to become functionally efficient during normal human development.

Transmission velocities of interhemispheric communication have been found to increase during postnatal development, further supporting the notion that interhemispheric communication is becoming more efficient after birth. Increasing transmission velocities have been noted in kittens (Grafstein, 1968), rats (Seggie & Berry, 1972), and in young children until 10 years of age (Salamy, 1978). Salamy's (1978) findings indicate that the most rapid developmental changes in interhemispheric communication actually occur early in childhood.

Little is known about the developmental aspects of the postsynaptic properties of commissural activity, which involve both excitatory and inhibitory effects (Giurgea & Moyersoons, 1979; Li & Chow, 1959; Marruzi, 1974; Toyama, Tokashiki, & Masunami, 1969). These effects may be more characteristic of the cortical regions which are interconnected (Eidelberg, 1969), suggesting there may be regional variation in the postsynaptic properties of cerebral commissure neurons. Even within regions, the electrical properties of individual commissural axons vary according to size and are subject to individual fluctuations (Swadlow & Waxman, 1979).

Although developmental neuroanatomy and electrophysiology show a postnatal increase in interhemispheric structures and function, few human behavioral studies have attempted to investigate developmental increases in intermanual transfer. Finlayson (1976) found that intermanual transfer of tactual-motor learning did not become significant until after 8 years of age. However, developmental changes in lateral asymmetry were not examined in Finlayson's study and may have influenced the measures of intermanual transfer. Studies comparing intermanual transfer and intramanual performance have reported that intermanual transfer appeared relatively

later on tests of fine motor coordination (Elliott & Connally, 1974) and tactile matching tasks (Galin, Johnstone, Nakell, & Herron, 1979). Galin et al. (1979) argued that their findings provide behavioral evidence of a late maturation of the corpus callosum relative to intrahemispheric structural development. In addition to these developmental changes, Kocel (1980) presented evidence that there may also be sex differences in the amount of intermanual transfer.

Relationships between Hemispheric Functional Specialization and Interhemispheric Communication

Although anatomical and physiological research supports the notion of a postnatal maturation of both hemispheric functional specialization and interhemispheric communication, it is not known if the two phenomena are causally, or even temporally, related. Several lines of evidence suggest that the two phenomena do interact during early human development. First, the time course of decreasing recovery from aphasia in childhood corresponds to the time course of commissural myelination (Denenberg, 1980; Selnes, 1974). Second, patients with congenital absence of the corpus callosum have been thought to lack hemispheric specializations for verbal and spatial skills (Saul & Gott, 1973; Saul & Sperry, 1968; Sperry, 1974). In contrast, commissurotomy in late childhood or adulthood typically leads to very large lateral asymmetries, indicating well-developed hemispheric specializations (Gazzaniga, Bogen, & Sperry, 1963, 1965, 1967; Sperry et al., 1969). A third line of evidence is that hemispherectomy cases show both linguistic and spatial abilities, suggesting that hemispheric functional specialization is normally mediated by the commissures (Kohn & Dennis, 1975). Finally, studies of association cortex in monkeys, cats, raccoons, and rats show that

most of these regions have extensive commissural connections (Ebner & Myers, 1965; Ivy, Akers, & Killackey, 1979; Karol & Pandya, 1971), making it likely that similar organization exists in the human brain.

The review of the literature of neuropsychological studies in children did not reveal any attempts to determine if lateral asymmetry measures were related to measures of intermanual transfer. Although there have been attempts to measure each separately, the tasks employed have been quite different from each other, making them difficult to compare. Stone (1980) pointed out some of the problems of analyzing relationships between lateral asymmetries and intermanual transfer in the same sample; however, he also pointed out solutions which were useful in the present study, such as statistically removing terms common to both lateral asymmetry and intermanual transfer measures.

The Developmental Sequence of Cerebral Functioning

In addition to the relative development of lateral asymmetry and intermanual transfer within specific tasks, a differential development between tasks in this study might be expected if they assess different aspects or levels of cognitive function. As examples of differential development, motor tasks have shown lateral asymmetries present by 4 years of age (Sparrow & Satz, 1970), whereas tactile/sensory tasks appear to show lateral asymmetries later (Finlayson & Reitan, 1976). The maturation of skills during normal childhood follows a sequence from motor to sensorimotor to language development according to Piaget (1952), Semmes (1968), and Van der Vlugt (1979).

Other theorists have also suggested that motor and sensory skills are evident sooner than are more complex linguistic and spatial skills in normal

and learning-disabled children (e.g., Fletcher & Satz, 1980; Piaget, 1952; Rose, 1980; Sparrow & Satz, 1970). This ontogenetic framework is supported by research on the development of behaviors in experimental animals (Fox, 1968), and is coincident with anatomical evidence for an earlier appearance of primary motor and sensory cortex than association cortex in the human brain (Blinkov & Glezer, 1968; Yakovlev & Lecours, 1967). The ontogenetic progression also follows an apparent phylogenetic trend for increasing cognitive capacity and volumetric expansion of the association cortex relative to primary cortex in mammalian species (Von Bonin & Bailey, 1961; Myers, 1965).

In summary, anatomical, physiological, and behavioral studies suggest there are early developmental increases in hemispheric functional specialization and interhemispheric communication, as well as in the temporal relationship between the two phenomena. These developmental changes have been thought evident in behavioral task performance as increasing magnitudes of lateral asymmetry and intermanual transfer. An exception to this statement, which has not been explained, is that a majority of studies has found that lateral asymmetries were not different at various ages in normal children. Since the regions of the cerebral cortex mature at different rates, the appearance of lateral asymmetries and intermanual transfer on specific behavioral tasks might be expected to differ according to the cognitive demands of each task. More complex cognitive abilities are thought to mature after perceptual and motor skills.

Rationale

The analysis of hemispheric functional specializations and interhemispheric communication with behavioral measures is predicated on three assumptions. The three assumptions are: (1) the performance of each hand reflects the activity of the contralateral hemisphere; (2) measures of lateral asymmetries in manual performance reflect the magnitude and direction of hemispheric functional specializations; and (3) measures of intermanual transfer reflect the magnitude of interhemispheric communication.

With these assumptions in mind, three tasks were selected which were thought capable of demonstrating developmental aspects of lateral asymmetry measures, intermanual transfer measures, and the relationship between these two measures in the same children. These tasks were motor speed, visual-motor speed, and tactual-motor speed. In addition, tactile naming, tactile matching and the pointing response on a picture vocabulary test were selected which investigated lateral asymmetries. Finally, test results for two children with early brain damage were reported in order to help verify the assumptions that these tests were sensitive to specific brain functions.

The general approach taken in this study focused on three basic questions:

- (1) Are lateral asymmetries present at 3 and 5 years of age, and are they of the same magnitude and direction at both ages?
- (2) Is the magnitude and direction of intermanual transfer of information the same at 3 and 5 years of age?
- (3) Is there a relationship between the magnitudes of lateral asymmetry measures and intermanual transfer measures at both 3 and 5 years of age?

The task dependency of these effects was investigated as it related to the questions above. The data were also examined for the possibility of effects related to sex differences.

Rationale for Specific Tests

Motor speed. Tests of motor speed have been used to make inferences about hemispheric specialization and interhemispheric communication. Fine motor speed on finger tapping and placing pegs in a board with one hand alone have been shown to reflect the integrity of the contralateral cerebral hemisphere in adults (Costa, Vaughan, Levita, & Farber, 1963; Reitan, 1955b) and children (Boll, 1974; Knights & Ogilvie, 1967; Reitan, 1974a) when brain-damaged subjects were compared with controls. The right hand typically performs faster and more accurately than the left hand in normal right-handed children 3 to 15 years of age, thus, the left cerebral hemisphere is thought to be specialized for fine motor abilities (Annett, 1970; Denckla, 1974; Finlayson, 1976; Knights & Moule, 1967). In the present study, it is assumed that the magnitude of right hand superiority for speed of unimanual (one hand) index finger tapping reflects the degree of left hemispheric specialization for motor skills.

Studies have found alternating or asynchronous bimanual movements of the hands or arms nearly impossible to perform following damage to the cerebral commissures (Kreuter, Kinsbourne, & Trevarth, 1972; Preilowski, 1972; Zaidel & Sperry, 1977), especially damage to the anterior half of the corpus callosum (Luria, 1973). Unimanual and synchronized bimanual movements were relatively less affected by commissural damage, in contrast to patients with unilateral cerebral lesions (Wyke, 1971). These studies suggest that bimanual alternate tapping skills in normal individuals reflect interhemispheric communication (Wolff & Cohen, 1980). In the present study, alternate finger and arm tapping speeds are assumed to reflect interhemispheric communication. Unimanual and bimanual synchronous speeds

are also measured for comparison, to investigate the possibility that interhemispheric communication matures relatively later than intrahemispheric processing of motor skills. Since bimanual alternate tapping speeds and lateral asymmetry of unimanual finger tapping were both measured in the same groups of children, inferences were made regarding a possible relationship between the magnitudes of interhemispheric communication and hemispheric specialization for motor skills in early childhood.

Visual-motor speed. Lateral asymmetries on tasks of visual-motor speed, such as removing an object from a rotating disk or other tasks requiring eye-hand coordination, appear to reflect hemispheric specializations. The clearest examples of this come from studies of commissurotomy patients who have shown definite right hand superiority over left hand for visual-motor skills utilizing verbal criteria, e.g., writing (Gazzaniga et al., 1967; Levy, Nebes, & Sperry, 1971). These patients demonstrated large left hand superiority for visual-motor skills with visual-spatial criteria, such as drawing or constructing a design with blocks (Bogen, 1969; Bogen & Gazzaniga, 1965; Gazzaniga et al., 1967; Zaidel & Sperry, 1977). Kimura (1979) and Kimura and Archibald (1974) have suggested the left hemisphere is specialized for manual sequencing (praxia); however, Gazzaniga (1981) argued that visually-guided manual activity is dependent on the verbal versus visual-spatial nature of the task. Supporting Gazzaniga's view, Epro and Granite (1979) found that normal adults had a small but significant left hand superiority for speed of constructing block designs. In addition, Reitan (1958) hypothesized that the right hemisphere is specialized for processing visual-spatial search strategies on the Trail Making Test. These studies suggest lateral asymmetries of visual-motor speed are sensitive to hemispheric

functional specialization for verbal and visual-spatial processing.

The Trail Making Test requires verbal, visual-motor, and spatial skills, and has been found to be one of the most sensitive indicators of cerebral damage in older children (Boll, 1974; Dunleavy & Baade, 1980; Knights & Ogilvie, 1967; Reitan, 1971). The test has two parts, A and B. Part A requires the child be able to count to 15 and is considered more sensitive to right hemispheric damage than Part B, which requires more complex verbal skills. In the current study, a modified version of the Trail Making Test, Part A, was devised which relied on directional nonverbal skills rather than sequential verbal skills, and was suitable for administration to 3-year-old children.

On tests which measure intermanual transfer of unimanual visual-motor information, practice effect is measured as improvement of one hand over the initial performance of the other. This intermanual transfer of visual-motor learning has been shown to be eliminated by commissural damage in humans (LeDoux, Wilson, & Gazzaniga, 1977, 1978; Zaidel & Sperry, 1977) and monkeys (Black & Myers, 1965), while intramanual learning was preserved. Since patients with unilateral cerebral lesions have still shown intermanual transfer on visual-motor tasks (Heap & Wyke, 1972), the amount of intermanual transfer has been thought to reflect the amount or efficiency of interhemispheric communication (Zaidel & Sperry, 1977). In the present study, intermanual transfer on the modified version of the Trail Making Test was assumed to reflect interhemispheric communication. Since lateral asymmetries were also measured on this instrument with the same children, it was possible to examine correlations between the magnitudes of lateral asymmetry and intermanual transfer.

Tactual-motor speed. Unimanual performance on tactual-motor tests, such as placing various blocks into similar holes in a formboard without the use of vision, is impaired by unilateral cerebral damage to the hemisphere contralateral to the performing hand (Reitan, 1955a, 1974a). On a modified version of the Raven's Colored Matrices test, which excluded the use of vision, commissurotomy patients performed better with their left hands than their right hands, indicating adults have a right hemisphere specialization on these tactual-motor tests (Zaidel & Sperry, 1973). Studies utilizing these tests have not reported the presence or absence of lateral asymmetries in normal subjects, possibly because intermanual practice effects tend to obscure the asymmetries. In this study, the lateral asymmetry of performance speed on a formboard task was considered to reflect the magnitude and direction of hemispheric functional specialization.

Intermanual transfer of learning on tactual-motor tests utilizing formboards or kinesthetic mazes was found to be impaired in commissurotomy and callosal agenesis patients (Ferriss & Dorsen, 1975; Goldstein, Joynt, & Hartley, 1975; Jeeves, 1965; Reynolds & Jeeves, 1977; Russell & Reitan, 1955; Solursh, Marguiles, Ashem, & Stasiak, 1965; Zaidel & Sperry, 1973). Since the majority of these patients lacked evidence for unilateral cerebral damage, failure of the second hand to improve upon the performance of the first hand has been attributed to poor interhemispheric communication. In the present study, intermanual transfer of tactual-motor learning was assumed to reflect interhemispheric transfer of learning. Correlations between lateral asymmetry and intermanual transfer were also examined using Stone's (1980) suggestions, in order to make inferences about the relationship between hemispheric functional specialization and interhemispheric communication in

normal 3- and 5-year-old children.

Tactile naming and tactile matching speeds. The left hemisphere is thought to be specialized for the ability to name objects by touch when the objects are out of the subject's view. Evidence for this hemispheric specialization comes from studies showing that naming deficits are more common after left than right hemisphere damage (Wheeler & Reitan, 1962; Golden, 1978), but more specifically from adults who have had commissurotomy. The latter patients have shown that tactile naming is accurate when the object (out of view) is presented to the right body side, but naming is usually impossible when the object is presented to the left hand, left visual field, or dichotically to the left ear (Damasio, Damasio, Castro-Caldas, & Ferro, 1976; Gazzaniga, Bogen, & Sperry, 1965, 1967; Gazzaniga & Freedman, 1973; Gazzaniga, Risse, Springer, Clark, & Wilson, 1975; Gazzaniga & Sperry, 1967; Goldstein et al., 1975; Larrabee, McKeever, Ferguson, & Rayport, 1980; Levy & Trevarthen, 1977; Risse, LeDoux, & Springer, 1978; Sperry et al., 1969; Springer & Gazzaniga, 1975; Springer, Sidtis, Wilson, & Gazzaniga, 1978; Sugishita, 1978; Zihl & Von Cramon, 1980). In a study by Larrabee et al. (1980) the authors provided a suitable control condition to show that left hand tactile naming difficulty in their patient resulted from commissurotomy, rather than from astereognosis (inability to recognize shapes) or loss of tactile sensitivity due to right hemisphere damage. Although their patient could not name objects presented to the left hand out of view, he was capable of tactile matching with the left hand, showing that both hands were capable of shape recognition. Similarly, normal children older than 5 years have been found to have a right hand superiority for tactile recognition of simultaneously presented letters, while a left hand advantage was found for tactile matching of nonsense shapes (Witelson, 1974, 1976).

The results of these experiments suggest that the left hemisphere is normally specialized to subserve tactile naming, while the right hemisphere may be specialized for tactile identification when verbalization is not involved. In the present study, lateral asymmetries for speed of onset of tactile naming and matching common objects were compared in 3- and 5-year-old groups in order to make inferences about the magnitude and direction of the underlying hemispheric functional specialization.

Pointing response to verbal stimuli. Since unimanual visual-motor performance has been found to reflect the activity of the cerebral hemisphere contralateral to the performing hand, lateral asymmetries of visual-motor performance are thought to represent left and right hemispheric specializations for verbal and visual-spatial task performances, respectively (Gazzaniga, 1981; LeDoux et al., 1977, 1978). Visual matching of complex shapes appears to be equally well subserved by either hemisphere (LeDoux et al., 1978), suggesting that hemispheric specializations may be manifest only in the pointing response (Gazzaniga, 1981). In the present study, the subjects were given the Peabody Picture Vocabulary Test (PPVT) and instructed to point to pictures of words spoken aloud by an examiner, and encouraged to guess when they did not know the word. It was assumed that the hand used (lateral asymmetry) for pointing would reflect the magnitude and direction of underlying hemispheric functional specialization in 3- and 5-year-old children, since correct responses might reflect a left hemisphere response to the linguistic stimuli, and incorrect responses might be based on nonverbal responding of the right hemisphere to the pictorial stimuli.

Analysis of results in combination. Since lateral asymmetry and intermanual transfer measures were obtained on a number of different tasks

given to the same subjects, relationships between measures on different tasks could be analyzed to construct hypotheses about common neural substrates. The measures were also analyzed in combination to see if they discriminated between age groups.

Effects of early brain damage. Test results were also reported for two children with evidence of brain damage since infancy to support the assumptions and hypotheses discussed in this paper. One child suffered from anoxia at birth and showed impairment of motor abilities, while the other had extensive damage to the right cerebral hemisphere and complete commissurotomy. The questions raised concern the capability of the behavioral tests to reflect various aspects of brain function and dysfunction. In turn, the test results were analyzed in terms of use in clinically describing the brain-behavior relations in these two patients.

General Methodology

Subjects

The subjects were 64 right-handed children from two age groups: 32 3-year-olds and 32 5-year-olds. Both age groups consisted of 16 boys and 16 girls. The 3-year-olds were selected from two Ottawa preschools, and the 5-year-olds from five kindergartens in the Ottawa Board of Education. The majority of children in these schools were considered to come from middle and upper-middle class families. None of the children included in the study were known to have neurological, emotional, or physical disorders, according to their teachers' and the examiner's observations. One child was excluded from the study on the basis of identified emotional problems and another because of a history of neurological disorders. The latter case is presented in a later section on the effects of early brain damage. Subjects were selected for the study after obtaining parental permission and after administration of a screening procedure. The screening required the children be right-handed and have receptive language skills above the fiftieth percentile for their age. Consecutive qualifying children were included in the study.

Procedure

The children were tested by the author over a three month interval from early November, 1980 to early February, 1981, interspersing the testing of subjects from the two age groups in order to reduce examiner practice effects. All testing took place on an individual basis in empty school rooms with the child seated at a small table and chair across from the examiner.

Three-year-olds were tested in either two 30-minute sessions or three

20-minute sessions, depending on the child's apparent level of attention during the sessions. The screening procedures always preceded the experimental tests. All sessions were completed within 14 days of each other, but usually on consecutive school days. Before testing any of the 3-year-olds, the examiner spent one week in free play at both preschools in order to establish rapport with the children. The examiner noted that rapport was important in the willingness of the 3-year-olds to participate, but 5-year-olds were generally eager to participate even though the examiner was a relative stranger. All 5-year-olds were tested in two 30-minute sessions with the order of test presentation the same as for the 3-year-olds. Both testing sessions were held within four days of each other for every 5-year-old subject. The data was analyzed by computer, using the Statistical Package for the Social Sciences (SPSS) and time sharing programs at Carleton University.

Screening Procedures

Handedness. Handedness was determined by observations of both preference and performance. Hand preference was determined, first of all, by instructing the subject to pick up a pencil presented at midline and then draw a circle. The hand used for drawing the circle was recorded as the preferred hand on this task. A second hand preference measure was obtained by observing which hand was used in response to a command from the examiner to, "Show me how you wave goodbye". In the 3-year-old group, hand preference was also determined in field observations by the examiner. All children included in the study showed a right hand preference on both tasks. In a third measure, not used for screening, the children were asked to show the examiner which hand they used for drawing. This question was asked after the hand preference was made, and at a time when the children had not held a pencil

for at least five minutes. In the 3-year-old group, 27 of 32 (84%) responded by showing the right hand, while 26 of 32 (81%) of the 5-year-olds responded by showing the right hand. Observations of the child's handedness appeared to be more accurate, on the average, than asking the child for this information.

After determining hand preference, each child was given a test of unimanual index finger tapping speed. Tapping speed was measured for each hand, as described in the following section on experimental tasks, entitled "Motor speed". Only those children who demonstrated a right-hand tapping speed that was as fast or faster than the left-hand tapping speed were included in the study.

Receptive language. Receptive vocabulary was assessed with the Peabody Picture Vocabulary Test (PPVT), Form b (Dunn, 1965). On this test, the subject was presented with four pictures drawn on a page (visual stimulus) that was divided into four quadrants. The subject was instructed to point to the picture that meant the same as a word spoken (verbal stimulus) by the examiner. Scores on the PPVT are considered to reflect receptive language capacity because they correlate more highly with the Verbal Scale of the Wechsler Intelligence Scale for Children (WISC) than the Performance Scale of the WISC (Dunn, 1965).

A summary of subject characteristics and PPVT scores for both age groups is presented in Table 1. The two age groups differed significantly in age, height, and PPVT raw scores (number correct). The PPVT IQ scores, which are equated for age, did not show a significant difference between age groups. No sex differences within age groups were found on any of these measures.

Table 1
Means and Standard Deviations for Summary Characteristics
and PPVT Scores of Both Age Groups

Measure	Age Group				Statistical Difference Between Groups: t
	3-year-olds		5-year-olds		
	Mean	SD	Mean	SD	
Age (years)	3.45	.27	5.40	.30	26.9*
Height (cm)	100.1	4.1	113.8	5.8	10.7*
PPVT Raw Score	45.3	7.1	61.3	5.2	10.0*
PPVT IQ Score	115.2	11.3	118.2	9.7	1.2

* $p < .001$..

Experimental Tasks

A series of five behavioral tasks were designed to assess different aspects of cerebral functioning. These tasks were: (1) motor speed; (2) visual-motor speed; (3) tactual-motor speed; (4) tactile naming and matching response onset speeds, and (5) picture vocabulary pointing response.

Motor speed: tapping. The tapping test was performed by having the subject place one or both arms on a 50 x 30 cm board covered with a cork surface and positioning the hands over two mechanical counters which had spring-loaded keys (Lafayette Hand Counter). The keys of the counters were positioned 5 cm above the board surface and separated by a distance of 36.2 cm in such a manner that they were 20.3 cm away from the edge of the board nearest the subject. Attached to the inside of both counters was a metal bar which protruded into a metal box containing a microswitch. The bar was directly connected to part of the key so that each time the key was depressed and released, it closed and opened the microswitch. The microswitch activated a pen on an Esterline Angus Operation Recorder, which made a chart recording of each hand's performance. A foot pedal also activated a pen on the recorder and was used to record the onset and offset of tapping in response to "go" and "stop" commands given by the examiner.

The subject was seated in a position midway between the two counters such that both arms could be placed symmetrically on the board. After four or five practice taps, preceding each tapping condition, the subject was instructed to tap as fast as possible when told to go, and to stop as soon as possible when told to do so. Five tapping conditions were administered in the following order: (1) unimanual finger tapping with right index finger; (2) unimanual finger tapping with the left index finger; (3) bimanual

alternate arm tapping with flexion at the shoulder joint only; (4) bimanual alternate finger tapping with both index fingers; and (5) bimanual synchronous finger tapping with both index fingers. Tapping speed was measured for 10 seconds although each condition was administered twice for 12 to 20 seconds, depending on the time required for the child to initiate the correct movements. During the four conditions in which the fingers tapped, the subject's hand was made into a fist with only the index finger pointing straight forward to the tapping key. The examiner held the subject's hand(s) such that only the index finger could move freely.

The tapping score was calculated as the average number of taps per 10 second interval for both unimanual conditions. In the bimanual conditions, the speed score was calculated as the average number of taps per 10 second interval per hand. The speed scores were measured from the initial correct tapping movement in order to control for individual differences in the speed of movement onset. Onset delays were also calculated and recorded as the time between the command to go and the first correct tapping movement.

Visual-motor speed: Trails R. This test was a simplified version of the Trail Making Test, Part A, for children (Reitan & Davison, 1974). In this test, the subject was presented with a clipboard holding an 8½ by 11 inch sheet of white paper which had drawings of six running rabbits, drawn from a picture in the Stanford Binet Intelligence Scale (Terman & Merrill, 1960), and one "rabbit hole" located on the page. The child was given a pencil and shown how to hold it in a standard position, then instructed to draw a continuous line as fast as possible, following the path on which the rabbits were running. The direction a rabbit pointed served to indicate the path, and each rabbit pointed to the next one in succession until reaching

the rabbit hole. The entire Trails R test consisted of one practice form and four test forms (A, B, C, and D). Each form was administered twice in immediate succession, once with each hand. The four forms of the Trails R test are shown in Figure 1. A one minute interval was included between forms during which time subjects observed slides of the Muppets in a Viewmaster stereoscope. For the Trails R test, hand order and form order were counterbalanced across subjects in each age group. Sixteen boys and 16 girls in both age groups were administered the test in the following hand order

format:

Form	Trial		Form	Trial	
	1	2		1	2
1	R → L		1	L → R	
2	L → R		2	R → L	
3	R → L		3	L → R	
4	L → R		4	R → L	

At the same time, eight boys and eight girls in both age groups were given one of the following formats to counterbalance forms:

Subject group	Form			
	1	2	3	4
1	A	B	C	D
2	B	C	D	A
3	C	D	A	B
4	D	A	B	C

The practice form consisted of only three rabbits and one rabbit hole, and was always administered before the other test forms to help ensure that the subject understood the instructions and to familiarize the subject with the use of the left hand.

Figure 1. The Four Forms of the Trails R Test (each reduced to 31% of original size).

The Trails R score was calculated as the speed of performance ($1/\text{time in seconds}$) for each complete page. A stopwatch was used to record the time from when the examiner said "go" until the pencil reached or passed close to the rabbit hole. Timing was discontinued if the subject lifted the performing hand from the page, in which case the subject was cautioned to keep the pencil on the paper. Timing was also discontinued if the subject made an error, in which case the examiner said, "stop", and the subject's hand was placed at the last correct rabbit. Then the examiner said, "Look carefully which way the rabbit is running". If the subject persisted in the wrong direction, the examiner added, "The rabbit runs this way", and included a finger movement from last correct rabbit to halfway towards the next correct one. The incorrect movements added to the total time of performance. Speed scores were recorded for both hands on each of the four forms of the test.

Tactual-motor speed: Formboard Task. The subject was seated before a 50 x 25 x 15 cm wooden box that had an open back and two hand holes cut into the bottom edge which were covered with cloth drapes. The hand holes were semicircular with a 10 cm diameter along the base and separated by 30 cm, as measured from the center of each hole. The subject was instructed to place both hands inside the box and one hand was given a 15 cm long, 2 cm diameter cardboard cylinder to hold while the other hand performed the formboard task. Both hands remained completely out of the subject's view.

Four different formboards, shown in Figure 2, were administered twice, once to each hand. Hand order and form order were counterbalanced across subjects as described for the Trails R test. Each formboard consisted of an 8 x 13 cm clear plexiglass board with two holes of different symmetrical

Figure 2. The Formboards. The top figure, drawn to scale, shows how the pieces fit into form A. The lower figures show each of the four forms.

shapes cut into the surface to a depth of 2 mm. The examiner grasped the subject's free hand and ran two of the subject's fingers passively over the perimeter of each hole, then placed a 2 mm thick piece of plexiglass in the subject's hand and said, "This shape goes into only one of the two holes. Put the shape into the right hole as fast as you can. Don't look." As soon as the subject accomplished the task, the examiner placed a second shape into the same hand and said, "This shape goes into the other hole. Go fast." The same procedure was then repeated immediately with the other hand. A minute rest period was placed between each different formboard during which time the subject was instructed to look through a Viewmaster stereoscope.

The score on the formboard task was determined as the speed of performance (1/time in seconds) required to complete a formboard each time it was administered. This yielded four scores for both hands, one score for each form. Timing was done with a stopwatch and began when the first object was placed in the subject's hand. Timing continued until the subject finished placing the second shape into its hole, and only stopped if the subject dropped a shape and could not immediately recover it.

Tactile naming and matching response speeds. This task employed the same wooden box described in the formboard task and was again used to shield both of the subject's hands from view. The examiner placed one of eight common items in one of the subject's hands. The subject was instructed to say the name of the object aloud and as fast as possible. When the examiner placed an object in the subject's hand, he also placed one finger in the palm of the subject's other hand in order to provide simultaneous tactile stimulation. Each of the eight items was presented in a set order, alternating hands each time, and with about 10 seconds between items. When

this first set of eight items was completed, the same items were presented again in a different order with each item going to the hand that did not feel it the first time. The order of the 16 item presentation was held constant across subjects, while the hand order was counterbalanced across subjects: half of the subjects in both age groups began with the right hand and half with the left hand.

The tactile naming sessions were tape-recorded and the delay in item naming (response onset speed) was measured with a stopwatch. Upon item presentation, the examiner said, "What is the name of this?" The item was placed in the subject's hand at the same moment "this" was spoken by the examiner. The delay between the onset of "this" and the onset of the subject's correct vocal response was used as the response onset speed. The response speed was calculated as $1/\text{time}$ in seconds for each item presentation.

After the naming task, the same objects were presented again, but in a different order and manner. Four objects were placed in front of the subject, who was then instructed to put his head face down on the table with both hands on the knees under the table and out of view. An object identical to one on the table was placed in the subject's hand. The subject was instructed to then let go of the item, look up, and point with the same hand as quickly as possible to the duplicate item on the table. This procedure was repeated for all four items, alternating hands each time. Again the examiner placed a finger in the subject's unused hand to provide dichotomous tactile stimulation and to restrain it from pointing, if necessary. A total of 16 item presentations were made and the order of hand presentation was counterbalanced across subjects as in the tactile naming task. Delays in responding were timed in the same way as for the naming task, however,

in this task the examiner said, "Good," as soon as the subject pointed to the correct item on the table, and this marked the offset of time on the tape-recorder.

Pointing response to verbal stimuli: PPVT. The PPVT was administered as a screening device and given in the conventional manner. During the administration, however, the examiner recorded the hand used to make the pointing response to each item. In addition to the raw score and IQ score obtained as part of the screening procedure, a laterality index score was obtained by comparing the number of spontaneous right and left hand pointing responses. A left hand error index was also computed, which expressed the ratio of left hand errors to the total number of left hand responses. In addition, the laterality of the pointing response was manipulated for 14 of the 3-year-old subjects upon readministration of the test, by having them point with only the left hand or only the right hand. In this second condition, the frequency and level of difficulty were recorded for the "wrong hand" responses.

Results

In this section, the results are subdivided according to the task or analysis. Each subdivision contains a brief discussion dealing with those results. A general discussion of all results is provided in the next section.

Results for Tapping Speeds

Lateral asymmetry. Lateral asymmetry of tapping was measured as the relationship between right and left index finger tapping speeds, which are shown in Table 2. The faster hand is defined as "superior". When the right hand is superior, the right:left (R/L) ratio is greater than 1.000. The R/L ratio for the 3-year-old group was $\bar{X} = 1.156 \pm .091$, and for the 5-year-old group, $\bar{X} = 1.159 \pm .102$. Both ratios were normally distributed, according to a χ^2 test for departure from normality (Hays, 1973, p. 726) and differed significantly from 1.000 ($t(31) = 9.92$ and $t(31) = 8.77$, $p < .001$, respectively), establishing the presence of a right hand superiority in the speed of unimanual finger tapping. These ratios of approximately 1.15 are also expressed as a 15% right hand superiority for both age groups. The mean right hand superiorities for the two age groups did not differ from each other, however, suggesting there was no difference in lateral asymmetry between the 3-year-olds and 5-year-olds. The difficulty with this approach to studying developmental changes in lateral asymmetry is that it assumes chronological age (CA) is an adequate indicator of maturity in cerebral motor functions. Yet, there was considerable variability in the tapping speeds between individuals in both CA groups. Subsequently, a decision was made that other maturational variables analyzed within the two groups might be sensitive to maturational changes in lateral asymmetry for tapping speeds.

The overall level of finger tapping speed ($R + L$) was originally considered a measure of fine motor maturation, but this measure could not be directly correlated with tapping lateral asymmetry (R/L) because the

Table 2
Means and Standard Deviations
in Each Tapping Condition

Condition	3-year-olds				5-year-olds			
	Boys		Girls		Boys		Girls	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Right Hand Finger Tapping	22.4	2.6	22.3	2.7	26.4	3.0	25.8	2.1
Left Hand Finger Tapping	19.0	2.0	19.7	2.2	23.3	2.7	22.0	2.7
Bimanual Alternate Arm Tapping	11.6	4.0	12.0	4.7	16.4	4.6	17.7	3.9
Bimanual Alternate Finger Tapping	9.2	3.7	10.6	5.4	17.1	3.6	17.6	3.7
Bimanual Synchronous Finger Tapping	18.7	3.5	20.0	3.3	25.0	2.9	24.7	3.4

Note. N = 16 for each mean and standard deviation.

two terms are not independent and the resulting correlation would only reflect the different variances in the tapping speeds for the two hands (Stone, 1980). Instead, the correlations between unimanual right and left finger tapping speeds were determined for both age groups, and the slopes of both regression lines were used to indicate whether the speed scores corresponded to a uniform distribution of the 15% right hand superiority in both age groups. Figure 3 shows the regression line corresponding to $R/L = 1.000$ (symmetry), the line corresponding to a 15% right hand superiority, and the obtained regression line (dotted) for 3-year-olds. The slope of the obtained regression line differs significantly from the line for 15% laterality ($t(30) = 2.605$, $p < .02$), indicating the 15% lateral asymmetry is not evenly distributed in the 3-year-old group. Using right hand speed scores as the basis for forming two 3-year-old subgroups, it was found that the slower 16 3-year-olds had a mean lateral asymmetry ($R/L: \bar{X} = 1.120 \pm .086$) which was significantly smaller than that of the faster 16 3-year-olds ($R/L: \bar{X} = 1.192 \pm .081$), as determined by a t-test on the difference between means ($t(30) = 2.361$, $p < .025$). By comparison, the lateral asymmetry of the 5-year-olds was evenly distributed across performance levels. These findings suggest that lateral asymmetry for tapping is changing during the third postnatal year, but not during the fifth year.

When lateral asymmetries for both age groups were correlated with other maturational variables: height, chronological age in months, PPVT raw scores, and PPVT IQ scores, none of the correlations approached significance, whether these variables were considered alone or in combination.

Figure 3. Right Hand (R. H.) Versus Left Hand (L. H.) Unimanual Index Finger Tapping Speeds for Individual 3-Year-Olds. Three regression lines show (1) symmetry (long solid diagonal line), (2) a uniform distribution of 15% right hand superiority (short solid line), and (3) the obtained distribution for 15% right hand superiority (dashed line).

Intermanual transfer: Bimanual cooperation. Bimanual cooperation was assessed in the final three tapping conditions administered to each child: alternate arm tapping, alternate finger tapping, and synchronous finger tapping. The means and standard deviations for the bimanual and unimanual tapping conditions according to age group and sex were presented in Table 2. Speed scores were normally distributed for both age groups in all conditions, as determined by χ^2 tests for the normality of sample distributions (Hays, 1973, p. 726). A statistical analysis of the differences between means was carried out with a univariate split-plot factorial (ANOVA) design with two between subjects (two age levels and two sex levels) and one within subjects (five tapping condition levels) variable. The ANOVA summary table is presented in Table 3. The 3-year-olds tapped more slowly than the 5-year-olds ($F(1,60) = 66.37, p < .001$). No main effect of sex, or age by sex interaction, was present. The tapping condition main effect was also significant, indicating the speed of tapping varied with the tapping condition ($F(4,240) = 203.5, p < .001$). The Age by Condition interaction was also significant ($F(4,240) = 5.99, p < .001$), but neither interaction with the sex effect was significant. When the Geisser-Greenhouse conservative F test was applied to protect against violations of symmetry and equality of the variance-covariance matrices, all three significant effects remained significant at the .001, .001, and .025 levels, respectively. The Age by Condition interaction is of particular interest because most of the interaction was between the alternating and nonalternating conditions. The relatively late maturation of the alternating conditions is evident upon examination of the ratio of 5-year-old to 3-year-old performance speeds in each tapping condition, as shown in Figure 4. The higher ratios for the

Table 3
Analysis of Variance Summary Table for Means of Tapping Conditions

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F
Between Subjects effects				
Age	1	2055.9	2055.9	66.37*
Sex	1	9.6	9.6	.31
Age x Sex	1	14.4	14.4	.47
Error	60	1858.7	30.9	
Within Subjects effects				
Tapping Condition	4	5769.7	1442.4	203.50*
Age x Condition	4	169.8	42.5	5.99*
Sex x Condition	4	24.3	6.1	.86
Age x Sex x Condition	4	21.7	5.4	.77
Error	240	1701.1	7.1	
Total	319	11625.0		

* $p < .001$.

Figure 4. Relative Difference between 3- and 5-Year-Old (y. o.) Tapping Speeds. The tapping conditions are: Right Hand Finger Tapping (R), Left Hand Finger Tapping (L), Bimanual Alternate Arm Tapping (AA), Bimanual Alternate Finger Tapping (AF), and Bimanual Synchronous Finger Tapping (SF).

two alternating conditions in Table 4 indicate they show a greater degree of change between 3 and 5 years of age relative to the other three tapping conditions.

Another method of viewing the age by condition interaction is by inspection of the first order Pearson Product moment correlation coefficients (r), presented in Table 4. The highest correlations are within the two alternating and the three nonalternating conditions, rather than between these two kinds of conditions. The pattern of correlations is in agreement with the suggestion by Wolff and Cohen (1980) that bimanual alternate tapping of arms and index fingers is subserved by a mechanism(s) that differs from mechanisms underlying nonalternate tapping performances.

Onset delays for each tapping condition in both age groups, shown in Table A of the Appendix, follow the pattern for tapping speeds with a relatively late maturation in the two alternate tapping conditions. The relative improvements are similar to those presented in Figure 3, except for synchronous finger tapping; however, the change in this condition is due largely to a few extreme scores in the 3-year-old group. Onset delays for alternate tapping show significant negative rank-order correlations with the speed of alternate tapping. See Table B of the Appendix. In the 5-year-olds, there is a negative relationship between onset delay and tapping speeds, since 24 of the 25 correlations for 5-year-olds in Table B show negative values for r . This evidence for increasing correlations between tapping conditions along with greater correlations between conditions in the 5-year-olds, also seen in Table 4, supports the notion that alternate tapping is gradually incorporated into a larger repertoire of tapping skills, although it perhaps originates as a separate ability. That

Table 4
Pearson Correlation Coefficients (r) for Mean Tapping Speeds

Tapping Condition	Tapping Condition				
	Right ^a	Left ^b	Alternate Arm ^c	Alternate Finger ^d	Synchronous Finger ^e
<u>3-year-olds</u>					
Right	1.00	.76	.34	.27	.47**
Left		1.00	.25	.33	.61***
Alternate Arm			1.00	.61***	.05
Alternate Finger				1.00	.27
Synchronous Finger					1.00
<u>5-year-olds</u>					
Right	1.00	.73***	.52**	.50**	.56***
Left		1.00	.53**	.49**	.65***
Alternate Arm			1.00	.57***	.43*
Alternate Finger				1.00	.26
Synchronous Finger					1.00

^aRight Hand Finger Tapping.

^bLeft Hand Finger Tapping.

^cBimanual Alternate Arm Tapping.

^dBimanual Alternate Finger Tapping.

^eBimanual Synchronous Finger Tapping

*p < .05.

**p < .01.

***p < .001.

is, with maturation there may be facilitory interactions between alternate tapping abilities and the other tapping skills.

Relationships between lateral asymmetry and bimanual cooperation.

Relationships between lateral asymmetry (R/L) and bimanual finger tapping performance were analyzed for both age groups. The purpose of this analysis was to make inferences about relations between degree of cerebral specialization and amount of cerebral interhemispheric transfer of motor functions. When asymmetry was examined as a function of alternate finger tapping speed in 3-year-olds, multiple regression trend analysis showed the presence of a significant quadratic polynomial trend ($R_{\text{quadratic}} = .37$, $B = 1.44$, $F = 4.627$, $p < .05$). Since the slower tapping 3-year-olds showed a positive correlation and faster 3-year-olds showed a negative correlation, the 3-year-old group was subdivided into slow and fast alternate tapping groups. A similar subdivision, based on speed of alternate tapping, was made in the 5-year-old group for comparison. In both age groups, 16 subjects were assigned to the slower group and 16 subjects to the faster group. As a control condition, subjects were also assigned to fast and slow subgroups on the basis of bimanual synchronous finger tapping speeds, in order to examine the correlation between speed of synchronous tapping and degree of lateral asymmetry for unimanual tapping.

Synchronous tapping was not correlated with degree of lateral asymmetry, as shown in Table 5, although there was a trend for a negative correlation. Alternate finger tapping correlations with lateral asymmetry were more difficult to interpret because there appeared to be effects related to sex and level of performance. The relation between alternate finger tapping and lateral asymmetry was analyzed further with a between subjects ANOVA design

Table 5
 Pearson Correlation Coefficients (r) between Lateral Asymmetry
 and Bimanual Performance on the Tapping Test

Condition	3-year-olds		5-year-olds	
	Boys	Girls	Boys	Girls
Bimanual Alternate Finger Tapping	+.47*	-.31	-.16	-.14
Bimanual Synchronous Finger Tapping	-.13	.00	-.29	-.11

* $p < .05$.

having three between subjects variables: age, sex, and alternate tapping speed, each with two levels. Fast and slow levels of the alternate tapping speed variance were used in the analysis. The means and standard deviations for lateral asymmetry as a function of all three variables are shown in Table 6. The ANOVA summary table is shown in Table 7. No age, sex, or alternate tapping speed main effects were present; however, the age by sex and sex by alternate tapping speed interactions approached significance: Age by Sex ($F(1,56) = 3.69, p = .060$) and Sex by Alternate Tapping Speed ($F(1,56) = 3.37, p = .072$). When subjects were categorized on the basis of alternate finger tapping onset delays, the pattern of ANOVA results was nearly the same, except only the Age by Sex interaction approached significance ($F(1,56) = 3.36, p = .072$). The ANOVA summary table is shown in Table C of the Appendix. When subjects were categorized on the basis of synchronous finger tapping speeds, none of the main effects or interactions approached significance.

These results suggest the degree of lateral asymmetry is positively related to the alternate finger tapping performance in 3-year-old boys, but not in 5-year-old boys. In contrast, it appears that 3-year-old girls perform more similarly to 5-year-old boys and girls. It is possible that 3-year-old girls have matured beyond a stage in which alternate tapping is positively correlated with lateral asymmetry, or there may be a more fundamental sex difference in the cerebral organization, with girls not showing the same relationships between alternate tapping ability and lateral asymmetry as boys. The data in this study favor the latter hypothesis of a sex difference in cerebral organization, because there were no sex differences in the speed of alternate tapping nor in the degree of lateral asymmetry

Table 6
Means and Standard Deviations for Lateral Asymmetry of Tapping
as a Function of Alternate Finger Tapping Speed

Alternate Finger Tapping Speed Group	3-year-olds				5-year-olds			
	Boys		Girls		Boys		Girls	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Slower 16 Subjects	1.14	.19	1.18	.11	1.14 ^a .10		1.20 ^b .10	
Faster 16 Subjects	1.21	.07	1.09	.05	1.13 ^b .06		1.16 ^a .14	

Note. N = 8 for each mean in 3-year-old group.

^aN = 9.

^bN = 7.

Table 7

ANOVA Summary Table for Means of Lateral Asymmetry on Tapping
as a Function of Alternate Finger Tapping Speed Group, Age, and Sex

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F
Between Subjects				
Age	1	.0001	.0001	.01
Sex	1	.0009	.0009	.01
Alternate Tapping ^a	1	.0034	.0034	.39
Age x Sex	1	.0325	.0325	3.69*
Age x Alt. Tapping	1	.0016	.0016	.18
Sex x Alt. Tapping	1	.0297	.0297	3.38*
Age x Sex x Alt. Tapping	1	.0170	.0170	1.93
Within Cells	56	.4932	.0088	
Total	63	.5775		

^aSlower and Faster 16 Subjects groups on Bimanual Alternating Finger Tapping.

*p < .07.

for tapping speed.

Qualitative observations. The tapping test was easily administered to all children with no apparent difficulties for the children in terms of conceptualizing the nature of the tapping movements. Generally, the 3-year-olds had difficulty maintaining the alternate movements for a full 10-second period, and their alternating movement errors usually consisted of a synchronization of the two hands or unimanual movements. Unimanual errors often occurred when the child watched one hand and ignored the other. There were no apparent problems maintaining bimanual synchronous or unimanual tapping movements by the 3-year-olds. The 5-year-olds generally had no difficulty maintaining the performance in any of the five tapping conditions.

Discussion. Even though there was no difference between the lateral asymmetry of unimanual finger tapping between the 3- and 5-year-old groups, an analysis within age groups indicated that maturational changes in the lateral asymmetry were present in the 3-year-olds, but were stable in the 5-year-olds. In a review of the literature, no other reports were found on lateral asymmetry measures for tapping speeds in 3-year-olds; however, the results are consistent with a study by Cernacek and Podivinsky (1972) showing some manual motor asymmetries are nearly complete by 2 or 3 years of age. The evidence for an early establishment of these skills is consistent with studies showing lateral asymmetries on finger tapping speeds and other fine motor skills do not change between 5 years of age and adulthood (Finlayson, 1976; Gardner, 1979; Peters & Durdin, 1978, 1979). An early postnatal motor lateralization is also consistent with evidence for an early maturation

of primary cerebral motor areas in the human brain (Blinkov & Glezer, 1965; Yakovlev, 1962).

The evidence presented here for a relatively late maturation of alternate tapping skills in comparison to other unimanual and bimanual tasks is consistent with Gazzaniga's (1970, 1974, 1981) hypothesis that there may be behavioral manifestations of late-developing interhemispheric communication in young children. Specific impairment of alternate tapping skills has been seen when the callosum is damaged, as shown by commissurotomy patients in studies by Kreuter et al. (1972) and Zaidel and Sperry (1977), suggesting alternate tapping skills depend on a cerebral mechanism which includes the corpus callosum. Luria (1969, 1973) reported that studies of brain-damaged patients have implicated a role of the anterior region of the corpus callosum as the region of interhemispheric transfer of motor cooperation between body sides.

The findings on the normal children in the present study also have implications for further studies of developing bimanual coordination in early childhood. Commissurotomy subjects show selective difficulty on bimanual same-direction knobturning (Preilowski, 1972) and young children show evidence of relatively late-developing bimanual knobturning (e.g., both hands counterclockwise) (Elliott & Connally, 1974; Maxwell, unpublished observations) compared to bimanual same-direction or unimanual knobturning speeds. A possible explanation for a callosal role in these asymmetrical tasks is that interhemispheric communication is necessary for cerebral inhibition of mirror movements, which are guided by lower brain centers (Connally & Stratton, 1968). Mirror movements do not disappear until 6 or 8 years of age (Abercrombie, Lydon, & Tyson, 1964) and are

often present in individuals with mental retardation (Fog & Fog, 1963), cerebral palsy (Abercrombie et al., 1964), and callosal agenesis (Dennis, 1976; D. Milner & Jeeves, 1979).

The relationship between lateral asymmetry and bimanual tasks was of major interest to the present study. In all three bimanual tapping speed conditions, there were trends for an inverse relationship to lateral asymmetry, except in the case of 3-year-old boys, who showed a positive relationship. The positive relationship in this group may indicate lateral asymmetries and interhemispheric communication for alternate tapping are positively correlated when the task skills are being acquired, as suggested by Dennis (1976). It may be that once the task has become simple, or automatic, it can be regulated by subcortical centers in the brain and the two phenomena are no longer related for this task. Evidence in support of this hypothesis is that if the task is made difficult for adults by administration of concurrent tasks, a lateralized interference with alternate finger tapping was noted (Wolff & Cohen, 1980). Perhaps even for adults, when a new and difficult skill is being acquired, a relation between interhemispheric communication and lateral asymmetry is present.

In summary, the children in this study showed a right hand superiority for unimanual finger tapping speed, and alternate tapping speeds increased relative to speeds in other tapping conditions. These results suggest interhemispheric communication may continue to develop after the establishment of a left hemispheric specialization for fine motor skills, and at least in the case of tapping, the relationship may be sex-specific. It was also noted that for older and faster children, greater lateral asymmetry tended to be related to slower bimanual tapping speeds. This is

important because it suggests developing interhemispheric communication lessens behavioral evidence of hemispheric functional specializations.

Results for Visual-Motor Speed: Trails R

Lateral asymmetry. The four forms of the Trails R test were given twice to all subjects with the order of presentation counterbalanced across subjects. Lateral asymmetry was determined using only the first trial scores on each of the four forms in order to avoid practice effects of the contralateral hand which were present during the second trials. For each subject, the lateral asymmetry measure consisted of two left hand and two right hand performances with half of the subjects beginning with the left hand and half with the right hand in both age groups. A one-way ANOVA on the mean performance speeds for each form showed that all four forms were equivalent and need not be further considered as a source of variance. The first trial right hand and left hand average speeds (Speed = $1/\text{time}$ in seconds) are shown in Table 8. These speed scores were normally distributed, unlike the time scores which were markedly skewed. The lateral asymmetry measure was L_1/R_1 , where subscript 1 denotes the first of two trials on each form, and both letters denoting hand represent the average of two scores. The L_1/R_1 measure was chosen, rather than R_1/L_1 because a significant left hand superiority ($L_1/R_1 > 1.000$) for the speed of performance was found for the entire group of 64 children: for L_1/R_1 , $\bar{X} = 1.158 \pm .367$ ($t(63) = 3.44$, $p < .002$). Forty-four (69%) of the children showed a left hand superiority on Trails R, even though none of these same children manifested a left hand superiority on unimanual finger tapping. The left hand superiority reached significance in the 5-year-olds: for L_1/R_1 , $\bar{X} = 1.205 \pm .393$ ($t(31) = 2.95$, $p < .01$), while the left hand advantage was only a trend in the 3-year-olds:

Table 8
Means and Standard Deviations of Speed Scores
for Both Hands on the Trails R Test

Hand	3-year-olds				5-year-olds			
	Trial 1		Trial 2		Trial 1		Trial 2	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Right	.113	.053	.139	.048	.153	.058	.182	.063
Left	.118	.043	.121	.053	.176	.052	.186	.059

for L_1/R_1 , $\bar{X} = 1.099 \pm .339$ ($t(31) = 1.63$, $p < .15$). This evidence does not represent a maturational increase in left hand superiority, since the mean lateral asymmetries (L_1/R_1) of the two age groups did not differ significantly. ($t(62) = 1.13$, $p < .30$). However, it does indicate a trend for greater lateral asymmetry in the 5-year-olds.

A further analysis into the lateral asymmetry on Trails R as a function of other maturational variables within the two age groups did not reveal any indication that the observed left hand superiority changes with maturation in either group. The lateral asymmetry did not change as a function of the level of performance at 3 or 5 years of age, as determined by an analysis of slopes similar to that performed on the unimanual finger tapping data. Also, lateral asymmetry did not vary as a function of height, PPVT IQ, PPVT raw score, or chronological age in months in either age group.

In conclusion, on first trials for each form, the left hand performed the Trails R faster on the average than the right hand in this group of 3- and 5-year-olds. A trend was present for greater left hand lateral asymmetry in the 5-year-olds over the 3-year-olds, and there was no evidence for a change in lateral asymmetry as a function of several maturational variables.

Intermanual transfer of learning. It might appear from the experimental design shown below that the transfer of learning should be measured as improvement on a given form of the test.

<u>Form</u>	<u>Trial 1</u>	<u>Trial 2</u>
1	$R_1 \longrightarrow$	L_2
2	$L_1 \longrightarrow$	R_2
3	$R_1 \longrightarrow$	L_2
4	$L_1 \longrightarrow$	R_2

For example, improvement might be measured as $R_2 - L_1$ and $L_2 - R_1$. These measures, however, would be deceptive because each hand starts from a different baseline speed on the first trial, i.e., L_1 scores are on the average higher than R_1 scores. Consequently, in this study each hand was compared to itself in order to obtain measures of intermanual savings between hands. The amount of improvement or "% savings" was calculated separately for both hands. Right hand % savings = $\left[\frac{(R_2 - R_1)}{R_1} \times 100 \right]$. Left hand % savings = $\left[\frac{(L_2 - L_1)}{L_1} \times 100 \right]$. Both equations include only one hand, but it is still the contralateral hand performance which actually preceded the second hand (R_2 or L_2) in both cases.

The mean performance speeds for first and second trials with each hand for both age groups are shown in Table 9, which also presents the average % savings for both hands and the average sum total % savings of both hands together. The total % savings measure is significant in the 5-year-olds, as determined by t-tests, against a hypothesis that % savings equals zero. An ANOVA split-plot factorial design was set up with two between subjects variables (age and sex) and % savings as a within subjects variable having two levels: right hand % savings and left hand % savings. The ANOVA summary table is shown in Table 10. No Age or Sex main effects were present; however, the % savings effect reached significance at ($F(1,60) = 6.95, p = .011$), and remained significant below the .05 level when the Geisser-Greenhouse conservative F was applied. The significant % savings effect indicated the right hand % savings were significantly higher than left hand % savings, and there were no significant interactions between variables. The most important aspect of these findings were that intermanual transfer was significant at both 3 and 5 years of age and was the same magnitude at both ages. Since

Table 9
Means and Standard Deviations for Intermanual Transfer
on the Trails R Test

Practice Effect	3-year-olds				5-year-olds			
	Boys		Girls		Boys		Girls	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Right Hand % Savings	60.6*	96.4	59.0**	76.1	67.2	133.1	43.1*	63.3
Left Hand % Savings	-13.7	87.2	11.5	131.2	17.7	113.4	12.2	53.4
Total % Savings	46.9	154.7	70.6	135.4	85.0*	114.7	55.3**	72.7

Note. Significance tests on null hypothesis that % savings = 0.0.

* $p < .05$.

** $p < .01$.

Table 10
ANOVA Summary Table for Mean Intermanual Transfer
on the Trails R Test

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F
Between Subjects Effects				
Age	1	1029.4	1029.4	.14
Sex	1	73.5	73.5	.01
Age x Sex	1	5684.4	5684.4	.75
Error	60	455660.0	7594.3	
Within Subjects Effects				
% Savings ^a	1	81659.0	81659.0	6.95*
Age x % Savings	1	3475.7	3475.7	.30
Sex x % Savings	1	4083.8	4083.3	.35
Age x Sex x % Savings	1	138.2	138.2	.01
Error	60	705280.0	11755.0	
Total	127	1257100.0		

^aTotal % savings were not included in this analysis.

*p = .011.

% savings is a relative measure of improvement, the fact that intermanual transfer kept pace with an increase in performance speeds suggests that the amount or efficiency of interhemispheric communication is greater at 5 than at 3 years of age.

Relationships between lateral asymmetry and intermanual transfer.

Lateral asymmetry was measured as the ratio of left hand speed to right hand speed on first trials for each form (L_1/R_1), while intermanual transfer of learning was measured as relative improvement or % savings on second trials over first trials for each hand. Simple correlations between the lateral asymmetry and intermanual transfer measures would not be meaningful because the terms in the correlations have a common element, R_1 or L_1 , and therefore are not independent terms. Stone (1980) suggested that in such cases an alternative method of analysis is to partial-out the variance due to the common term, R_1 or L_1 , statistically removing its effect on the correlation between lateral asymmetry and intermanual transfer. This is equivalent, for example, to removing the variance in lateral asymmetry due to R_1 , obtaining a residual (d_1), and removing the variance in right hand % savings due to R_1 , obtaining the residual (d_2), then correlating the residuals, d_1 with d_2 .

The correlations between lateral asymmetry and % savings before and after partialling-out the common first trial terms are given for both age groups in Table 11. All correlations reached statistical significance and there appeared to be little effect of partialling-out the common terms. The sign of the correlation reflects whether the numerator or denominator of the L_1/R_1 term was correlated with the % savings measure. The negative correlations between lateral asymmetry and left hand % savings indicate that as the left hand performs increasingly better than the right, the left hand is less able to learn from the right hand's experience. The positive correlations between

Table 11
 Pearson Correlation Coefficients Between Lateral Asymmetry
 and Intermanual Transfer on Trails R

Intermanual Transfer Condition	3-year-olds	5-year-olds
Right Hand % Savings		
Without R_1 Partialled-out	+.61*	+.77*
With R_1 Partialled-out	+.48*	+.68*
Left Hand % Savings		
Without L_1 Partialled-out	-.53*	-.81*
With L_1 Partialled-out	-.54*	-.80*

* $p < .001$.

lateral asymmetry and the right hand % savings mean that as the left hand performs increasingly better than the right, the right hand is more able to learn from the left hand's experience.

A second method of analysis for the relationship between the same lateral asymmetry and intermanual transfer measures was also suggested by Stone (1980) and is less complex than the analysis presented above. Stone argued that the correlation, such as that between a laterality measure ($R_1 - L_1$) and a learning measure ($L_2 + L_1$) is essentially the same as the correlation between R_1 and L_2 . In the present study, that is not entirely useful because R_1 and L_2 could be highly correlated with each other simply because they both correlate with L_1 . In order to clarify the situation, the common term (L_1) must be partialled-out of the correlation between R_1 and L_2 . That represents the correlation between lateral asymmetry and the left hand % savings, removing the common variance they share with L_1 . Similarly, for the right hand % savings, L_1 and R_2 were correlated and variance due to R_1 was partialled-out. The correlations before and after partialling-out the common terms are presented in Table 12. They concur with the results of the preceding analysis, lending further support to the notion that the greater the degree of left hand superiority, the greater the amount of intermanual transfer.

Qualitative observations. This task was easy to administer to 5-year-olds, but many of the 3-year-olds initially had difficulty understanding the sample form. Only a few 3-year-olds needed more than two sample form practice trials to show they understood the task. The 3-year-olds generally made more errors on the Trails R test than the 5-year-olds, and many of these errors were of a type in which the child perseverated in drawing a connecting line in the same wrong direction, despite the efforts of the

Table 12

Pearson Correlation Coefficients (r) between First and Second Trials of Trails R

Hand Conditions Correlated	3-year-olds	5-year-olds
R_1 with L_2	$+.79^*$	$+.87^*$
R_1 with L_2 and L_1 removed	$+.63^*$	$+.79^*$
L_1 with R_2	$+.83^*$	$+.56^*$
L_1 with R_2 and R_1 removed	$+.77^*$	$+.56^*$

* $p < .001$.

examiner to point out the nature of the error. Two other qualitative observations of interest concerned the performance of each hand. Thirty of the children were asked which hand performed the test fastest, all 30 children asked responded that the right hand was faster and in only five cases was this response correct. A few 3-year-olds said they did not know which hand was faster, then indicated the right hand. The second observation was that the three-point pincer grasp (mature pencil grasp) was always maintained throughout each trial after being imposed on the child by the examiner, even though the child usually picked up the pencil with a less mature grasp, e.g., simian grasp, as described by Gardner (1979). This suggests that formal instruction may be an important factor in the development of a "proper" writing grasp, in addition to the proximo-distal maturation of neuromuscular control of the extremities (Ayres, 1974; Gardner, 1979). A final note is that the Trails R test was clearly the most popular of the tests used in the present study. Often the children would ask to play with the "rabbit game" during the second session.

Discussion. The presence of a left hand superiority on Trails R is consistent with lateral asymmetries noted for tests requiring nonverbal visual-spatial analyses, and suggests a right hemispheric superiority for performance of this task. The finding is similar to that of adult commissurotomy subjects who show marked left hand advantages for speed and accuracy of picture drawing and putting blocks together to copy a design (block design) (LeDoux, Wilson, & Gazzaniga, 1978). A small, but significant, left hand advantage on block design has also been found in normal adult subjects (Epro & Granite, 1979). Reitan (1955b, 1958) found the Wechsler (WAIS) Block Design subtest and Trail Making Test, Part A, sensitive to

right hemispheric damage, also supporting a right hemisphere superiority for this type of visual-spatial skill. Rourke and Finlayson (1975) reported that learning disabled children with evidence of right hemisphere dysfunction on other neuropsychological measures showed poor performance on the Trail Making Test, Part A and Part B, while children with left hemispheric dysfunction showed relatively poorer performance on Part B, which requires more verbal skill. However, a significant hemispheric specialization for Trails R or Trail Making, Part A, may not be specifically visual-spatial in nature, because LeDoux et al. (1978) found commissurotomy subjects could correctly match block design pairs presented to either visual half-field. Rather, the specialization may be present in the motor expression or motor planning of these visual-spatial skills (LeDoux et al., 1978; Gazzaniga, 1981). The evidence presented in this study suggests such a right hemispheric specialization is present by 5 years of age, although a similar trend was also seen at 3 years of age.

The intermanual transfer (% savings) measures provided evidence for a unilateral transfer of interhemispheric information in which the left hand was able to train the right hand, but the right hand could not train the left hand. An explanation for unidirectional learning based on incidental learning in which the left hemisphere is somehow dominant (e.g., Heilman, 1979), is less parsimonious than an explanation based on unidirectional transfer of information. The former explanation is inconsistent with the absence of transfer on visual-motor tasks given to commissurotomy subjects (LeDoux et al., 1978; Zaidel & Sperry, 1977), whereas unidirectional interhemispheric transfer from a trained hemisphere to the untrained hemisphere, but not the reverse, has been demonstrated in a number of experimental animal preparations

(Buresova, Bures, & Nadel, 1972; Doty & Negrao, 1973; Negrao & Doty, 1969).

A unidirectional interhemispheric transfer on Trails R would seem to be dependent on cerebral specialization already established in the right hemisphere, as opposed to being specific to Trails R, because the left hand superiority for performance speed was noted even in initial Trails R performances. The findings are consistent with experimental studies which found that specialized hemisphere can send information to the unspecialized hemisphere when the unspecialized hemisphere is called upon to perform, but the reverse process does not occur.

Intermanual transfer and lateral asymmetry maintained a close relationship at both 3 and 5 years of age. This may indicate the cerebral systems necessary for Trails R performance are continuing to mature as the skills necessary for task performance are being acquired between 3 and 5 years of age. The early maturation of some of the Trail Making test skills combined with the verbal skills learned later may help to explain the high sensitivity of the Trail Making tests to brain damage in older children (Boll, 1974; Dunleavy & Baade, 1980), while tasks requiring more complex cognitive skills, such as the Category Test or Tactual Performance Test, are more sensitive to brain damage in adults (Knights & Tymchuck, 1968; Reitan, 1974a).

In summary, the Trails R test provided evidence that lateral asymmetries for right hemisphere performance skills are present in early childhood. Continuing improvement of performance speed may be based on a strong relationship between the degree of hemispheric specialization and interhemispheric transfer of information present at 3 and 5 years of age. The nature of this relationship may be further explained by evidence for a

unidirectional transfer of information, which suggests the specialized hemisphere may be responsible for the transfer of information.

Results for Tactual-Motor Speed: Formboard Test

Before determining lateral asymmetries on the Formboard test, equivalence of the four formboards (shown in Figure 2) was examined. It was found that Form A was significantly easier to perform than the other three forms. Further analysis, however, revealed mean performance times for Form A in both age groups were equivalent to the other forms during the first two sets of trials. Since a lack of equivalence between forms would contribute a large amount of irrelevant variance to lateral asymmetry and intermanual transfer measures, only the first two sets of trials were used for the analysis of lateral asymmetry and intermanual transfer of learning.

Lateral asymmetry. The group means and standard deviations of the left and right hand speed scores used to calculate lateral asymmetry on the Formboard are shown in Table 13. These speed scores are two to three times slower than Trails R speeds. The Formboard test tended to be easy for a few and difficult for most of the children. Consequently, speed scores tended to be skewed and violated the assumption that they came from a normally distributed population of speed scores, according to chi-square tests (Hays, 1973, p. 726). Lateral asymmetry was measured as the ratio of first trials R_1/L_1 , since there was slight and insignificant overall right hand superiority: R_1/L_1 , $\bar{X} = 1.069 \pm .590$. Lateral asymmetry also violated the assumption of normality using chi-square tests (Hays, 1973, p. 726) and transformation of lateral asymmetry failed to produce a sample distribution that could satisfy the assumption of normality. An analysis of frequencies using the binomial approximation to the normal distribution indicated that as many subjects were faster with

Table 13
Means and Standard Deviations for Speed of Performance
of Both Hands on the Formboard Test

Hand	3-year-olds				5-year-olds			
	Trial 1		Trial 2		Trial 1		Trial 2	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Right	.039	.030	.039	.018	.067	.035	.082	.052
Left	.038	.026	.055	.041	.068	.034	.073	.046

the right hand as subjects who were faster with the left hand, which meant there was no evidence for lateral asymmetry on this task. Both the 3- and 5-year-old groups failed to show lateral asymmetries. Lateral asymmetry measures for the two groups also failed to differ from each other, according to a Mann-Whitney test for independent samples.

In addition, Spearman rank order correlations showed that lateral asymmetry in both age groups did not vary as a function of other maturational variables: height, PPVT IQ, PPVT raw score, and chronological age in months. A detailed analysis of the correlation between R_1 and L_1 to look for changes in asymmetry as a function of performance level was not undertaken because the correlations between R_1 and L_1 failed to reach significance in both age groups. In summary, there was no evidence for a lateral asymmetry in the speed of formboard performance in this group of 3- and 5-year-olds, nor was there any evidence for a correlation between the lateral asymmetry measure and the other maturational variables. Perhaps this lack of measurable asymmetry reflects the difficulty of this test.

Intermanual transfer of learning. Intermanual transfer, or % savings, was measured as improvement of the second performance speed over the first by the same hand: $[(R_2 - R_1)/R_1] \times 100$, and $[(L_2 - L_1)/L_1] \times 100$. This approach was discussed earlier in the Trails R results section, and differs here in that only one trial speed, rather than the average of two trials, was used for R_1 , R_2 , L_1 , and L_2 . The % savings scores, which were not normally distributed (Hays, 1973, p. 726), failed to differ significantly from zero in both age groups, as determined by binomial approximations of the normal distribution. Mann-Whitney tests of age, sex, and hand differences also failed to show any significant differences in the % savings measure. The

results indicate there was no evidence for intermanual transfer of learning on this test.

Relationship between lateral asymmetry and intermanual transfer. Even though the lateral asymmetry and intermanual transfer measures did not reach statistical significance, it was still considered possible that the lateral asymmetry measure could be correlated to the % savings measure. Correlations were determined and analyzed for both age groups according to the partial correlation methods described in the Trails R results section: (1) between R_1/L_1 and the % savings terms, and (2) between R_2 and L_1 , as well as between L_2 and R_1 . In both methods, Spearman rank order correlation coefficients were determined and found to correspond quite closely with the Pearson product moment correlation coefficients from which the common terms, L_1 and R_1 , could be partialled-out. In the first analysis, lateral asymmetry and intermanual transfer measures showed a strong correlation until the common term was removed, as shown in Table 14. This analysis failed to support the notion of a unique relationship between the lateral asymmetry and % savings measures, and instead indicated that the relationship between these measures was explainable by the common term in each. One of the partialled terms reached significance at the .05 level in the 5-year-olds, but this was not given further consideration because the unpartialled Spearman correlation was somewhat lower than the Pearson correlation. In the second analysis, Spearman and Pearson correlations between R_2 and L_1 , as well as between L_2 and R_1 did not reach statistical significance, regardless of whether the R_1 and L_1 terms, respectively, were partialled out. The two analyses concur and suggest that on this formboard task, intermanual transfer and lateral

Table 14
Correlation Coefficients between Lateral Asymmetry
and Intermanual Transfer on the Formboard Test

Intermanual Transfer Condition	3-year-olds	5-year-olds
Right Hand % Savings		
Without R_1 Partialled-out	-.65 ^{***} (-.60 ^{***})	-.55 ^{***} (-.66 ^{***})
With R_1 Partialled-out	-.25	-.32
Left Hand % Savings		
Without L_1 Partialled-out	+.57 ^{***} (+.54 ^{**})	+.54 ^{***} (+.44 [*])
With L_1 Partialled-out	+.18	+.38 [*]

Note. Parentheses indicate Spearman rank order correlations, otherwise Pearson coefficients are indicated.

* $p < .05$.

** $p < .01$.

*** $p < .001$.

asymmetry measures were not related in these 3- and 5-year-old groups.

Qualitative observations. The Formboard test was very difficult for both age groups, and the children often commented they did not like the test. In support of this, a pilot study found that unless the examiner had good rapport with the 3-year-olds, they would often quit during the first trial. In the present study, rapport was probably facilitated by intertrial use of the Viewmaster stereoscope, which appeared to be far more rewarding than the Formboard trials.

It appeared the children seldom used a consistent strategy to place the blocks into the appropriate holes, but rather they usually kept pushing the blocks around until they found a hole and tried to fit the block into the hole without regard for shape. The 3-year-olds also appeared to have more trouble actually handling the blocks and they dropped the blocks far more often than did the 5-year-olds. Based on this observation, it can be suggested that motor manipulation skills accounted for most of the difference in the level of performance between the 3- and 5-year-olds. This test was also given to the children without hiding the formboards from view, and they performed more than three times faster, which was faster than the speed of performance on the Trails R test. This observation points out the test is made considerably more difficult by eliminating the use of the visual modality during task performance.

Discussion. The restricted use of vision on the Formboard test made it very difficult for both age groups. This was reflected in high between and within subject variability, not only in speed of performance, but also in strategies employed during performance of this tactual-motor test. Inability to perform this

test in a consistent manner probably accounted for the absence of lateral asymmetries and intermanual transfer. Perhaps the skills necessary for Formboard performance mature after 5 years of age, consistent with Finlayson's (1976) finding that intermanual transfer on the Tactual Performance Test was significantly greater in a group of 9- to 14-year-old children than in a group of 5- to 8-year-old children. If his group differences were affected by changing lateral asymmetries, it may be that these measures also show late maturational increases.

Two possible sources of late-maturing skills on the Formboard test are tactile skill development and development of spatial skills. On tests requiring unimanual tactile abilities administered to children, lateral asymmetries are not usually observed in children, or at least not before 8 years of age (Finlayson & Reitan, 1976; Flanery & Balling, 1979; Knights & Norwood, 1980), and then usually favor the right hand. On tactile tests with stimuli applied simultaneously to both hands, the left hand (right hemisphere) has been found superior to the right hand for nonsense shapes which cannot be readily verbalized, as early as 6 years of age (Cioffi & Kandel, 1976; Witelson, 1974, 1976). However, Galin et al. (1979) found intermanual transfer of tactile recognition significantly greater at 5 years of age than at 3 years of age. This finding suggests the skills necessary for adequate Formboard performance were more complex than tactile recognition.

The other possibility mentioned was that developing spatial skills, thought to be normally subserved by the right hemisphere (Reitan, 1955b), may be necessary for adequate Formboard performance. Teuber (1962) found damage to the temporal lobe of the right hemisphere appeared to have the greatest effect on the second performance of a tactual formboard that had been rotated

90 degrees. Zaidel and Sperry (1973) found a left hand superiority on a tactual version of Raven's Colored Matrices task in adult commissurotomy patients. In the present study, the 3-year-olds' overall Formboard performance speeds (average of all four trials used in the analysis) correlated only with their PPVT scores, as shown in Table D of the Appendix. Ability to comprehend or attend to the verbal instructions of the Formboard task may have been important for performance of the 3-year-old group. In the 5-year-old group, no correlation between the Formboard performance and the PPVT was found, but the average Formboard speeds did correlate with average speeds on Trails R. This correlation had more apparent validity than the Formboard-PPVT correlation noted for the 3-year-olds because spatial skills and sensorimotor skills presumably are necessary for both the Formboard and Trails R tests.

A later development of spatial skills would also be consistent with Piaget's (1952) descriptions of behavioral development. The Formboard test may require mastery of conservation skills normally developing by 7 or 8 years of age at the end of Piaget's concrete operational stage (Piaget, 1952; Singer & Singer, 1969). Recently, it was suggested that interhemispheric communication may be necessary for performance of Piagetian conservation tasks which require spatial analysis skills developing between 6 and 8 years of age (Kraft, Mitchell, Languis, & Wheatley, 1980).

It appeared neither hemisphere was capable of adequately guiding Formboard performance at 3 or 5 years of age. Possibly this resulted from later maturation of complex tactual or spatial skills necessary for task performance. The later postnatal maturation of these skills may correspond to a later anatomical maturation of parietal and temporal lobe association areas and their interconnecting commissural fibers (Von Bonin & Bailey, 1961; Yakovlev & Lecours, 1967).

In summary, the Formboard test presented in this study apparently required skills not yet acquired by 3 and 5 year old children. The difficulty of the task for these children was reflected in large variability within and between subjects which might account for absences of measurable lateral asymmetry, intermanual transfer of learning, or any relationship between the two measures. Since these findings are in contrast to the significant effects seen on the Trails R test for the same children, the findings support a hierarchical development of lateral asymmetry and intermanual transfer that is dependent on the task requirements. It appears that visual-motor or visual-spatial skills necessary for Trails R performance develop earlier than the complex tactual or spatial skills necessary for the Formboard test.

Results for Speed of Response Onset: Tactile Naming and Matching

Speeds of naming and matching. Tactile naming and matching response delays were converted to response speeds ($1/\text{time}$ in seconds), the latter measure being normally distributed, according to chi-square tests for normal distribution of sample data (Hays, 1973, p. 726). Means and standard deviations for each item for both 3- and 5-year-old groups are presented in Tables 15 and 16. Average speeds of naming and matching varied considerably between items and a significant practice effect was present for the average speeds of the first and second set of eight trials at both ages. In general, naming (response onset) speeds were faster than matching speeds and 5-year-olds were faster than 3-year-olds. When item speeds were rank ordered separately for 3- and 5-year-olds, significant rank order correlations between age groups were obtained for the naming condition and matching condition, but rank order correlations between naming and matching conditions within both age groups were not significant. Only the second set of items was used in this analysis, since the speeds

Table 15
Means and Standard Deviations for Speed of Response Onset
for Items on the Tactile Naming Test

Trial #	Item	3-year-olds		5-year-olds	
		Mean	SD	Mean	SD
First Set					
1	Penny	.375	.227	.392	.200
2	Kleenex tissue	.489	.235	.542	.274
3	Toothbrush	.286	.169	.354	.155
4	Spoon	.503	.204	.646	.227
5	Watch	.191	.145	.291	.140
6	Ball	.580	.209	.589	.208
7	Paper	.481	.201	.596	.215
8	Pencil	.555	.236	.606	.289
Second Set					
9	Ball	.616	.249	.603	.174
10	Penny	.616	.214	.510	.186
11	Kleenex tissue	.683	.265	.788	.220
12	Paper	.642	.290	.705	.252
13	Spoon	.638	.249	.756	.175
14	Watch	.358	.248	.517	.267
15	Pencil	.621	.264	.622	.273
16	Toothbrush	.403	.214	.576	.184

Table 16

Means and Standard Deviations for Speed of Response Onset
for Items on the Tactile Matching Test

Trial #	Item	3-year-olds		5-year-olds	
		Mean	SD	Mean	SD
First Set					
1	Spoon	.179	.095	.290	.098
2	Ball	.219	.097	.302	.097
3	Pencil	.259	.110	.383	.104
4	Paper	.290	.161	.401	.110
5	Toothbrush	.294	.147	.363	.113
6	Kleenex tissue	.327	.166	.446	.123
7	Watch	.312	.134	.389	.113
8	Penny	.313	.116	.427	.124
Second Set					
9	Kleenex tissue	.344	.143	.405	.105
10	Toothbrush	.342	.125	.416	.140
11	Penny	.333	.115	.373	.131
12	Pencil	.408	.169	.457	.140
13	Ball	.393	.134	.425	.095
14	Spoon	.440	.175	.458	.101
15	Paper	.408	.158	.445	.147
16	Watch	.406	.136	.436	.120

appeared to have stabilized. These findings suggest that naming response speeds do not reflect differences in object shape, making it more likely that they reflect verbal skills necessary for object naming.

Lateral asymmetries on tactile naming. Lateral asymmetries for the naming task were determined by comparing two individual items presented in one set which were: (1) nearly equivalent in mean response onset speed, and (2) presented to different hands, permitting an intermanual comparison of speed. Information from other items was not considered because large differences in item speeds tended to mask lateral asymmetries. Lateral asymmetries were determined independently for both age groups, using two speed-equivalent items on the first set of trials and two items on the second set of trials. A right/left hand speed ratio (R/L) was formed, and the resulting sample distribution violated the assumption of normality, according to the chi-square test described by Hays (1973, p. 726). Rather than transform the variables, a frequency count was made of those subjects who were faster in responding to the right hand stimulus and those who were faster with the left hand. These frequency counts and the specific items used in the first and second trials for 3- and 5-year-olds are presented in Table 17. In the 3-year-old group, a significant number of subjects had a right hand superiority on the first naming trial, according to a binomial approximation of the normal distribution ($Z = 2.12$, $p < .05$), while there was no evidence for lateral asymmetry in the 5-year-old group. The difference between the two age groups was significant with $\chi^2(1) = 5.11$, $p < .025$. No tendency for a lateral asymmetry was present on the second trials for either age group. In conclusion, for 3-year-olds, there was evidence for right hand superiority on tactile naming response onset speed upon initial

Table 17
Lateral Asymmetry Frequencies for Tactile Naming Speeds

Direction of Lateral Asymmetry	3-year-olds	5-year-olds
	Set # 1	Items 2 and 7
Right Hand Superior	22	13
Left Hand Superior	10	19
	Set #2	Items 12 and 13
Right Hand Superior	18	16
Left Hand Superior	14	16

Note. Names of items numbered are found in Table 15.

Table 20
Mean Item Numbers for Instructed Use of One Hand
by 3-year-olds on Modified PPVT

Subject Number	Average Item Number		Number of "Wrong-Hand" Responses
	"Correct-Hand" Responses	"Wrong-Hand" Responses	
Instructed Right Hand Use			
1	43.3	68.7	2
2	44.6	37.0	1
3	45.0	74.0	1
4	33.7	57.4	5
5	43.7	56.0	1
6	36.8	50.8	4
7	37.2	58.0	1
8	37.5	41.0	1
Group	$\bar{X} = 40.2$ $SD = 4.4$	$\bar{X} = 55.4$ $SD = 12.5$	
Instructed Left Hand Use			
1	45.6	29.5	4
2	33.3	29.8	3
3	45.0	31.0	2
4	31.1	22.0	1
5	36.2	15.8	3
6	37.8	25.5	2
Group	$\bar{X} = 38.2$ $SD = 6.0$	$\bar{X} = 25.6$ $SD = 5.9$	

Table 18
Lateral Asymmetry Frequencies for Tactile Matching Speeds

Direction of Lateral Asymmetry	3-year-olds	5-year-olds
	Set # 1	Items 4 and 7
Right Hand Superior	11	15
Left Hand Superior	21	17
	Set #2	Items 15 and 16
Right Hand Superior	18	13
Left Hand Superior	14	19

Note. Names of items numbered are found in Table 15.

same items were used in the naming and matching tasks, and the matching tasks were always second, the presence of lateral asymmetries only on first trials for 3-year-olds may be related to learning to perform each task, and may be modified by effects due to familiarity with the items.

Within the two chronological age groups, lateral asymmetries for tactile naming and matching were not correlated with other maturational variables: height, PPVT IQ, PPVT raw score, or chronological age in months. Since 5-year-olds performed significantly faster than 3-year-olds and were significantly less lateralized on these tasks, further analysis of lateral asymmetry as a function of the level of performance within chronological age groups was not undertaken.

Qualitative observations. There were no difficulties administering the tactile naming task, and the children seemed to enjoy it. Several 3-year-olds and 5-year-olds expressed surprise that the test was easy. The tactile matching task was more difficult than tactile naming and this was reflected in the gradual improvement during the first set of matching items in both age groups (see Table 17). Unlike the naming task, the matching task required the child learn a sequence of motor movements and make whole arm responses which likely slowed the matching response onset speeds.

Discussion. Evidence from the present study for a right hand advantage on the tactile naming test and a left hand advantage on the tactile matching test during the first performance of the 3-year-olds is not consistent with other studies of normal children employing dichotomous tactile stimulation (Witelson, 1974, 1976, 1977), especially since the lateral asymmetries were not present at 5 years of age. Perhaps this suggests that lateral asymmetries for tactile skills are often not found in children (e.g., Finlayson & Reitan, 1976) because the skills undergo a decrease early in childhood.

At the present time, it is not possible to distinguish between this and another possibility: that the results are specific to the response (motor) aspects of particular tactile sensory tasks with the manifest lateral asymmetries arising in the motor system, as suggested by LeDoux et al. (1978) and Gazzaniga (1981). The differential directions of the lateral asymmetries is important to note because they match the directions expected if the left hemisphere were specialized for language functions and the right hemisphere for spatial functions. The results were made more convincing by the fact that the tests used the same items and were given to the same children.

Clearly, the larger lateral asymmetries seen at 3 years of age in the present study do not support the notion that behavioral evidence of cerebral specializations increase with age, nor that the brains of young children are unspecialized for language or spatial skills. Rather, lateral asymmetries may be evident when the task is made easy enough for the child. In this study, it was interesting that the lateral asymmetries seen upon initial task performance by the 3-year-olds were not evident in the 5-year-olds. However, this does not appear to indicate a decrease in function of cerebral specialization, because there is much evidence for a highly specialized brain in adults.

Instead, the results suggest that increasing interhemispheric communication may be masking behavioral expression of cerebral specializations. Perhaps in terms of behavioral expression, interhemispheric communication increases relatively faster than cerebral specialization. This suggestion is consistent with Gazzaniga's (1970, 1981) hypothesis that young children have relatively poorer interhemispheric communication than adults and perhaps show some behavioral signs of lower interhemispheric communication found in commissurotomy adult subjects when they are compared to normal adults.

It is also consistent with hypotheses that normal functions of the corpus callosum cover up behavioral evidence of cerebral specializations, in normal (adult) subjects (Ellenberg & Sperry, 1980).

It is more difficult to interpret the lack of lateral asymmetry in 3-year-olds upon second trial performance of the tactile naming and matching tasks. One possible explanation is that lateral asymmetry decreased as the task became easier to perform. Another possibility is that in both tests, the unspecialized hemisphere performing second made use of interhemispheric communication from the specialized hemisphere which had practiced. A third explanation might be that the unspecialized hemisphere learned the correct responses from listening to the specialized hemisphere, or watching it match the items. It is not possible to distinguish between these potential explanations on the basis of data presented in this study.

In conclusion, the tactile naming and tactile matching tests suggest that hemispheric functional specialization for some simple linguistic and spatial aspects of tactile sensory skills are present at 3 years of age, but appear to be absent for the same tasks at 5 years of age. The smaller lateral asymmetry at 5 years of age is consistent with increasing interhemispheric communication during early childhood. Although the results do not appear to be in agreement with some other studies employing tactile stimuli, the lateral asymmetries observed may be highly dependent on the nature and complexity of the tasks.

Results for Picture Vocabulary: Lateral Asymmetry of the Pointing Response

Lateral asymmetry. The Peabody Picture Vocabulary Test was administered to all children and a record was kept of the number of correct and incorrect responses as well as the hand used each time for pointing. Means and standard deviations for these spontaneous pointing response frequencies are shown in

Table 19. The total number of spontaneous right hand responses was greater than the number of left hand responses in all 32 3-year-olds and in 29 of 32 5-year-olds. A lateral asymmetry index was computed for each subject as the number of right hand responses divided by the total number of responses made: $(R/(R+L))$. An index of .50 indicated no asymmetry and 1.00 indicated 100% right hand responses. The mean lateral asymmetry index was $\bar{X} = .89 \pm .12$ for the 3-year-old group and $\bar{X} = .80 \pm .28$ for the 5-year-olds. Both indices are negatively skewed and violate assumptions of normality, according to a chi-square test for normality of sample distributions (Hays, 1973, p. 726). The index means do not differ significantly on a Mann-Whitney test for rank order of index scores, even though the 5-year-olds tended to make more left hand responses than the 3-year-olds. For 13 left-handers, also tested during part of the screening procedure, the lateral asymmetry index was $\bar{X} = .38 \pm .25$ for seven 3-year-olds and $\bar{X} = .29 \pm .36$ for six 5-year-olds. Both left-hander indices differed significantly from the right-hander indices at the .01 level on Mann-Whitney tests, but they did not differ significantly from each other. Thus, the PPVT lateral asymmetry index appeared to be an indicator of hand preference.

Further analysis of left hand responses showed the 3-year-olds had a significantly higher left hand error rate than the 5-year-olds. A left hand error index was computed for each subject as the number of left hand errors divided by the total number of left hand responses. An index score of .00 indicated no left hand errors and 1.00 indicated all left hand responses were errors. Only right-handed subjects were included in this analysis and further analyses. Out of the total 64 subjects, 24 3-year-olds and 22 5-year-olds made at least one left hand response and the other 18 subjects, who did not make any left hand responses, were excluded from analysis. The

Table 19
Means and Standard Deviations for Pointing Responses
on the PPVT

Hand Responses	3-year-olds		5-year-olds	
	Mean	SD	Mean	SD
Right Hand				
Total Number	46.6	7.6	37.5	15.0
Number of Errors	11.0	3.9	10.5	4.9
Left Hand				
Total Number	5.8	6.8	8.4	10.8
Number of Errors	2.6	3.0	2.8	3.8

left hand error index for 3-year-olds was $\bar{X} = .36 \pm .34$ and for 5-year-olds, $\bar{X} = .19 \pm .25$. The mean indices differed significantly according to a Mann-Whitney test ($Z = 2.12, p < .05$). This finding suggests the 3-year-olds tended to reserve the left hand for pointing to items they did not know verbally, while 5-year-olds tended to use the left hand throughout the test.

In order to further elucidate the nature of lateral asymmetry in pointing responses, the PPVT was readministered in an unstandardized fashion to 14 3-year-olds. A group of eight of the 3-year-old children was instructed to use only their right hands, while six other children were instructed to use only their left hands. All subjects made at least one spontaneous error, which consisted of attempting to point with the wrong hand. The individual and group results are shown in Table 20 and expressed in terms of item numbers. Higher item numbers indicate more difficult items. Mann-Whitney tests on the group results showed the mean item numbers of right and left "correct-hand" instructed responses did not differ from each other, while mean item numbers for spontaneous left and right hand error responses differed significantly at the .001 level. In other words, the right hand attempted to point to easy verbal items, while the left hand attempted to point to difficult or unknown items. These results suggest the higher left hand error rates seen for 3-year-olds on the conventional PPVT administration were not due to a right hand fatigue effect. If fatigue was responsible for higher left hand error rates, the left hand should have fatigued also during instructed use of the left hand, but in this condition, left hand responding actually appeared to strengthen as the test items became more difficult. These findings also indicated a tendency for the right hand of 3-year-olds to be used for pointing to verbally known items, those with low item numbers, while the left

Table 20
Mean Item Numbers for Instructed Use of One Hand
by 3-year-olds on Modified PPVT

Subject Number	Average Item Number		Number of "Wrong-Hand" Responses
	"Correct-Hand" Responses	"Wrong-Hand" Responses	
Instructed Right Hand Use			
1	43.3	68.7	2
2	44.6	37.0	1
3	45.0	74.0	1
4	33.7	57.4	5
5	43.7	56.0	1
6	36.8	50.8	4
7	37.2	58.0	1
8	37.5	41.0	1
Group	$\bar{X} = 40.2$ $SD = 4.4$	$\bar{X} = 55.4$ $SD = 12.5$	
Instructed Left Hand Use			
1	45.6	29.5	4
2	33.3	29.8	3
3	45.0	31.0	2
4	31.1	22.0	1
5	36.2	15.8	3
6	37.8	25.5	2
Group	$\bar{X} = 38.2$ $SD = 6.0$	$\bar{X} = 25.6$ $SD = 5.9$	

hand was used for pointing to more difficult items.

In order to find if the 3-year-olds' pointing responses to verbally unknown items were simply guessed, or constituted a pictorial strategy, a few items were sampled to see whether different children tended to select the same wrong picture or whether their responses were randomly distributed among all three incorrect alternative pictures. The distribution of responses to two difficult items and one easy item are shown in Table 21. Subjects who did not reach the item during testing were excluded from analyses. For the two difficult items, "pledging" and "gnawing", the responses were unevenly distributed ($\chi^2(2) = 17.88$ and $\chi^2(2) = 14.00$, respectively, $p < .01$ in both cases). For "pledging", picture number 1 was usually chosen; for "gnawing", picture number 2 was chosen most often. Thus, it appeared there was a favorite incorrect response which was not determined by position of the pictures on the page. Pictures 1 and 2 were further away from the subject than pictures 3 and 4. In contrast, there was no evidence for a favorite alternative response to "hydrant", which was known to most of the 3-year-old children:

These results support a conclusion that, at least in 3-year-olds, left hand pointing tends to be used for responses which are based on a visual, or nonverbal criterion, namely the pictorial stimuli. In contrast, it appears the right hand responses tend to be used when pointing is based on a verbal criterion necessary for correct responding.

Qualitative observations. The PPVT was very easy to administer; however it was important to show only one page of the test booklet at a time, since the 3-year-olds would otherwise scan both pages. It

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Table 21

Number of 3-year-old Children Selecting Each of Four Alternate Pictures of PPVT

Verbal Stimulus	Pictorial Stimulus Number ^a				Number of Ss not in Analysis
	1	2	3	4	
"Pledging"	16	2	9*	3	2
"Gnawing"	6*	12	4	0	10
"Hydrant"	3	2	23*	2	2

*Correct response.

^aPictorial Stimuli Layout as presented to subject:

1	2
3	4

appeared the hand pointing responses by the children were preceded by fixing their eyes and head on the picture chosen. This was true even for incorrect responses, and may suggest that the visually determined choice and appropriate ocular movements guide the hand (arm) movements to the child's selection.

Discussion. The PPVT lateral asymmetry index provided an unusual measure of handedness because the score reflected performance based on the verbal stimuli. At the same time, a number of errors have to be made by the subject in reaching a performance level ceiling, and these pointing responses might then be based on another criteria related to attractive qualities of the pictorial stimuli. The results supported an hypothesis that there is a dissociation between a strong right hand superiority for pointing responses to pictures based on verbal criteria (correct responses), and greater tendency for left hand pointing when the criteria are not based on the verbal stimuli (error responses).

A significant dissociation between hands for responding to visual and verbal stimuli was found in the 3-year-olds, but not in the 5-year-olds. These findings indicate the 5-year-olds had smaller lateral asymmetries than the 3-year-olds. Smaller asymmetries were also noted for the 5-year-olds on the tactile-naming and matching tests, and, similar to those results, the PPVT results may indicate an increase in interhemispheric communication. On this basis, it can be speculated that an increasing left hand efficiency may be the result of increased access of the right hemisphere to linguistic specializations of the left hemisphere. In fact, it may also reflect an increased ability to combine visual-spatial and linguistic processing in the right hemisphere. Further support for a role of interhemispheric communication

in correct left hand responding was that despite the verbal criterion, left-handers tended to point correctly with the left hand even though language representation was likely in the left hemisphere (Rasmussen & Milner, 1977). However, even here it was noted that the left-handers were less asymmetrical than right-handers, perhaps suggesting interhemispheric processing of linguistic and manual skills is not as efficient as intrahemispheric processing. Myers (1965) also provided evidence in experimental animals that interhemispheric processing is less efficient than intrahemispheric processing.

Forced pointing with the right or left hand to pictorial answers in a dichotic listening experiment did not produce similar dissociation of pointing responses in adult commissurotomy subjects (Springer & Gazzaniga, 1975). These authors measured the number of correct responses with each hand. Forced pointing did not change total scores in the present study, either. Instead, spontaneity of the pointing responses appeared crucial, even though the child's arms were not required to be in a standard or symmetrical starting position. The 3-year-olds in this study often made considerable effort to bring the left hand into play for error responses. The failure of total response scores to indicate a lateralized deficit in commissurotomy subjects then, may reflect their ability to make an ocular-motor fixation response that can cue either hand. In the present study, it was noted that ocular fixation on the target to be selected preceded the pointing response. Similarly, commissurotomy subjects may be able to point to correct verbal items with the left hand if the left hemisphere is allowed to direct the right hemisphere's gaze to the appropriate answer.

In summary, there appeared to be a dissociation between right hand responding to correct answers on the PPVT and left hand to incorrect answers

in 3-year-olds. The difference may reflect the left hemisphere's superiority for processing verbal stimuli necessary for correct responding, and the right hemisphere's tendency to take over when response criteria are not based on verbal stimuli. A similar dissociation was not evident in the 5-year-olds, although a trend was present. The results were also similar to the findings for tactile naming and tactile matching and again suggest increasing interhemispheric communication may account for the smaller lateral asymmetries in the 5-year-old group.

Analysis of Lateral Asymmetry and Intermanual Transfer Measures

in Combination

In the previous five sections, results for single tests were analyzed. This section examines relationships within and between lateral asymmetry and intermanual transfer variables for both age groups. Analyses relied on both univariate and multivariate approaches to answer questions about the relations among variables and ability to discriminate between age groups.

Relationships Among Tests

The first method of analysis was to examine first-order correlation coefficients between each pair of variables. Spearman correlation coefficients were chosen because several first-order Pearson correlation coefficients were affected to a large extent by a few outlying values. Also, Spearman correlations are less sensitive than Pearson correlations and to some degree offset the tendency to make type I errors (rejecting null hypothesis when it is true) when examining large numbers of correlation coefficients. Spearman correlation coefficients for lateral asymmetry and intermanual transfer measures are shown in Table 22. In the 3-year-old group, the right hand superiority on tactile naming was weakly related to

Table 22

Spearman Rank Order Correlations between Test Measures for 3-year-old Group

Test Measures

Test Measures	Tapping	Trails	Formbd	Naming	Matching	PPVT	Alternate	Trails	Trails	Formbd	Formbd
	LA (R/L)	LA (L/R)	LA (R/L)	LA (R/L)	LA (L/R)	LA (R/Tot)	Finger Tap	% Save Right	% Save Left	% Save Right	% Save Left
Tapping LA (R/L)	1.00	.21	-.27	.33*	-.14	-.05	.06	.30	.13	.16	-.23
Trails LA (L/R)		1.00	-.09	.35*	-.16	-.17	-.22	NC ^b	NC	.04	-.17
Formbd LA (R/L)			1.00	.07	.11	-.27	-.18	.06	-.23	NC	NC
T-Naming LA (R/L)				1.00	.01	-.38**	.05	.54***	-.03	.01	.04
T-Match LA (L/R)					1.00	-.05	-.06	.11	-.03	-.02	.17
PPVT LA (R/Tot)						1.00	.08	-.22	.09	.27	-.19
Alt. Fingers Tap							1.00	-.11	.28	-.06	-.12
Trails % S Right								1.00	-.08	.02	.17
Trails % S Left									1.00	.22	.20
Formbd % S Right										1.00	-.31
Formbd % S Left											1.00

^aLA = Lateral Asymmetry.^bNC = Not Calculated.

*p < .07.

**p < .05.

***p < .001.

three other lateral asymmetry measures: right hand superiority for unimanual tapping ($r = +.33$, $p < .07$), left hand superiority on Trails R ($r = +.35$, $p < .07$), and inversely related to the frequency of PPVT right hand pointing responses ($r = -.38$, $p < .05$). Right hand superiority on tactile naming was also associated with right hand % savings on Trails R ($r = +.54$, $p < .001$). In other words, for 3-year-olds, it appeared that the greater the right hand superiority on tactile naming, the greater the use of the left hand in pointing to pictures on the PPVT and also the greater the intermanual transfer of information from the left to the right hand. Since 3-year-olds tended to make relatively more left hand errors than 5-year-olds on the PPVT, the inverse PPVT index correlation with tactile naming may indicate a simultaneous lateral asymmetry of right hand superiority on verbal and left hand superiority on nonverbal visual-spatial tasks.

Spearman correlation coefficients for the 5-year-old group are shown in Table 23. Unlike the 3-year-old group, no correlations between lateral asymmetry measures were noted; however, a few correlations between intermanual measures and between intermanual measures and lateral asymmetry measures were seen. In the latter, it is interesting to note that rank order correlation between lateral asymmetry for tactile naming was related only to left hand % savings on Trails R ($r = +.46$, $p < .01$). Left hand % savings on the Formboard were inversely related to right hand superiority for unimanual finger tapping ($r = -.45$, $p < .01$). Right hand % savings on the Formboard were inversely related to left hand superiority on Trails R ($r = -.38$, $p < .05$), and right hand % savings on Trails R ($r = -.42$, $p < .05$), but tended to have a direct relationship to left hand % savings on Trails R ($r = -.33$, $p < .07$).

In other words, if the right hand could learn from the left on the Formboard,

Table 23

Spearman Rank Order Correlations between Test Measures for 5-year-old Group

Test Measure	Test Measure											
	Tapping, LA (R/L)	Trails LA (L/R)	Formbd LA (R/L)	Naming LA (R/L)	Matching LA (L/R)	PPVT LA (R/Tot)	Alternate Finger Tap	Trails % Save Right	Trails % Save Left	Formbd % Save Right	Formbd % Save Left	
Tapping LA ^a (R/L)	1.00	-.30	-.32	-.14	.03	-.12	-.18	-.09	-.01	.13	-.45***	
Trails LA (L/R)		1.00	.22	-.19	-.07	-.15	.04	NC ^b	NC	-.38**	.16	
Formbd LA (R/L)			1.00	-.28	-.27	.09	-.05	.15	-.17	NC	NC	
T-Naming LA (R/L)				1.00	-.05	-.19	.30	.01	.46***	.13	-.04	
T-Match LA (L/R)					1.00	.05	.17	.28	.02	.27	-.27	
PPVT LA (R/Tot)						1.00	-.22	-.31	-.10	-.20	.03	
Alt. Finger Tap							1.00	.30	.27	-.04	.11	
Trails % S Right								1.00	-.46***	-.42**	.17	
Trails % S Left									1.00	.33*	.03	
Formbd % S Right										1.00	-.28	
Formbd % S Left											1.00	

^aLA = Lateral Asymmetry.^bNC = Not Calculated.

*p < .07.

**p < .05.

***p < .01.

the left hand tended to learn from the right hand on Trails R. The tendency for intermanual transfer measures on Trails R and Formboard tasks to be correlated in the 5-year-olds, but not in the 3-year-olds, may reflect greater interhemispheric transfer or greater ability to perform these tasks, or both.

When all 64 children were considered as one group, most correlations between different tests reflected correlations present in a single age group. In a few cases, however, trends which were similar in the two age groups combined to give a significant correlation for the whole group. See Table 24. These correlations consisted of an inverse relationship between right hand superiority on the Formboard and right hand superiority on unimanual finger tapping ($r = -.32$, $p < .05$), a direct relation between the amount of right hand % savings on the Formboard with left hand % savings on the Trails R ($r = +.30$, $p < .05$), and a tendency for the PPVT right hand superiority to be inversely related to right hand % savings on Trails R.

Two multivariate approaches were taken to further examine relationships between variables in the whole group of 64 children. The first approach was to perform canonical correlations between lateral asymmetry variables and intermanual transfer variables. A significant canonical correlation was obtained for a combination of three lateral asymmetry variables: PPVT, tactile naming, and unimanual finger tapping, with three intermanual transfer variables: alternate finger tapping, right hand % savings on Trails R, and left hand % savings on Trails R. The canonical variates are shown in Table 25. The correlation is significant with $R_c = +.45$, Wilks' $\lambda = .74$, $\chi^2(9) = 17.7$, $p < .038$. The significance of this correlation is almost entirely due to a positive relationship between the degree of right hand

Table 24

Spearman Rank Order Correlations between Test Measures for all Children in Study

Test Measures	Test Measures										
	Tapping LA (R/L)	Trails LA (L/R)	Formbd LA (R/L)	Naming LA (R/L)	Matching LA (L/R)	PPVT LA (R/Tot)	Alternate Finger Tap	Trails % Right	Trails % Left	Formbd % Save Right	Formbd % Save Left
Tapping LA ^a (R/L)	1.00	-.04	-.32**	.14	-.07	-.09	-.09	.09	.09	.15	-.30
Trails LA (L/R)		1.00	.02	.04	-.13	-.09	.01	NC ^b	NC	.09	.03
Formbd LA (R/L)			1.00	-.12	-.05	-.08	-.11	.08	-.17	NC	NC
T-Naming LA (R/L)				1.00	.00	-.24	-.11	.29**	.15	.09	.03
Match LA (L/R)					1.00	-.08	-.01	-.06	.00	.13	-.05
PPVT LA (R/ Tot)						1.00	-.11	-.24*	.00	.00	-.06
Alt. Finger Tap							1.00	-.02	.22	-.03	-.11
Trails % S Right								1.00	-.26	-.19	.20
Trails % S Left									1.00	.30**	.13
Formbd % S Right										1.00	-.30**
Formbd % S Left											1.00

^aLA = Lateral Asymmetry.^bNC = Not Calculated.

*p < .07

**p < .05

Table 25

Canonical Correlation Analysis of Lateral Asymmetry
and Intermanual Transfer Variables

Variables	Canonical Variable Coefficients
<u>Lateral Asymmetry</u>	
PPVT (R/Tot)	.023
Tactile Naming (R/L)	-.966
Finger Tapping (R/L)	-.161
<u>Intermanual Transfer</u>	
Trails % Savings Right Hand	-.982
Trails % Savings Left Hand	-.249
Alternate Finger Tapping	.333

Note. - N = 64.

superiority on tactile naming and right hand % savings on the Trails R. First order correlations suggest this relationship is mainly accounted for in the 3-year-olds.

Principal component factor analysis with iteration using the six variables listed above was performed on scores from the entire group of 64 children. Two factors were identified as accounting for a significant amount of intersubject variation. Variables loading on the first factor (eigenvalue = .990, accounting for 57% of variance) were lateral asymmetry on tactile naming, right hand % savings on Trails R, and to a lesser extent, PPVT lateral asymmetry, as shown by the factor score coefficients in Table 26. The second factor (eigenvalue = .736, accounting for 43% of variance) loaded mainly on alternate finger tapping scores. The first factor supports the significance of the first order correlations noted in the 3-year-old group. A second principal component analysis examined relationships between five variables: lateral asymmetry on unimanual finger tapping and Trails R, and intermanual transfer on alternate tapping, right hand % savings on the Formboard, and left hand % savings on the Formboard. One significant factor was identified which showed loadings by the lateral asymmetry of finger tapping and left hand % savings on the Formboard (eigenvalue = .641, accounting for 64.1% of variance), as shown in Table 27. The factor-score coefficients have different signs, reflecting a significant negative correlation between these two variables in the 5-year-olds.

In summary, the analyses of relationships among tests suggest that the measures of lateral asymmetry and intermanual transfer on different tests are not the same at 3 and 5 years of age. Measures on simpler tests tended to be correlated at 3 years of age, while measures on more difficult tasks were correlated at 5 years of age.

Table 26
Principal Component Analysis of Lateral Asymmetry
and Intermanual Transfer Variables

Variables	Factor Score Coefficients	
	Factor 1	Factor 2
PPVT (R/ Tot)	-.170	-.155
Tactile Naming (R/L)	.307	-.022
Finger Tapping (R/L)	.076	.020
Trails % Savings Right Hand	.532	-.081
Trails % Savings Left Hand	-.036	.153
Alternate Finger Tapping	.035	.654

Note. N = 64.

Table 27
Second Principal Component Analysis of Lateral Asymmetry
and Intermanual Transfer Variables

Variables	Factor Score Coefficients
	Factor 1
Finger Tapping (R/L)	.415
Trails R (L/R)	.022
Alternate Finger Tapping	-.016
Formboard % Savings Right Hand	.114
Formboard % Savings Left Hand	-.405

Note. N = 64.

Factors Discriminating between Age Groups

The second objective of the multiple task analysis was to see if linear combinations of test results discriminated between age groups, implying maturational changes in lateral asymmetry or intermanual transfer, or both. This objective was achieved by performing three multivariate analyses of variance (MANOVA) with stepwise discriminant function analyses using: (1) lateral asymmetry measures, (2) intermanual transfer measures, and (3) a combination of the two kinds of measures to discriminate between the two age groups.

The first discriminant analysis was performed with the lateral asymmetry results from the PPVT, tactile naming, Trails R, and unimanual finger tapping. The discriminant function reached statistical significance ($R_c = .40$, Wilks' lambda = .84, $\chi^2 = 10.58$, $p < .014$). Three variables entered in the discriminant function: PPVT, Trails R, and tactile naming measures of lateral asymmetry. Table 28 shows the Wilks' lambda, Rao's V change, and the standardized discriminant function coefficients for each variable. The PPVT and tactile naming lateral asymmetry measures lead to the greatest discrimination between groups, and Trails R contributed insignificantly, and for a different reason, as indicated by the difference in signs of the discriminant function coefficients. The difference in signs was due to greater lateral asymmetry on Trails R (left hand superiority) at 5 than at 3 years of age, while right hand superiorities were larger in the 3-year-old group for PPVT and tactile naming.

A second MANOVA and stepwise discriminant function analysis was performed on three intermanual transfer measures: alternate finger tapping, right hand % savings on Trails R, and left hand % savings on Trails R. Only alternate finger tapping entered in the discriminant function, which

Table 28

Summary Table for Lateral Asymmetry Measures

Entering into a Discriminant Function between Age Groups

Lateral ^a Asymmetry Measures	Wilks Statistic		Rao's Statistics			Standardized Discriminant Function Coefficients
	Lambda	p	V	V Change	p	
Tactile-Naming (R/L)	.937	.046	4.148	4.418	.042	-.794
PPVT (R/ Tot)	.869	.014	9.330	5.182	.023	-.626
Trails R (L/R)	.840	.014	11.852	2.522	.112	.435

^aLateral asymmetry measures are listed in order of stepwise entry into the discriminant function.

was significant at the .001 level of probability.

A third MANOVA and stepwise discriminant function analysis examined a combination of six lateral asymmetry and intermanual transfer variables: PPVT, tactile naming, unimanual finger tapping, right hand % savings on Trails R, left hand % savings on Trails R, and alternate finger tapping speed. The discriminant function included two lateral asymmetry variables: PPVT and tactile naming, as well as the alternate finger tapping measure. The discriminant function reached significance ($R_c = .70$, Wilks' lambda = .51, $F^2(3) = 40.45$, $p < .001$). The summary table is shown in Table 29. Alternate finger tapping was the most important variable in the discriminant function, although tactile naming and PPVT lateral asymmetries also contributed. The signs of the coefficients for the three variables differ because alternate finger tapping speeds were greater at 5 years of age, while lateral asymmetries of the PPVT and tactile naming lateral asymmetries were smaller at 5 years of age.

An attempt to discriminate between sexes on the three combinations of variables discussed above did not yield any significant discriminant functions.

In summary, the 3- and 5-year-old groups can be discriminated on the basis of lateral asymmetry measures. The lateral asymmetries on the PPVT and tactile naming contributed more significantly to this discriminant function, and these tests showed smaller mean lateral asymmetries at 5 years of age, suggesting a maturational decrease in lateral asymmetry in early childhood. Bimanual alternate finger tapping speeds provided the largest discrimination between groups for all variables examined.

Discussion. The univariate and multivariate analyses support a pattern of results in which the lateral asymmetry for tactile naming is related to a number of other measures on the PPVT, tapping, and Trails R in the 3-year-old

Table 29

Summary Table of Lateral Asymmetry and Intermanual Transfer Measures
Entering into a Discriminant Function between Age Groups

Test ^a Measures	Wilks Statistic		Rao's Statistics			Standardized Discriminant Function Coefficients
	Lambda	p	V	V Change	p	
Alternate Finger Tapping	.551	.001	50.56	50.56	.001	.887
Tactile-Naming (R/L)	.526	.001	55.80	5.24	.022	-.264
PPVT (R/ Tot)	.512	.001	58.99	3.19	.074	-.176

^aTest Measures are listed in order of stepwise entry into discriminant function.

group, while 5-year-olds showed relationships between intermanual savings on the Formboard and other intermanual transfer and lateral asymmetry measures. Since the Formboard was distinctly more difficult than the other tasks, the pattern supports two developmental theories of cerebral functioning. The first theoretical framework concerns whether functional hemispheric specializations and interhemispheric communication are related during acquisition of abilities necessary for a task (Dennis, 1976). Accordingly, these cerebral functions or the processes they reflect, may converge to facilitate more efficient task acquisition, as suggested by studies of learning in commissurotomy patients (Ellenberg & Sperry, 1980). This is also consistent with a second framework: development of lateral asymmetry follows a hierarchical pattern, like that described by Sparrow and Satz (1970) in which the cerebral hemispheres become specialized for certain abilities as the abilities are acquired. It may be that regardless of a possible causal relationship between the development of hemispheric specialization and interhemispheric communication, both may be important during acquisition of difficult new tasks, even in adulthood, consistent with experimental findings for adults performing concurrent tasks (Wolff & Cohen, 1980).

Against the expectation that lateral asymmetries would be of greater magnitude at 5 than at 3 years of age, lateral asymmetries at 5 years of age were actually smaller on the PPVT (either index) and tactile naming, and also tended to be smaller on tactile matching. Only Trails R showed a tendency for an increase in lateral asymmetry between 3 and 5 years of age. Since the alternate finger tapping speeds increased while PPVT and tactile naming lateral asymmetries decreased, it is suggested that increasing interhemispheric communication may be responsible for failure of lateral asymmetry measures to reflect increasing hemispheric functional specialization.

in normal children.

In summary, there appeared to be relationships within and between measures of lateral asymmetry and intermanual transfer on various tests. These relationships were different at 3 and 5 years of age. In the 3-year-old group, lateral asymmetry on the first trial of the tactile naming task was correlated with a few other measures, while the intermanual transfer measures on the Formboard and Trails R tests appeared to be important in the 5-year-olds. The results support the hypothesis that lateral asymmetry and intermanual transfer measures show closer relationships when the task is being acquired and when it is neither too difficult nor too easy for subjects to perform.

Effects of Early Brain Damage

The test results reported for normal 3- and 5-year-old children in this study have implications for interpreting results from the same tests given to brain-damaged children. Similarly, results from brain-damaged children offer some independent confirmation that these tests are sensitive to brain functions. In this section, test results are reported for two children with different kinds of brain damage from infancy. Both case histories reported are based on interviews with the mother of the child. The first case, J.D., attended the Carleton Memorial Preschool. The second case, B.B., was located with the assistance of the Child Study Clinic at the University of Washington.

Case 1: mild cerebral palsy. J.D. was a 3 year and 6 month old female at testing, who was born prematurely at 28 weeks gestation, weighing 920 grams (approximately 2 lbs.). Apgar scores evaluating vital signs at birth (Apgar, 1953) were low: Apgar equalled 2 at one minute and 3 at five minutes. During the first month after birth, she developed severe complications which

included pneumonia, respiratory distress syndrome, congestive heart failure requiring surgery, seizures, and rickets. Respiratory difficulties required assisted breathing through the first four months, and J.D. left the hospital for the first time six months after birth. At 3 years of age, a neurological examination revealed a general decrease in muscle tone and bilaterally increased tendon reflexes, confirming a mild spasticity also evident in her difficulties learning to walk. She was also below the third percentile in height, weight, and head circumference. Occupational and speech therapy assessments indicated her skills were average, or slightly below average, in fine motor movement, visual perception, receptive language, and visual-spatial functioning. Her major areas of deficit were reported to be in the areas of expressive language, which was nearly absent at the time of the current assessment, and gross motor abilities. The symptoms reported here are consistent with anoxic or hypoxic (oxygen deficiency) damage to the central nervous system which primarily affects motor systems (Azzarelli, Meade, & Muller, 1980). J.D. attended preschool in the same classroom with the same teachers as 16 other 3-year-old subjects in this study. She was cooperative, happy, and attentive during test sessions.

The examiner noted that J.D. exhibited a mild degree of spasticity, especially when running, and a stitched wound on her chin attested to her difficulties with gait. Test results are shown in Table 30. J.D. was left handed, according to the measures of hand preference and performance on unimanual tapping, as well as classroom observations. Motor (tapping) and visual-motor (Fraits R) speeds were much below those of the other 3-year-olds on both body sides. In contrast to these scores and expressive

Table 30
Normative Data for 3- and 5-year-olds and Test Results
for Two Brain-Damaged Children

Measures	Normative Data				Brain-Damaged Children	
	3-year-olds		5-year-olds		J.D. ^a	B.B.
	Mean	SD	Mean	SD		
Age (years)	3.45	.27	5.40	.30	3.50	10.92
<u>Peabody Picture Vocabulary Test</u>						
Raw Score	45.3	7.1	61.3	5.2	41	62
IQ Score	115.2	11.3	118.2	9.7	111	71
Mental Age	4.53	1.08	7.08	1.08	3.92	7.25
Pointing Index (R/Total)	.89	.12	.80	.28	.96	.80
Left Hand Point Error Index (L errors/L Total)	.36	.34	.19	.25	.00 ^b	.71
<u>Tapping</u>						
Right Finger	22.4	2.7	26.1	2.6	6.0	22.0
Left Finger	19.4	2.1	22.7	2.7	8.5	12.0
Alternate Arm	11.8	4.4	17.1	4.2	1.3	10.5
Alternate Finger	9.9	4.6	17.4	3.7	2.8	0.0
Synchronous Finger	19.4	3.4	24.9	3.2	7.0	7.0
Lateral Asymmetry (R/L)	1.16	.10	1.16	.09	.58	1.83
						continued

^aJ.D. was the only left-handed child in the study.

^bJ.D. made 2 left hand responses.

Table 30, continued

Measures	Normative Data				Brain-Damaged Children	
	3-year-olds		5-year-olds		J.D. ^a	B.B.
	Mean	SD	Mean	SD		
<u>Trails R</u>						
Speed (pages/sec)	.123	.049	.174	.058	.032	.065
% Savings Right	59.8	85.4	55.2	103.2	7.2	11.0
% Savings Left	-1.1	110.4	14.9	87.3	-3.6	5.0
Lateral Asymmetry (L/R)	1.10	.34	1.21	.39	1.01	1.20
<u>Tactile-Naming^d</u>						
Speed (items/sec)	.48	.22	.55	.19	CND ^c	.51
<u>Tactile-Matching^d</u>						
Speed (items/sec)	.34	.13	.39	.12	CND	.29

^aJ.D. was the only left-handed child in the study.

^cCND = Could Not Do.

^dData is only for items B.B. could do with right hand.

language difficulties, her receptive language skills on the PPVT were above average for her chronological age, suggesting cerebral language areas were relatively intact. Her strong right hand pointing response on the PPVT, in contrast to other left-handers, perhaps implies handedness had been altered by damage to motor systems. Tactual-motor (Formboard) skills in the absence of vision were below average, required more than two minutes, and were discontinued to avoid frustrating her. It was evident during the Formboard task she had difficulty grasping objects when they were hidden from view. Tactile naming skills were not tested due to her lack of expressive language. Perseveration tendencies were evident as repeated selection of the same object during tactile matching, and as scribbling over single rabbit drawings during the Trails-R test. It is not known if these tendencies reflected cognitive immaturity or cerebral dysfunction. The results provided some evidence that motor lateral asymmetries had been modified by brain damage. Intermanual transfer appeared below average on Trails R (% savings) and bimanual cooperation was below average on alternate finger tapping relative to other finger tapping scores. Alternate arm tapping was almost impossible, perhaps reflecting greater impairment of gross motor movements relative to fine motor movements.

The pattern of results was typical of cases of mild cerebral palsy due to prematurity and suggested some, or perhaps most, later developing cerebral areas, such as those subserving cognitive language skills, remained intact, while motor output systems undergoing more rapid developmental changes in the perinatal period sustained impairment. The results offer a favorable prognosis for J.D. in terms of further regular educational training with adjunct speech and physical therapies.

Case 2: Right hemisphere damage with complete commissurotomy. B.B., a 10 year and 9 month old girl, was born with an extensive Sturge-Weber hemangioma (a congenital vascular malformation) over the right cerebral hemisphere, which was externally evident over the right anterior quadrant of the scalp and forehead. Seizures on the left body side began at 3 months of age. At 5 years of age, a temporal lobe seizure focus was noted in the right hemisphere. Surgery was performed to remove multiple seizure foci from the right hemisphere, but seizures returned despite anticonvulsant drug treatment. Right body side seizures began to occur, probably due to formation of new left hemispheric foci resulting from transcallosal bombardment of abnormal activity from the right hemisphere. In order to stop transcallosal spread of seizure activity, B.B. underwent a complete commissurotomy in June, 1980. The option of a right hemispherectomy was also presented to her parents; however, it was felt that in spite of the evidence for right hemisphere damage, B.B. might have some right hemisphere functions. This notion was supported by a neurosurgeon who commented that underneath the hemangioma, the surface of the right cerebral hemisphere appeared quite healthy.

Since early childhood, B.B. has had poor tactile sensitivity and poor motor skills on her left body side, as well as below average eyesight and poor peripheral vision. She had a slight delay in speech development, although other developmental milestones were normal. She also had problems with stuttering and slowed speech, and was in special education classes. Immediately after commissurotomy, she had severe difficulty finding words or names for common objects while speaking. Such language impairments are common immediately following commissurotomy (Bogen, 1979; Sussman, Gur, Gur,

O'Connor, Harner & Reivich, 1981). A further slowing of speech and slow reading speeds were also noted in spite of good auditory memory and comprehension of spoken or written material. B.B. made an excellent recovery after the surgery and attended a summer camp 16 days later. Considering her history of difficulties, B.B. is relatively high-functioning and recently spoke to a large group of Boy Scouts about her experiences with epilepsy and neurosurgery. Although enrolled in a special education grade three class, she was tutoring first and second graders in basic arithmetic. At the time of testing, she was also improving in physical training designed to increase motor coordination on her left body side.

The current testing was undertaken on May 12, 1981, at the patient's home, 11 months after complete commissurotomy. At testing, B.B. presented as a friendly child who had some difficulties with gross motor coordination. Although she expressed being tired from the day's activities, she was attentive and eager to perform the tasks presented.

B.B. was right handed on measures of hand preference and performance. Motor (tapping) and visual-motor (Trails R) speeds were below average. The left hand was much slower than the right hand on unimanual finger tapping, as shown in Table 30, evidently reflecting right hemisphere damage. Also, she could not turn a knob on an Etch-A-Sketch toy with her left hand. Unlike other commissurotomy patients (Zaidel & Sperry, 1977), B.B. was able to perform alternate arm tapping movements but alternate finger tapping was not possible. In response to instructions and demonstrations to perform alternate finger tapping, she could perform only unimanual or bimanual synchronous finger tapping. Left body side impairment was also evident on tactile naming and matching. B.B. could not name objects in her

left hand and appeared to guess when questioned. She could not perform tactile matching with the left hand, indicating that the main problem on these tactile tests was loss of tactile perception or synthesis (astereognosis) likely due to right hemisphere damage.

Observations on two tests, however, were not readily explainable in terms of right hemisphere damage. The first observation was that the left hand performed a little faster than the right hand on the Trails R test. This observation is not consistent with an hypothesis that the left hemisphere has taken over proximal control of left arm movements because the right hand should have been faster in that case. Rather, the impaired right hemisphere appeared capable of some visual-spatial analysis and control of the left hand or arm. The % savings measure on Trails R suggests little or no interhemispheric communication and argues against an incidental learning effect similar to the findings of LeDoux et al., (1978). However, without an intramanual control condition it is not possible to distinguish between poor Trails R learning or poor interhemispheric transfer of learning. A second observation supporting visual-spatial functioning in the right hemisphere was that on the PPVT, B.B. made seven left hand responses with great effort and five (71%) were errors, while only ten (36%) of 28 right hand responses were errors. An error rate of 75% is chance level. The results support an hypothesis stated earlier: lower interhemispheric communication might manifest on the PPVT as a dissociation between the right hand pointing to pictures based on verbal criteria (correct responses), and left hand pointing when the criteria are nonverbal (incorrect responses).

In summary, B.B.'s test results were consistent with damage to the right cerebral hemisphere with loss of motor and sensory abilities on the left

body side. Given the presence of a total commissurotomy, the left hand performance on the Trails R and PPVT supported the notion that the right hemisphere of this child was capable of some visual-spatial and visual-motor processing. It is not known if the left hand abilities were present from an early age or represent more recent developments, such as those due to maturation of cerebral functions or experience, e.g., her physical training program.

Discussion. Test results from these brain-damaged patients can be interpreted in terms of the normative data presented for the 3- and 5-year-old children. Comparing the results for J.D. to the normative data, there appeared to be early bilateral damage to the motor systems with some cerebral systems evidently quite intact. The results are consistent with a perinatal history of anoxia with selective damage to motor systems and sparing of late-developing association areas of the cerebral cortex (Azzarelli et al., 1980). The relatively faster metabolic rate of primary cerebral cortex and lower motor centers probably explains their selective vulnerability to anoxia at birth, while late developing association cortices are more vulnerable to anoxia in adults (Jilek, Travnickova, & Trojan, 1970). A similar explanation may hold for loss of left hand motor and sensory skills with a Sturge-Weber hemangioma present prenatally over the right hemisphere in the case of B.B. Late-developing association cortices might be responsible for some evidence of left hand participation in visual-spatial functioning in this patient who also had a commissurotomy.

A comparison of B.B.'s results to the normative data clearly indicate a left body side deficit quite distinct from those of J.D. Most of these deficits were probably due to the presence of early right hemisphere damage. The results from these two patients suggest these tests were sensitive to

different aspects of brain function when taken in combination. This points out the usefulness of having normative data available for comparison.

The results for tactile naming and matching, in the case of B.B., point out the benefit of using the matching condition as a control for left hand astereognosis due to right hemispheric damage. Larrabee et al. (1980) ruled out astereognosis as a basis for left hand anomia in a commissurotomy patient by showing the patient could perform tactile matching with the left hand. In the present study, B.B. could not perform tactile naming or tactile matching with her left hand; consequently, effects due to right hemisphere damage and those due to commissurotomy could not be distinguished on the basis of these results.

Another important aspect of these results was seen in the lateral asymmetry of the PPVT pointing response. The PPVT results suggest the presence of a dichotomy between right-hand pointing to correct items under verbal criteria, and left-hand pointing to incorrect items under nonverbal or pictorial criteria. The results also suggest that J.D. was left-hemisphere dominant for language, but might also have indicated lack of interhemispheric communication since she did not use the left hand to perform under a verbal criterion.

Both brain-damaged patients showed unusual lateral asymmetries and poor intermanual transfer. In these cases, it was difficult to know if the damage had impaired hemispheric specializations, and in the case of J.D., whether interhemispheric communication was actually intact. It is possible in the case of J.D. that intermanual transfer and lateral asymmetries could not be shown because the tests were too difficult for her. A similar explanation may hold for the absence of these phenomena for normal 3- and

5-year-olds on the Formboard. If that was the case, poor intermanual transfer in J.D. may reflect the lower level of ability of brain-damaged patients, including commissure-damaged patients, rather than impaired interhemispheric transfer, per se (e.g., Russell & Reitan, 1955). For such tests it would be useful to incorporate an intramanual learning control condition to find if the patient's cerebral hemispheres are capable of learning information that is supposed to be transferred between them.

In conclusion, results from the brain-damaged patients help confirm the assumption that the tests used in this study were sensitive to brain functions. They also support some assumptions made about specific aspects of the experimental tests, e.g., a dissociation between language and visual-spatial functions for the PPVT pointing response. The results of tests taken in combination support the idea that the effects of early brain damage can be quite specific and that functional cerebral specializations can be present at a very early age, despite damage in the perinatal or prenatal periods of development.

General Discussion

The present study investigated lateral asymmetries, intermanual transfer, and relationships between the two kinds of behavioral measures in 64 3- and 5-year-old children. The main issues concerned the age of appearance of lateral asymmetry and intermanual transfer, whether they change in magnitude, and whether they are temporally related during early childhood. Lateral asymmetry and intermanual transfer measures were obtained on tests of motor (tapping), visual-motor (Trails R), and tactual-motor (Formboard) speed. Lateral asymmetries were also measured for speed of tactile naming and matching response onsets, as well as for the frequency of pointing responses for picture vocabulary (PPVT).

On the test of tapping speed, speed subjects were asked to tap as fast as possible on two mechanical counters with their finger(s) or arms. A 15% right hand superiority was obtained at 3 and 5 years of age, indicating no change in lateral asymmetry across chronological ages; however, the magnitude of lateral asymmetry was greater in the faster 3-year-olds, suggesting some changes in cerebral motor organization may still be in process at that age. Bimanual alternate finger and arm tapping speeds relative to unimanual or bimanual synchronous finger tapping speeds were greater at 5 than at 3 years of age, suggesting a relatively later maturation of interhemispheric communication than intrahemispheric processing on this task. The bimanual alternate finger tapping (intermanual transfer) score tended to positively correlate with the degree of lateral asymmetry in 3-year-old boys, but not in girls or 5-year-olds. The trend for a sex difference in the relationship at 3 years of age was similar to the results of Wolff and Cohen (1980) who found a sex difference in the interaction of lateralized tasks on simultaneous.

bimanual alternate finger tapping in normal adults.

The Trails R test of visual-motor speed required the children connect drawings of running rabbits with a pencil as fast as possible with one hand, then ~~the~~ the other hand on a duplicate form. Four forms were used. Lateral asymmetries were measured by comparing counterbalanced left and right hand performance on the first attempt for each form. A left hand superiority was significant at 5 years of age and also showed a trend at 3 years. The magnitude of left hand superiority did not differ significantly between the 3- and 5-year-old groups, suggesting no development changes occurred between these ages. Intermanual transfer was measured as the relative improvement (% savings) of a hand when it performed second over the same hand when it performed first, which provided a control for lateral asymmetries in performance. Intermanual transfer was significant at 3 and 5 years of age, but only in one direction. The right hand could learn from the specialized left hand's performance, but the reverse was not true, suggesting a unidirectional interhemispheric transfer of learning. Lateral asymmetry and intermanual transfer measures were positively correlated on Trails R at 3 and 5 years of age, even when variance resulting from terms common to each were statistically removed from the correlation, suggesting a positive relationship between the degree of hemispheric functional specialization and interhemispheric communication.

The experimental design for the Formboard test was the same as Trails R, but required the subject place two shapes into holes in a board with one hand, then the other on four different boards. No lateral asymmetries were identified, nor was there any evidence of intermanual transfer. Significant correlations obtained between lateral asymmetry and intermanual transfer appeared to be

spurious because they were no longer found when variance due to common terms was removed from the correlations. The Formboard task appeared to be very difficult for both age groups, and lack of positive findings may reflect an inability of the children to approach this task with a consistent cognitive strategy.

On the tactile naming and matching test the children were told to name or point to objects when presented to the right or left hand out of view (as quickly as possible). A right hand superiority was found at 3 years of age but not at 5 years of age for tactile naming. A trend for a left hand superiority for tactile matching was also found in the 3-year-olds, but not in the 5-year-olds. The direction of lateral asymmetries was consistent with verbal and spatial aspects of task performance, while the smaller magnitudes at 5 years of age may indicate an increasing role of interhemispheric communication in the waning of manifest lateral asymmetries.

On the Peabody Picture Vocabulary Test (PPVT), the children were instructed to point to the picture that meant the same as a spoken word. The hand used for pointing was recorded. Both 3- and 5-year-olds usually pointed with their right hands. However, compared to the 5-year-olds, the 3-year-olds used their left hand relatively more often to make incorrect responses. This larger lateral asymmetry for left hand error rate in the 3-year-olds was found to be unrelated to fatigue and appeared to be based on the preference of the children for certain pictures. This may indicate a right hemispheric specialization for visual-spatial skills by 3 years of age, which, like the tactile naming and matching, is no longer behaviorally evident at 5 years possibly due to an increase in interhemispheric communication.

Analyses of the results in combination were performed. An examination

of relations among task measures of lateral asymmetry and intermanual transfer showed that simpler tests, such as the PPVT and tactile naming, tended to be correlated at 3 years of age, while more difficult tasks, e.g., the Formboard, showed correlations at 5 years of age. These relationships may be evident only when the task is cognitively difficult. An attempt was also made to discriminate between age groups (3 and 5 years) on the basis of selected lateral asymmetry and intermanual transfer measures. Bimanual alternate finger tapping speed provided the greatest discrimination between groups, while among the measures of lateral asymmetry, the PPVT left hand error index and tactile naming provided the best discrimination, based on smaller lateral asymmetries at 5 than at 3 years of age.

The cases of two children with evidence of early brain damage were presented in order to provide information about hypotheses made in the study regarding specific cerebral functions in normal children. For example, superior left hand performance on the Trails R test by the commissurotomy patient, B.B., who had congenital right cerebral damage provided a strong indicator that this test reflects specialized right hemispheric functioning. However, the extrapolation of such results to normal children was viewed cautiously, since the extent of anatomical damage was unknown in both cases. The test results for "normal" children could also be used to evaluate specific deficits in the brain-damaged children, indicating the tests may be useful in clinical evaluations. For example, B.B.'s abnormally large lateral asymmetry for unimanual finger tapping likely reflects deficient right hemispheric functioning. It was noted, however, that the designs of the Trails R and Formboard test in this study were not adequate to determine

whether the absence of intermanual transfer reflects impaired interhemispheric communication or impaired learning in general. The addition of an intramanual learning condition would be helpful in clinical application of the design used in these tests.

The basic assumptions underlying the interpretation of lateral asymmetries and intermanual transfer as measures of developing intra- and interhemispheric processing were called into question by the results of this study. One assumption, that measures of intermanual transfer reflect the magnitude of interhemispheric communication appeared to be valid. An exception, however, might be that a relative measure, such as % savings, tended to mask increasing efficiency of interhemispheric communication if it keeps pace with increasing intrahemispheric processing. A second assumption was that lateral asymmetries in manual performance reflect the direction and magnitude of hemispheric functional specializations. While this may apply to the direction of lateral asymmetries, the magnitudes of lateral asymmetries did not support this assumption. In fact, lateral asymmetries on the PPVT left hand pointing index and tactile naming indicated smaller lateral asymmetries were present at 5 than at 3 years of age. If the second assumption was entirely accepted, the findings would conflict with evidence from studies showing the adult brain has a high degree of functional specialization (e.g., Luria, 1973). A more likely explanation for smaller lateral asymmetries in the 5-year-olds is that lateral asymmetries reflect hemispheric specialization, but they are gradually ameliorated by developing interhemispheric communication. This is consistent with a normal role of the cerebral commissures in the dissolution of behavioral asymmetries which might otherwise result from a laterally specialized brain (Selnes, 1974).

The third assumption was that the performance of each hand reflects activity of the contralateral hemisphere. This assumption would appear to be less valid at 5 than at 3 years of age, since lateral asymmetries on the PPVT and tactile naming were smaller at 5 years of age. It may be that as hemispheric interaction increases, hand performance increasingly reflects information processing by the ipsilateral hemisphere, and both hemispheres working together.

It should be noted that the subjects in the present study did not constitute a "normal" or random sample. For example, the 64 subjects tested on the five tests were all right-handed. Since right- and left-handers may have differences in the organization of cerebral functions (e.g., Warrington & Pratt, 1981), this study may have selected out some variance in cerebral organization normally encountered in the population. Another point was that subjects in this study came from a variety of socioeconomic backgrounds, which may have affected the experimental findings, particularly if early experiences have differential effects on the development of intra- and interhemispheric functional organization. Finally, the subjects in the present study were selected partly on the basis that they had receptive language scores at the fiftieth percentile ($IQ = 100+$) or higher for their chronological age. It is difficult to predict how the obtained measures might be different in a sample with a wider range, or lower range, of receptive abilities.

An important aspect of the experimental task design in the present study was that it examined lateral asymmetry and intermanual transfer on the same or similar tasks in the same children. The design permitted an analysis of relationships between the two measures. For example, using similar kinds

of tapping conditions, it was possible to make inferences regarding relative differences in the development of intra- and interhemispheric processing and to see how the measures in the tapping conditions correlated with each other. A major problem to overcome in this kind of analysis was the lack of independence, or presence of common terms, in the lateral asymmetry and intermanual transfer measures on Trails R and the Formboard tests. Using Stone's (1980) suggestions for removing variance shared between intermanual transfer and lateral asymmetry, it was shown that correlations between the two measures on the Formboard were spurious: attributable to the lack of independence. However, on a similar analysis of Trails R, positive correlations were still present after variance due to non-independence of measures was removed from the correlations. The example illustrated the usefulness of Stone's (1980) recommendations for future research in this area. A limitation in the design of the present study was the large number of statistical results reported, which increased the likelihood of finding results significant which occurred only by chance (type I errors). This point emphasizes the importance of examining the entire pattern of results rather than just a few. Another potential problem in this study was that learning and performance measures are different and not necessarily comparable, for example, different units are used in comparing % savings with lateral asymmetry of speeds on the Trails R and Formboard tests. However, positive correlations between % savings and lateral asymmetry were obtained for Trails R, suggesting this was not a problem. Learning and performance are often difficult to separate (Fernald & Fernald, 1978), and they may share a common cerebral basis on the Trails R test.

Hemispheric Functional Specialization

The lateral asymmetries observed in this study varied markedly depending on the test administered. For motor speed (tapping), pointing response (PPVT), and verbal response speeds (tactile naming), lateral asymmetries were present at 3 years of age. However, on the visual-motor task (Trails R, a significant left hand superiority for performance speed was obtained only for the 5-year-olds, and on a tactual-motor task (Formboard), no lateral asymmetries were noted at either age. At the same time,

lateral asymmetries were observed in the 3-year-old group, but not in the 5-year-old group. These tests included the PPVT (left-hand error index), tactile naming, and tactile matching.

These results supported previous research using electrophysiological (Crowell et al., 1973; Gardiner & Walter, 1977; Molfese et al., 1975), anatomical (Wada et al., 1975; Witelson & Pallie, 1973), and behavioral techniques (Annett, 1970; Gilbert, 1973; Ingram, 1975; Lewkowicz et al., 1979; Nagafuchi, 1970) showing lateral asymmetries and hemispheric specializations are present in infancy or before 5 years of age. This evidence for an early appearance of some hemispheric functional specializations supports Semmes' (1968) hypothesis that the two cerebral hemispheres have inherently different neural organizations. The results of this study failed to support hypotheses that the cerebral hemispheres have equal potential for specializations in early childhood (Krashen, 1973; Lenneberg, 1967).

The absence of a lateral asymmetry or intermanual transfer of learning on the Formboard test, together with the relationships of Formboard measures with measures on other tasks only at 5 years of age (see Table 23 and Table D of the Appendix) suggest that lateral asymmetries arise later for more difficult tasks. This is consistent with the concept of a developmental gradient in brain-behavior relations (Brown, 1979). It appears that sensory and motor skills normally arise in early childhood, followed by more complex problem-solving abilities which continue to mature into adulthood (Arlin, 1975; Fletcher & Satz, 1980; Hiscock & Kinsbourne, 1980a; Knights & Tymchuk, 1968; Piaget, 1952; Reitan, 1974a; Sparrow & Satz, 1970). The time course of behavioral development, including lateral asymmetries and intermanual transfer, may parallel the development of specific brain structures. For example, the earlier appearance of motor and sensory skills in behavioral development fits the earlier postnatal cytological and morphological maturation of the motor and sensory cortex, while association cortex, thought necessary for more complex cognitive linguistic and spatial skills, continues

to mature into adulthood. E. Milner (1967) questioned whether the late phylogenetic development of layer 3 of the cerebral cortex is responsible for a left hemisphere specialization of speech functions in humans. Layer 3 also receives heavy commissural fiber terminals in the association cortex and continues to show cellular changes in childhood, attaining adult morphological features only after 8 years of age (Rabinowicz et al., 1977).

If cognitive processes develop hierarchically, perhaps lateral asymmetries cannot be identified before children can use a consistent (cognitive) strategy to perform a given task. In fact, since hemispheric functional specialization refers to a comparison between the two hemispheres, it is not logical to discuss specialization of one hemisphere when neither can complete the task. Accordingly, the earliest a lateral asymmetry can be identified for a given task should be during the acquisition of the cognitive ability to perform the task.

When task difficulty is considered, the late postnatal appearance of laterality on a single task does not indicate that the subject has one or two functionally unspecialized hemispheres, contrary to Corballis and Morgan (1978). These authors cited studies of facial recognition (Carey & Diamond, 1977; Phippard, 1977) to hypothesize that the right hemisphere is not specialized for visual-spatial skills until about 10 years of age. However, since in children younger than 10 years of age neither hemisphere can process complex facial recognition material, it is not possible to distinguish whether facial recognition skill acquisition reflects right hemispheric development, the development of general cognitive abilities, or both. In addition, the results for one task do not preclude the possibility that easier visual-

spatial tasks show a right hemispheric specialization at an earlier age. The presence of a significant left hand superiority on Trails R and a significant PPVT left hand error index in the current study suggests some right hemispheric specializations are present by 3 years of age, consistent with Piazza's (1977) evidence for auditory and motor specializations of the right hemisphere in preschool children. These findings are contrary to Corballis and Morgan's (1978) hypothesis that right hemispheric specialization is achieved by default after the left hemisphere has become specialized for language functions.

The decline in lateral asymmetry noted on the tactile naming and PPVT left hand error index in this study may have implications for understanding the development of interhemispheric communication. Several other behavioral studies have reported larger lateral asymmetries on motor and sensory tests in younger children than in older children and adults (Denckla, 1974; Ingram, 1975; Hicks, 1975, reported in Davidson, 1978; Knox & Kimura, 1970; Rosszkowski, Snellbecker, & Sacks, 1979, reported in Hiscock & Kinsbourne, 1980b; Wolff & Hurwitz, 1976). Molfese et al. (1975) also reported electrophysiological evidence for larger hemispheric asymmetries in the visual responses of infants than in older children and adults. They have suggested developmental increases in interhemispheric communication may be responsible for declining lateral asymmetries. In the present study, the PPVT and tactile naming measures showing relatively smaller lateral asymmetries at 5 years of age were relatively simple, compared to the Trails R and Formboard tasks. Thus, it may be that interhemispheric communication only leads to a decrease in lateral asymmetry after a skill has been acquired.

Satz et al. (1975) criticized studies showing larger lateral asymmetries at younger ages on grounds that ceiling effects artificially attenuated the

lateral asymmetries at later ages. In the present study, the smaller asymmetries on the PPVT cannot be due to a ceiling effect because failure to perform the task was criterion for the ceiling. A similar approach was taken by Galin, Johnstone, and Herron (1978) with the Kohs Blocks which are graded for difficulty. Similarly, the lateral asymmetries for tactile naming and tactile matching tasks did not appear to produce a ceiling effect because the time of response was measured rather than the frequency of errors.

The evidence for a decline in lateral asymmetries in this study and in the other studies cited may have important implications for neuropsychology because it questions the basic assumption that lateral asymmetries reflect the magnitude of hemispheric functional specialization. Similar views were expressed by Kershner (1981) and Teng (1981) that the magnitude of dichotic listening asymmetries did not reflect the degree of hemispheric specialization in normal adults and children. The effects of interhemispheric communication on lateral asymmetries in behavioral performance are also reflected in the frequent observation that simultaneous (dichotic) listening often results in a paradoxical loss of information presented to the ear ipsilateral to a lateralized cerebral lesion. For example, left hemisphere lesions often cause an unexpected loss of ipsilateral left ear information because the damage involved commissural fibers and prevented right hemisphere (left ear) information from reaching specialized language areas in the left hemisphere (Damasio & Damasio, 1979; Denes & Caviezel, 1981; Goodglass, 1967; Sparks, Goodglass, & Nickel, 1970).

In the present study, it was found that young children with a right hand preference performed faster with the left hand on a visual-motor task (Trafls R), supporting Gazzaniga's (1981) hypothesis that lateral asymmetries

of motor performance may be dependent on the linguistic or spatial nature of the task. Kimura and Archibald (1974) hypothesized that the left hemisphere is specialized for sequential motor skills as a consequence of language representation in the same hemisphere. However, left-handers tend to have a language representation in the left hemisphere (Rasmussen & Milner, 1977), despite lateral asymmetries for motor and auditory performance favoring the left hand and left ear (Warrington & Pratt, 1981). Wolff and Hurwitz (1976) suggested that left hemispheric specializations for both speech processing and serial organization of motor skills may be coincidental rather than functional.

In summary, lateral asymmetries were present at 3 years of age on the tasks which appeared relatively easy. The tapping and Trails R tests were lateralized at 5 years of age or perhaps later, when the PPVT and tactile naming showed smaller lateral asymmetries than at 3 years of age. It is suggested that lateral asymmetries arise during acquisition of abilities to perform a task, consistent with a developmental increase in hemispheric functional specialization, but may decrease or show no change once the task is acquired. A possible reason for decreases or unchanging lateral asymmetries during development is that interhemispheric communication increases, giving each body side greater access to ipsilateral hemispheric functioning.

Interhemispheric Communication

The present study provides support for the presence of interhemispheric communication at 3 years of age on Trails R and tapping. Alternate tapping was possible for most of the 3-year-olds and all of the 5-year-olds, who performed significantly faster than the 3-year-olds, suggesting interhemispheric communication was greater in the 5-year-olds. Intermanual transfer of visual-motor learning was present at 3 years of age, and although the magnitude of

transfer (% savings) was not greater at 5 years of age, transfer kept pace with the greater speed of performance at 5 years of age, suggesting greater efficiency of interhemispheric communication in the 5-year-olds (e.g., Myers, 1965). As mentioned previously, larger or same size lateral asymmetries at 3 years of age, relative to 5 years of age, may also indicate an increase in interhemispheric communication between these ages on the PPVT and tactile naming. Evidence for an early development of interhemispheric communication is also seen in work by Fox, Aslin, Shea, and Dumais (1980) who found that stereopsis (binocular vision) is present in human infants. Stereopsis is apparently dependent on normal early callosal development in experimental animals (Elberger, 1979; Pettigrew, 1974). Like lateral asymmetry, interhemispheric communication might be evident only on tasks as the cognitive abilities are acquired. Thus, intermanual transfer measures likely follow a development gradient that depends on inter- and intrahemispheric processing capacities.

The tapping test results in the present study suggest a relatively later maturation of interhemispheric communication of motor information relative to the development of intrahemispheric processing. This reflects an earlier maturation of primary motor and sensory cortex in young children. These cortical areas have distal extremity representations with little or no commissural interconnections in mice, cats, raccoons, monkeys, and probably in man (Ebner & Myers, 1965; Karol & Pandya, 1971; Jones & Powell, 1968; Pandya & Vignolo, 1971; York & Caviness, 1975). However, it appears a general principle that cortical-brainstem connections develop before cortical-cortical connections in the brains of experimental animals (Anker & Cragg, 1974; Cragg, 1975; Wise & Jones, 1976, 1977, 1978). Thus, commissural

activity may develop relatively more slowly than intrahemispheric processing even in later developing association cortex. For a given skill, this implies specialization for intrahemispheric information processing is present somewhat earlier than the interhemispheric communication of information.

Rather than viewing the cerebral commissures as a single structural unit, it appears there are regional variations that correspond closely with the cortical regions they interconnect. This follows logically because the fibers originate and terminate in cortical areas that are largely homologous, e.g., posterior commissural fibers interconnect both occipital lobes (Karol & Pandya, 1971). The importance of regional organization within cerebral commissure fibers is reflected in the findings that they transmit information characteristic of the areas they interconnect (Berlucchi, Gazzaniga, & Rizzolatti, 1967). In addition, partial commissurotomy patients show behavioral signs of disconnection specific to the region disconnected (Damasio, Chui, Kassel, & Corbett, 1980; Gazzaniga, Risse, Springer, Clark, & Wilson, 1975; Springer & Gazzaniga, 1975; Zihl & Von Cramon, 1980). For example, sectioning of the middle of the corpus callosum can result in a specific loss of intermanual transfer of tactile information with no other intermanual disconnection signs (Dimond, Scammell, Brouwers, & Weeks, 1977). Thus, the differential maturation of interhemispheric communication for certain tasks may reflect not only the overall level of commissural integrity, but also the efficiency of specific commissural regions. For example, bimanual alternate finger tapping may require earlier developing commissural fibers of the anterior corpus callosum, while the Trails R test may require later maturing fibers which interconnect the posterior parietal lobes, implicated in programming motor activity (Mountcastle, Lynch, Georgopoulos, Skata, & Acuna, 1975; Wyke, 1971) as well as performance of visual-spatial skills (Critchley, 1953, 1966).

Gazzaniga (1970, 1974, 1981) suggested that interhemispheric communication may develop relatively later than intrahemispheric processing due to a relatively late postnatal maturation of the cerebral commissures which could result in behavioral signs of interhemispheric unconnection (similar to disconnection) in young children. Galin et al. (1979) suggested 3-year-olds are more like commissurotomy patients than are 5-year-olds. This idea is supported to some extent by the present study. The 3-year-olds did appear to show behavioral signs more similar to the commissurotomy patients than to individuals with callosal agenesis. The presence of a lateral asymmetry on tactile naming at 3 years of age, but not at 5 years of age, was similar to the adult commissurotomy patients (Gazzaniga et al., 1975; Sperry et al., 1969), but was unlike the patients with agenesis of the corpus callosum (Dennis, 1976; Jeeves, 1965; Reynolds & Jeeves, 1977; Saul & Sperry, 1968) and commissurotomy patients who have had the anterior commissure spared (Risse et al., 1978). The presence of the anterior commissure in most acallosal patients (Loeser & Alvord, 1968) may explain the difference from complete commissurotomy patients and suggests that interhemispheric communication of tactile naming information can proceed via the anterior commissure.

There are, of course, difficulties in using commissurotomy patients for inferring normal cerebral functions. Although commissurotomy adult patients and normal young children may show similarities in their performance on a few tasks, it should be kept in mind that the anatomical bases for these comparisons is distinctly different. Most of the commissurotomy patients have had longstanding brain damage, since most patients had epilepsy and brain surgery, both of which can cause further damage (Karol & Pandya, 1971; Sokoloff, 1976), and a possible reorganization of cerebral functions (B. Milner, 1962). However, as Damasio et al. (1980) pointed out, work on patients with callosal tumors, callosal agenesis, and vascular lesions, as well as the experimental animal studies, have shown enough consistency that specific behavioral results of commissural damage can be

identified. Also, pre- and postoperative neuropsychological performances (Sperry et al., 1969) and comparisons to patients with unilateral brain damage have helped identify those deficits specific to transection of the cerebral commissures.

In addition to quantitative evidence that 3-year-olds showed more signs of interhemispheric unconnection than the 5-year-olds, e.g., the late maturation of bimanual alternate finger tapping results in this study, or intermanual transfer of tactile matching (Galin et al., 1979), several qualitative observations in the present study led to similar suggestions. When 3-year-olds had difficulty with bimanual alternate finger tapping, they often reverted to unimanual or bimanual synchronous finger tapping, like the commissurotomy patient, B.B. A few observations made during administration of the PPVT were unique to the 3-year-olds. Several 3-year-olds made an unusually great effort to bring the left hand up to make an incorrect pointing response, again like B.B. Also, several 3-year-olds circled above the page of pictures with the left hand, then suddenly realizing the correct answer, pointed with the right hand. This was never seen with the hand order in reverse. A third observation, reminiscent of Gazzaniga and others' observations of commissurotomy patients, was that the 3-year-olds sometimes made confabulations about incorrect selections. For example, one 3-year-old used his left hand to select a picture of a soldier when the stimulus word was "barber". The child then said, "Hey, the barber's got a gun!" and told the examiner that barbers are supposed to cut hair, not shoot people.

A few findings in the present study suggested that behavioral signs of interhemispheric unconnection in the 3-year-olds were not the same as the disconnection manifest in commissurotomy patients. (1) Bimanual alternate finger tapping is possible at 3 years of age, but nearly impossible for

commissurotomy patients. (2) Commissurotomy patients have not shown intermanual transfer of visual-motor learning (LeDoux et al., 1977, 1978; Zaidel & Sperry, 1977), however, the normal 3-year-olds in this study did show significant transfer on Trails R. Finally, (3) lateral asymmetries on tactile naming were not very large, in contrast to the dramatic loss of left hand naming abilities often brought about by complete commissurotomy. As mentioned, these differences between the intermanual transfer in normal and commissurotomy patients may represent a difference in the quantity of interhemispheric communication. In the course of normal development, interhemispheric communication would be expected to show a gradual increase as the cerebral commissures mature.

The evidence in this study for a developmental increase in intermanual transfer and decreasing lateral asymmetry is consistent with the notion that the cerebral commissures normally force the two hemispheres to work together (Ellenberg & Sperry, 1979, 1980). Kinsbourne (1974) suggested the normal role of the corpus callosum permits a rapid redistribution of attention between the two cerebral hemispheres. The adaptive significance of attentional unity may be that the interaction permits the normal brain to function better than the sum of its two parts (Denenberg, 1980).

Evidence for increasing interhemispheric communication supports the concept that excitatory functions of the cerebral commissures increase during development, however, this does not necessarily imply that inhibitory action does not show a similar increase. Selnes (1974) suggested that excitation of one hemisphere area may require a simultaneous inhibition of the other. Similarly, both processes may be necessary for rapid lateral attention shifts (Dimond, 1976a; Kinsbourne, 1979). Meyerson (in Schaltenbrand et al., 1972)

reported low levels of stimulation to callosal fibers produced inhibition at cortical sites, while the same fibers produced cortical excitation at higher stimulus levels. The developmental pattern may be specific to callosal regions and callosal fibers which differ in their rate of maturation (Blinkov & Glezer, 1968) and electrical properties (Eidelberg, 1969). Consequently, the differential development of excitatory and inhibitory commissural functions would be difficult to understand from behavioral evidence presented in the current study.

In summary, the behavioral evidence in this study suggests interhemispheric communication increases between 3 and 5 years of age and may develop relatively later than the intrahemispheric processing of similar information. The degree of intermanual transfer appears to depend on the task in question, which likely follows a developmental hierarchy of skills. The behavioral evidence is consistent with anatomical and physiological evidence for a gradual postnatal maturation of commissural systems and interhemispheric communication. The evidence in this study also suggested that normal functioning of the cerebral commissures forces the two hemispheres to work together.

Relationships between Hemispheric Functional Specialization and Interhemispheric Communication

While many authors have speculated on the presence of relationships between normally developing hemispheric specialization and interhemispheric communication (e.g., Orton, 1937; Denenberg, 1980), few have offered a means of testing their hypotheses. In the present study, data from the tapping and Trails R tests offered some behavioral evidence for a temporal relationship between

hemispheric functional specialization and interhemispheric communication. Although causal relationships cannot be inferred from these data, the pattern of results does offer some evidence concerning a number of hypotheses.

Intermanual transfer and lateral asymmetry may be related when a task ability is being acquired or when a task is difficult, according to work by Teuber (1962) and Dennis (1976). Support for this concept is present in a comparison between intermanual transfer and lateral asymmetry on tapping and Trails R. Trails R showed positive correlations between these measures at 3 and 5 years of age, while a positive correlation was present only on tapping in the 3-year-olds boys. At the same time, Trails R skills appeared to mature later because there were relatively greater differences in performance speed between 3 and 5 years of age on Trails R than on tapping. The lack of any such relationship on the Formboard test may indicate the absence of ability to acquire the appropriate performance strategies. The Trails R and Formboard tasks may require cognitive strategies which mature later than the motor abilities required for tapping speed (Reitan, 1974a). These results suggest it may be useful to consider that the appearance and change in the interactions between interhemispheric communication and hemispheric functional specializations during development may be dependent on cognitive demands of the task, as has been suggested for both processes alone.

A causal role of the cerebral commissures in the development of hemispheric functional specialization has been inferred from studies of acallosal patients who often fail to show lateral asymmetries on neuropsychological tests (Bryden & Zurif, 1970; Dennis, 1976; Ettlinger, Blakemore, Milner, & Wilson, 1972; Jeeves, 1965; Lehman & Lampe, 1970; Netley, 1972, 1977; Reynolds & Jeeves, 1977; Saul & Sperry, 1968; Solursh et al., 1965). However, Dennis (1981)

has presented a convincing argument that these studies have not been able to tell whether cerebral specialization is absent or whether there is simply impaired access to normally lateralized cerebral processors. Acallosal patients also appear to have a normal proportion of right-handers, suggesting a typical left hemispheric specialization (D. Milner & Jeeves, 1979) and signs of interhemispheric disconnection on motor tasks (Ferriss & Dorsen, 1975; Field et al., 1978; Jeeves, 1965).

Evidence in the present study does not support a causal role of the corpus callosum in the initiation of hemispheric functional specializations. As discussed previously, for a given task, the lateral asymmetries appeared to precede the intermanual transfer or to be smaller at 5 than at 3 years of age, suggesting a relatively later development of interhemispheric communication. The results support Dennis' (1981) conclusions that it is premature to suppose left hemispheric specialization for speech is callosally determined.

If the cerebral commissures were, in fact, responsible for initiating hemispheric functional specializations in normal development, a positive correlation between magnitudes of left and right lateral asymmetries would be expected for verbal and spatial tasks, respectively, because more efficient interhemispheric communication would lead to a generally more specialized brain. On two roughly equivalent tasks, tactile matching and tactile naming, the 3-year-olds showed lateral asymmetries in different directions, yet the asymmetries were not significantly correlated. In other words, it appeared that right hemispheric specialization had no relationship to left hemispheric specialization. Perhaps this suggests the two cerebral hemispheres are predisposed to acquire particular functional specializations, as proposed by Semmes (1968). Another possibility is that increasing interhemispheric

communication obscures the relationship between two measures of lateral asymmetry because it interferes with the interpretation of lateral asymmetry as a measure of hemispheric functional specialization.

As in adults, the normal functions of the developing interhemispheric communication appear to entail a dissolution of lateral asymmetries in behavioral performance. This role may be adaptive in allowing functionally specialized regions to form without producing lateralized behavioral abilities. From this perspective, it seems plausible that lateral asymmetries should not show a normal developmental increase because interhemispheric communication would permit expression of hemispheric functional specialization. Perhaps this helps to explain Hecaen's (1976) ideas better. He suggested that some hemispheric specialization is present from birth and gradually increases, while the ability to recover from aphasia in childhood reflects the time limits of cortical plasticity, not the onset of specialized function. Hecaen's hypothesis does not explain why normal children fail to show developmental increases in lateral asymmetries. The answer may lie in the development of a lateral asymmetry covering-up process resulting from postnatal developments in interhemispheric communication. Further, Davidson (1978) has suggested a late development of the cerebral commissures may play an essential role in the ability of children to recover from aphasia.

Another aspect of intermanual transfer and lateral asymmetry found unexpectedly in this study concerned an unidirectional transfer of learning on Trails R. It was suggested the specialized hemisphere could transfer information to the other hemisphere, but transfer in the other direction did not occur. One possible explanation is the specialized hemisphere inhibits the other during activation, but excites or transmits information

to the other hemisphere when the task requires activation of the other (unspecialized) hemisphere. This is consistent with Selnes' (1974) suggestion that one role of the cerebral commissures may be to ensure that excitation of a specialized hemisphere is accompanied by inhibition of the other hemisphere. Similarly, Doty and Overman (1977) found the corpus callosum transmits information, but does not transfer the memory engram, indicating the specialized hemisphere can transmit information to the other hemisphere without losing its specialization. In fact, overtraining of one hemisphere in experimental animals appears to increase hemispheric specialization (Buresova, Bures, & Nadel, 1972). This adds further support for a role of the cerebral commissures in maintaining a low level of lateral asymmetry despite development of hemispheric functional specializations. The results of the Trails R study also suggest the specialized hemisphere may be in charge of regulating interhemispheric communication, consistent with Gazzaniga (1974) and Gazzaniga and LeDoux (1978) who hypothesized that specialized motor output systems provide a final cognitive path for organization and control of behavior.

In conclusion, the results of the present study bear on several hypotheses concerned with the normal relationship of interhemispheric communication and hemispheric functional specialization during development. They suggest the presence of a temporal relationship between the two phenomena which is present depending on task demands. One possibility is that the phenomena are present at the same time and facilitate learning and performance. Although a causal link between the two phenomena cannot be inferred from the data, the role of

developing interhemispheric communication appears to include the prevention of behavioral expression of hemispheric functional specializations.

The modus operandi for normal commissural activity may be that it provides inhibition or excitation from the specialized hemisphere to the other hemisphere depending on which hemisphere (hand) is required to perform the task.

Many authors have focused on the potential significance of late-maturing interhemispheric communication in postnatal behavior, while little recognition has been given to the significance of late-maturing association cortex or the differential development of various regions of the cerebral commissures and commissural fibers. The pattern of results in the present study favor the gradual postnatal development of complete intra- and interhemispheric subsystems, rather than a later maturation of the entire network of commissural fibers relative to the two cerebral hemispheres. The former concept is consistent with Himwich's (1976) notion that the cerebral hemispheres develop as a collection of organs, each maturing at different rates.

Sex differences. No sex differences in lateral asymmetry measures were found on any tasks in the present study. This finding agrees with McGlone's (1980) statement that sex differences in lateral asymmetry are rarely found in childhood. Also, sex differences have not been found in the morphological asymmetries of infant brains (Chi, Dooling, & Gilles, 1977; Wada et al., 1975), contrary to Lansdell's (1964) observations of Conel's work, nor have sex differences been noted in children recovering from acquired aphasia (Woods & Teuber, 1978). Two recent reports of neuropsychological outcome of unilateral cerebral damage in adults have implicated greater hemispheric

functional specialization in males (Inglis & Lawson, 1981; McGlone, 1977). However, Kertesz and Sheppard (1981) were able to attribute sex differences to the epidemiology of neurological diseases, consistent with adult neuropathology studies (e.g., Hutchinson & Acheson, 1975).

Sex differences were not found on measures of intermanual transfer in the present study, although sex differences were nearly significant in the interaction between bimanual alternate tapping and the lateral asymmetry of unilateral tapping. Although it stands alone in the present study, this sex difference appears to be analogous to findings for adult subjects who show very large sex differences in the interference of verbal tasks on bimanual alternate tapping performance (Wolff & Cohen, 1980). These results suggest sex differences in cerebral organization but an accurate characterization of these differences will require further work. Kocel (1980) found lateral asymmetries were smaller for females, and suggested they may have a greater degree or earlier development of interhemispheric communication than males. However, Kocel was not justified in drawing such conclusions because the sex differences could have been unique to the interaction of lateral asymmetries with intermanual transfer as noted for the tapping test in this study as well as by Wolff and Cohen (1980).

Recommendations for Future Studies

Individual Differences

Individual differences in test performance were not studied in the present report. Subjectively, it appeared that the differences were within the range of chance deviation, however, some children appeared to be distinctly better in some skills than in others. For example, one child was quite poor on tasks requiring motor performance, showing small lateral asymmetries for motor and visual-motor performance, but performed well above average on tests of verbal expression and receptive language. Specific deficits noted for the two brain-damaged children presented in this study also suggested the tests were sensitive to individual differences in cerebral functioning. This is encouraging from the view that the tests may be sensitive to differential development of cerebral structure and function. A drawback of this approach, however, is the possibility that the test results are not necessarily descriptive of the performance of individual children. Some individuals may prefer to process cognitive information consistently in one hemisphere (Reitan, 1974b), especially if there is a later postnatal development of the ability to make lateral attention shifts (e.g., Kinsbourne, 1979). An exploration of the patterns of individual differences in the performance of these tests might be worth pursuing, perhaps using Q type factor analysis (see Fisk & Rourke, 1979); however, more children would be required than the 64 tested in the present study.

Implications for the Role of Learning in Cerebral Organization

The tasks administered in the present study did not examine the effects of learning on the development of cerebral organization. Any early learning experiences with similar tasks may or may not have affected the performance.

of children in this study. It has been shown in experimental animal studies that early sensory stimulation can affect cellular development and differentiation in the cerebral cortex and corpus callosum (Buisseret & Imbert, 1976; Diamond, Lindner, Johnson, Bennett, & Rosenzweig, 1975; Lund & Mitchell, 1979; Rhoades & Dellacroce, 1980; Wiesel & Hubel, 1965). Greater early sensory stimulation may lead to a greater degree of interhemispheric communication and hemispheric functional specialization (Denenberg, 1980; Denenberg, Zeidner, Rosen, Hofmann, Garbanati, Sherman, & Yutzey, 1981). The cellular basis for such changes might include axoplasmic transport and synapse formation (Benjamins & McKhann, 1976; Lubinska, 1975). If task practice affects intermanual transfer, it would be useful to identify the neural mechanisms involved.

The results of the present study cast doubt on some previous methods for stimulating greater cerebral development. Since there were no tests showing significantly greater lateral asymmetries at 5 than at 3 years of age in the present study, the results fail to support ideas that methods designed to increase lateral asymmetry will increase hemispheric specialization or interhemispheric interactions (Delacato, 1966; Orton, 1937; Palmer, 1964). In fact, on the tapping test, the 5-year-olds and 3-year-old girls with greater lateral asymmetries tended to have slower bimanual tapping speeds. Perhaps previous methods of increasing manual asymmetries, such as tying a child's hand behind his back to increase right-handedness, might have worked by decreasing both right hemisphere efficiency and interhemispheric communication.

The results suggest caution in the interpretation of lateral asymmetries as behavioral indicators of cerebral development. Large asymmetries in manual performance have been seen in commissurotomy patients and patients with unilateral cerebral disease, suggesting the normal brain has two functionally specialized hemispheres. However, while it may be advantageous

to have a specialized brain (Teuber, 1974), it is not necessarily advantageous to show large lateral asymmetries in task performance. This again points out the problem of interpreting the degree of lateral asymmetry as a reflection of the magnitude of hemispheric functional specialization.

Implications for Clinical Studies

Remediation procedures based on practice of intermanual transfer may be an area of clinical therapy worthy of pursuit; however, it should be noted there were no indications in the present study that such procedures have any remediation value for developmental disabilities or maturational lags.

A number of researchers have studied lateral asymmetries in the performance of learning disabled children in order to find if hemispheric functional specialization might be deficient. While some studies have suggested children with learning disabilities have smaller lateral asymmetries than normals (Birch & Belmont, 1964; Witelson & Rabinovitch, 1972; Zurif & Carson, 1970), others have found the lateral asymmetries of these children are comparable to normals (Springer & Eisenson, 1977; Witelson, 1977). In a recent study, Keefe and Swinney (1979) found smaller lateral asymmetries were related to the occurrence of two dyslexic subgroups having lateral asymmetries in different directions which tended to cancel out lateral asymmetries for the entire group. In fact, Kershner (1981) and Mamen (1981) suggest lateral asymmetries may be larger for individual dyslexic children than for normals. Just as with the brain-damaged children in this study, bilateral or unilateral hemispheric dysfunction seen in learning-disabled children (Duffy, Denckla, Bartels & Sandini, 1980) may lead to a greater degree of lateral asymmetry on neuropsychological tests.

Large lateral asymmetries in dyslexic children could also indicate lower interhemispheric communication, as suggested by Gazzaniga (1973), and Yeni-Komshian, Isenberg, and Goldberg (1975). Impaired interhemispheric communication has been suggested by studies of learning-disabled children using behavioral (Badian & Wolff, 1977; DeHaven, Mordock & Loykovich, 1969) and electrophysiological techniques (Sklar, Hanley, & Simmons, 1972). The behavioral tests described in the present study may be useful in isolating intra- and interhemispheric deficits or developmental lags in learning disabled children.

The approach used in this study might also be applicable to the identification of intra- and interhemispheric deficits following traumatic head injury (Alexander & Putnam, 1966; Rubens, Mahowald, & Geschwind, 1977). Another clinical population with evidence of intra- and interhemispheric dysfunction are those individuals with psychiatric disorders, especially schizophrenia and manic-depressive psychoses (Carr, 1980; Dimond, Scammell, Pryce, Huws, & Gray, 1979a; Galin, 1974; Green & Kotenko, 1980; Gur, 1978; Pic'l, Magaro, & Wada, 1979; Schweitzer, 1979; Taylor, Greenspan, & Abrams, 1979; Wexler, 1980). Beyond evaluation of cerebral dysfunction in psychiatric patients, it may be possible to evaluate the success of treatment with the methods presented in this study. For example, it would be possible to test for changes in intermanual transfer following direct stimulation of the corpus callosum which has been shown to alleviate depression and anxiety in psychiatric patients (Laitinen, 1972). Similar tasks may also be useful in evaluation of the effects of the drug piracetam, which increases interhemispheric communication and has been shown to improve performances of normal and schizophrenic adults on various cognitive tasks (Dimond, 1976b; Dimond, Scammell, Pryce, Huws, & Gray, 1979b).

Summary and Conclusions

Three issues in early neuropsychological development were addressed in this study. The first issue was whether lateral asymmetries in behavioral performance are the same magnitude and direction at 3 and 5 years of age. The second issue was whether intermanual transfer is the same magnitude and direction at 3 and 5 years of age. The third issue concerned the possible presence of a temporal relationship between intermanual transfer and lateral asymmetries in early childhood. It was initially assumed that lateral asymmetries in behavioral performance reflected hemispheric functional specialization. In addition, it was assumed that intermanual transfer measured interhemispheric communication, and that the performance abilities of one hand reflected activity of the contralateral hemisphere.

The rationale for the present study was to administer tests which could measure both intermanual transfer and lateral asymmetry in the same children. In addition, two tests were designed which examined lateral asymmetries alone in these same children.

The major results of this study were as follows: (1) Lateral asymmetries favoring the right or left hand were present at 3 years of age for tests of motor speed, speed of onset of tactile naming, and frequency of pointing responses to picture vocabulary. None of these lateral asymmetry measures had a greater magnitude at 5 years of age, and on the latter two tasks, lateral asymmetries were greater at 3 years of age. (2) Intermanual transfer was present at 3 and 5 years of age on the motor and visual-motor tasks, but not on a tactual-motor task. On the motor task, the speed of bimanual coordination (intermanual transfer) matured relatively later than the unimanual speeds (lateral asymmetry). On the visual-motor task, there was evidence for

unidirectional transfer of visual-motor information. (3) Positive correlations between intermanual transfer and lateral asymmetry was found only in 3-year-old boys on the motor task, 3- and 5-year-olds on the visual-motor task, and no correlations were found on the tactual-motor task. These results suggested that lateral asymmetries and intermanual transfer may both be manifest at various times of development and are dependent on cognitive task demands.

The conclusions of this study were as follows:

(1) Lateral asymmetries on some easy motor and verbal tasks are present at 3 years of age, suggesting some degree of hemispheric specialization is present by that age.

(2) The basic assumption that the magnitude of a lateral asymmetry reflects the degree of hemispheric specialization does not appear to be true for normal development. Rather than suggesting that hemispheric specialization remains unchanged or decreases, it is suggested that smaller lateral asymmetries at 5 than at 3 years of age reflect increasing interhemispheric communication.

(3) When lateral asymmetries were present, their direction appeared to reflect the direction of hemispheric functional specialization.

(4) Intermanual transfer was evident at 3 years of age, suggesting interhemispheric communication is present by that age.

(5) Intermanual transfer was greater at 5 years of age on a motor task, suggesting postnatal increases in intrahemispheric communication which may mature later than the development of interhemispheric processing.

(6) The age at which lateral asymmetries and intermanual transfer were present appeared to depend on the cognitive demands of specific tasks.

(7) The findings of this study are consistent with a role of the cerebral commissures in preventing the behavioral expression of specialized cerebral functions as lateral asymmetries in performance.

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Appendix

Table A

Means and Standard Deviations for Tapping Onset Delays

Tapping Condition	3-year-olds		5-year-olds	
	Mean	SD	Mean	SD
Right Hand Finger Tapping	.296	.361	.236	.495
Left Hand Finger Tapping	.324	.433	.250	.311
Bimanual Alternate Arm Tapping	.934	1.287	.633	1.188
Bimanual Alternate Finger Tapping	1.121	1.619	.592	1.149
Bimanual Synchronous Finger Tapping	.550	1.064	.253	.295

Note. All delay measures expressed in seconds.

Appendix

Table B

Spearman Rank Order Correlation Coefficients between Mean Tapping Speeds
and Mean Tapping Onset Delays

Onset Delay in Tapping Condition	Tapping Condition				
	Right	Left	Alternate Arm	Alternate Finger	Synchronous Finger
3-year-olds					
Right	-.23	-.05	.10	-.16	.02
Left	-.32	-.20	-.13	-.01	.11
Alternate Arm	.03	.09	-.40*	-.17	-.07
Alternate Finger	.08	.14	-.35*	-.38*	.14
Synch. Finger	-.04	.00	.10	.23	.18
5-year-olds					
Right	-.24	-.18	-.38*	-.26	-.27
Left	-.03	-.06	-.07	-.35*	.07
Alternate Arm	-.17	-.03	-.32	-.29	-.20
Alternate Finger	-.24	-.25	-.23	-.27	-.17
Synch. Finger	-.35*	-.31	-.30	-.43*	-.16

*p < .05

Appendix

Table C

ANOVA Summary Table with Lateral Asymmetry for Finger Tapping
as a Function of Alternate Finger Tapping Onset Delay

Source	Degrees of Freedom	Sum of Squares	Mean Squares	F
Between Subjects Effects				
Age	1	.00015	.00015	.02
Sex	1	.00014	.00014	.02
Age x Sex	1	.03182	.03182	3.37*
Alt. Tapping ^a	1	.00290	.00290	.31
Age x Alt. Tapping	1	.00733	.00733	.77
Sex x Alt. Tapping	1	.00687	.00687	.72
Age x Sex x Alt. Tapping	1	.00002	.00002	.00
Within Cells	56	.53104	.00948	
Total	63	.58028		

^aBimanual Alternate Finger Tapping: Slow and fast onset groups.

* $p < .07$.

Appendix

Table D

Pearson Correlation Coefficients between Tests
using Overall Levels of Performance

Test	Test					
	Tapping ^a	Trails R ^b	Formboard ^c	Tactile Naming ^d	PPVT Raw Score	PPVT IQ Score
3-year-olds						
Tapping	1.00	.02	.15	-.01	.19	.05
Trails R		1.00	.24	.23	.11	-.02
Formboard			1.00	.24	.48**	.37*
Tactile-naming				1.00	.01	.01
PPVT Raw Score					1.00	NC ^e
PPVT IQ Score						1.00
5-year-olds						
Tapping	1.00	-.17	.22	-.20	.18	.15
Trails R		1.00	.35*	.49**	-.01	-.08
Formboard			1.00	.38*	-.01	-.06
Tactile-naming				1.00	-.23	-.19
PPVT Raw Score					1.00	NC
PPVT IQ Score						1.00

^aTotal Score for five tapping conditions.

^bTotal Score for eight trials on Trails R.

^cTotal Score for first four trials of Formboard.

^dTotal Score for two items used from set # 1 to calculate lateral asymmetries.

^eNC = Not Calculated.

*p < .05

**p < .01.

END

0	2	H	0	9	H	8	2
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FIN