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Temporal sequencing and visuo-spatial ability in left- and right-handed poor and average readers

Schneider, Ellen Marci, Ph.D.

City University of New York, 1992

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**TEMPORAL SEQUENCING AND VISUO-SPATIAL ABILITY
IN LEFT- AND RIGHT-HANDED POOR AND AVERAGE READERS**

by

ELLEN M. SCHNEIDER

A dissertation submitted to the Graduate Faculty in
Psychology in partial fulfillment of the requirements for
the degree of Doctor of Philosophy, The City University of
New York.

1992

c 1992

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This manuscript has been read and accepted for the Graduate Faculty in Psychology in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

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Abstract**TEMPORAL SEQUENCING AND VISUO-SPATIAL ABILITY
IN LEFT- AND RIGHT-HANDED POOR AND AVERAGE READERS**

by

Ellen M. Schneider

Adviser: Professor Tina Moreau

Contemporary theories have attributed reading disability to deficiencies or strengths in certain cognitive functions, including temporal sequencing and visuo-spatial ability. Impairments or strengths in these functions have also been associated with left-handedness. The findings, however, have been conflicting. The present study examined the relationships among reading ability, hand preference, sequencing, and spatial skills.

The subjects were 46 average and poor readers (boys aged 7.5-11.5) who were right- or left-handed. Poor readers obtained Gray Oral Reading Test-R scores which were at least 1.5 standard deviations below their scores on a nonverbal intelligence test; average readers performed similarly on the reading and intelligence tests. Left-handers performed at least 6 of 10 activities on the Harris Test with the left hand, including writing; right-handers performed 9 of 10 activities with the right hand.

Five sequencing tasks were administered: auditory verbal (digits)--repetition of digit sequences; auditory

verbal (words)--repetition of word sequences; visual verbal--pointing to sequences of pictures (familiar objects); visual nonverbal--pointing to sequences of pictures (nonsense shapes); and motor--replication of finger sequences. Two spatial tests were administered: the Right-Left Orientation Test and the Spatial Orientation Memory Test.

Average readers performed better than poor readers on the auditory verbal (digits), visual verbal, visual nonverbal, and motor sequencing tasks, and showed a tendency towards better performance on the auditory verbal (words) task. Right-handers performed better than left-handers on the auditory verbal (words) task, and showed a tendency towards better performance on the auditory verbal (digits) and motor tasks. Although reading groups did not differ on spatial tasks, left-handers performed better than right-handers on the Right-Left Orientation Test. There were no interactions between reading and handedness groups.

These results confirm reports of a general sequencing impairment among poor readers for visual and nonverbal as well as auditory and verbal stimuli. The sequencing deficit was manifested by left- as well as right-handed poor readers. The hypothesis that left-handers would have poor sequencing and good spatial skills, due to weak left and strong right hemisphere functioning, was partially supported.

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Introduction

The present study examined the relationships among reading ability, hand preference, and certain cognitive abilities in elementary school-aged boys. The study was addressed to several long-standing, controversial issues in the literature: (a) the nature of the cognitive strengths and weaknesses exhibited by reading disabled children, (b) the nature of the cognitive strengths and weaknesses exhibited by left-handers, and (c) the relationship between reading disability and left-handedness as it relates to cognitive function (e.g., Geschwind & Galaburda, 1987; Levy, 1969; Orton, 1937). These issues are of theoretical as well as practical interest as they may have implications for understanding both the etiology of reading disability and the origin of left-handedness, and may aid in the identification, diagnosis, and/or remediation of reading disability.

The present study addressed a number of questions regarding temporal sequencing and visuo-spatial ability, namely: (a) whether boys (7.5 to 11.5 years of age) who are poor readers differ from boys who are average readers; (b) whether right-handed boys differ from left-handed boys, and (c) whether the disparity between right-handed average readers and right-handed poor readers is significantly different from the disparity between left-handed average readers and left-handed poor readers.

Although temporal sequencing deficits have been demonstrated in poor readers (e.g., Bakker & Schroots, 1981; Gould & Glencross, 1990), the nature of the deficit is not clear. Some researchers have reported that poor readers are impaired in the sequencing of auditory and/or verbal stimuli but not in the sequencing of visual and/or nonverbal stimuli (e.g., Bakker, 1972; Gould & Glencross, 1990), whereas others have found that poor readers are deficient in sequencing both visual and nonverbal, as well as auditory and verbal stimuli (e.g., Denckla, Rudel, & Broman, 1981; Gordon, 1980). To resolve this controversy, it would be necessary to employ procedurally-matched sequencing tasks, including auditory verbal sequencing, visual verbal sequencing, visual nonverbal sequencing, and motor sequencing. The present study did this.

Left-handedness has also been associated with cognitive deficits. Some investigators have hypothesized that left-hemisphere mediated cognitive functions (e.g., language) are weaker in left- than in right-handers due to delayed growth of the left hemisphere (e.g., Geschwind & Galaburda, 1987). Sequencing, which has been demonstrated to depend primarily on left cerebral hemisphere functioning (Efron, 1963; Kim, 1976) has been hypothesized to be impaired in left-handed subjects.

Spatial ability has been reported to be associated with both reading ability and handedness. Some studies have reported impaired visuo-spatial skills in reading disabled

subjects (e.g., Benton, 1984) and in left-handers (e.g., Levy, 1969), while others have reported that spatial ability is enhanced in reading disabled subjects (e.g., Gordon, 1988a, 1988b; Symmes & Rapoport, 1972) and Geschwind and Galaburda (1987) have hypothesized that it is enhanced in left-handers. The conflicting arguments and empirical results may be due to the fact that different aspects of visuo-spatial ability were assessed in the different studies. To clarify this question, the present study employed two visuo-spatial tests which assess very different aspects of spatial function--the Right-Left Orientation Test (Benton, Hamsher, Varney, & Spreen, 1983), which assesses knowledge of right and left body parts, and the Spatial Orientation Memory Test (Wepman & Turaidis, 1975), which assesses memory for the orientation of geometric forms.

Reading Disability: General Considerations

Definition and Diagnostic Criteria

The phenomenon of reading disability has been variously labeled and defined. A few of the terms used to describe the condition include primary reading retardation, constitutional dyslexia, specific dyslexia, specific reading disability, unexpected reading failure (Symmes & Rapoport, 1972), and developmental reading disorder (American Psychiatric Association, 1987). In the present literature

review, these terms are used interchangeably to refer to the same underlying disorder.

Regardless of the term used to label it, reading disability is generally conceptualized as reading failure which is not caused by low intelligence, socio-economic factors, or inadequate education (Pavlidis, 1990a). It is distinguished from general reading backwardness which is due to either low intelligence, socio-economic factors, or poor schooling (Rutter, 1978). Because of various conceptual and procedural problems, a more precise definition of the disorder has not been agreed upon.

Some recent attempts to define reading disability are illustrative of the lack of consensus. For example, the definition of dyslexia formulated by the World Federation of Neurology (1968) is as follows: "A disorder manifested by difficulty in learning to read despite conventional instruction, adequate intelligence, and sociocultural opportunity. It is dependent upon fundamental cognitive disabilities which are frequently of constitutional origin" (p. 11). According to the National Joint Committee for Learning Disabilities, learning disabilities including dyslexia "are intrinsic to the individual and presumed to be due to central nervous system dysfunction" (Hammill, Leigh, McNutt, & Larsen, 1981, p. 336).

The International Reading Association (1981) defined dyslexia as: "A medical term for incomplete alexia; partial but severe, inability to read; historically (referred to as)

word blindness. Note: Dyslexia in this sense applies to persons who ordinarily have adequate vision, hearing, intelligence, and general language functioning. Dyslexia is a rare but definable and diagnosable form of primary reading retardation with some form of central nervous system dysfunction. It is not attributable to environmental causes or other handicapping conditions" (p. 95).

The American Psychiatric Association (1987) established the following diagnostic criteria for developmental reading disorder: "A. Reading achievement, as measured by a standardized, individually administered test, is markedly below the expected level, given the person's schooling and intellectual capacity (as determined by an individually administered IQ test). B. The disturbance in A significantly interferes with academic achievement or activities of daily living requiring reading skills. C. Not due to a deficit in visual or hearing acuity or a neurologic disorder" (p. 44).

The American Psychiatric Association criteria, as well as the definitions proposed by other investigators, are based upon the assumption of a discrepancy between actual and expected reading performance. However, no standard procedure to measure the discrepancy has been developed. A commonly used method of measuring the discrepancy is a reading score which is 1 to 2 years below the child's grade level. However, several problems are associated with this type of assessment. First, a 1 or 2 year discrepancy for a second or third grader is different from a 1 or 2 year

discrepancy for a fifth or sixth grader, since the type of impairment and the rate of learning vary from one year to the next (Gordon, 1988a). Second, using a "below grade level" criterion implies that children whose reading skills are at grade level but whose intellectual skills are above average are not to be considered reading disabled, even though a dyslexic etiology may be present (Gordon, 1988a).

Several investigators (e.g., Elliot, 1981; Ericson, 1975; and see review by Heath & Kush, 1991) have proposed the use of a reading-IQ discrepancy to identify reading disabled children. Specifically, a reading quotient (in the form of a standard score with a mean of 100 and an SD of 15) would be required to fall a certain number of standard deviations (e.g., 1.5 SDs) below the individual's IQ score. This approach would solve the first problem noted above, i.e., that the magnitude of the discrepancy would differ for children in different school grades. The magnitude of the required discrepancy in this case would be proportionate to the child's IQ. The use of a reading-IQ discrepancy would also solve the second problem noted above, i.e., that children who have normal reading skills but above average intelligence would be inappropriately excluded from the dyslexic group. In this case, such children could be included in the dyslexic group if they met all other criteria for reading disability (i.e., if the reading disturbance significantly interfered with academic achievement or activities of daily living requiring reading

skills, and was not due to a deficit in visual or hearing acuity or to a neurologic disorder (American Psychiatric Association, 1987)).

Epidemiology

Estimates regarding the prevalence of reading disability vary depending upon the criteria used. Estimates of the total number of children whose reading skills are significantly below chronological and mental age vary between 10 and 15% (see Gaddes, 1976). However, only a small number of these are likely to have specific reading disability. Yule and Rutter (1976) conducted an epidemiological survey in which they distinguished between "backward readers," who were underachieving in reading regardless of their intellectual abilities, and "reading retarded" children, who were underachieving in reading (by two standard errors) relative to their intellectual level and chronological age. They found that the rate of reading disability ranged from 3.5 to 6%, instead of being at the expected rate of 2.28% if reading ability was normally distributed. It was also found that the mean nonverbal IQ of the reading retarded group (102.5) was higher than that of the backward readers (80). Reading retardation was associated with language problems and had a higher ratio of males to females (3.3 to 1) than did reading backwardness. In contrast, reading backwardness was associated with neurological disorders and other developmental problems.

Retarded readers made less progress in reading and spelling between 10 and 14 years of age, but made more progress in mathematics, than did the backward readers (Yule, 1973).

The incidence of reading retardation appears to vary somewhat in different countries. The prevalence in the United States and Britain seems to be about 30 per 1000 boys and 5 per 1000 girls of elementary school age. The frequency may be slightly higher in Denmark and Sweden and lower in Japan, Italy, and Spain (see Benton, 1975). One explanation offered for the differing rates between countries relates to the different rules of pronunciation and different degrees of grapheme-phoneme correspondence in different languages (Claiborne, 1906, cited in Hynd & Cohen, 1983). Another interpretation is that reading disability goes unrecognized in some countries (Benton, 1975). In addition, different diagnostic criteria for reading disability are probably used in different countries, which could also explain the variations in rate.

Many studies have documented a sex difference in the prevalence of reading disability. For example, Bettman, Stern, Whitsell, and Gofman (1967) found that in a group of 47 poor readers, 43 (91%) were boys. Symmes and Rapoport (1972) found that in a group of 54 retarded readers with at least average intelligence, there was only one girl. In both studies, the children had been screened for neurologic disorder, hearing impairment, and emotional disturbances.

Hier (1979) argued that strong lateralization of language to the left hemisphere and spatial ability to the right hemisphere in males, and more bilateralization of these functions in females serves to limit the general level of language abilities in males, thereby predisposing them to dyslexia. He proposed further that strong lateralization of language in males would mean that unilateral left hemisphere injury would have a more detrimental effect in males than in females.

More recently, Geschwind and Galaburda (1985a, 1985b, 1985c, 1987) proposed an alternative theory to account for the sex difference in the incidence of developmental dyslexia. According to this theory, the higher level of prenatal testosterone in males than in females is associated with delayed development of the left hemisphere. Markedly delayed neuronal migration would result in disordered cortical architecture and neurons in abnormal locations. Regions of disordered cytoarchitecture in left hemisphere language areas have been found in the brains of several childhood dyslexics. The higher rate of these anomalies in males accounts for the sex difference in the incidence of dyslexia. According to Geschwind and Galaburda (1987), the theory also accounts for the higher incidence of left-handedness in males as well as in those with developmental dyslexia (see p. 52-55).

Symptomatology

The main characteristics of reading disabled children include reading failure, and spelling and handwriting problems. It is important to note that certain cognitive symptoms precede manifestation of the reading difficulty. These include delayed language development (in 20% of cases), and sequencing problems for such activities as putting clothes on in the proper order, remembering the order of days of the week, months of the year, etc. (in more than 50% of cases) (Pavlidis, 1990a).

Pavlidis (1990a) has compiled a list of symptoms commonly found in children with developmental reading disorder. Such children have been found to exhibit anywhere from a few to most of these characteristics, in varying degrees of severity. According to Pavlidis, children with reading disability not only exhibit reading difficulties, but also show inconsistent school performance. For instance, many achieve "A" grades in the arts and sciences but fail in English and/or math. They often do not read for pleasure. Their reading may be characterized by monotonous tone, mispronunciation, and very slow speed. They tend to substitute words (e.g., car for automobile), abbreviate words (e.g., run for running), and omit filler words such as "the" and "a". They tend to make grammatical errors and to have difficulty reading handwritten material.

Children with reading disability often show bizarre spelling, with particular difficulty with long words and

inconsistent spelling of the same word, even in the same sentence. They also have difficulty with punctuation, and they show persistent reversals (e.g., tab for bat) beyond 7 to 8 years of age. They tend to have poor handwriting and write very slowly (Pavlidis, 1990a).

About 50% of reading disabled children have difficulty with oral language, including delay in onset. Many make speech errors that are similar to those made in reading and writing. They also tend to have short attention spans and show impulsivity, hyperactivity, and distractibility. School failure often leads to secondary psychosocial problems, such as low self-esteem, hypersensitivity to criticism, low self-confidence, and the tendency to give up easily (Pavlidis, 1990a).

Children with reading disability may manifest erratic eye movement patterns during reading and during non-reading sequential tasks that simulate the non-verbal aspects of reading. They also may have problems with timing and coordination in activities such as ball games, and they have difficulty keeping a rhythm in dancing or singing (Pavlidis, 1990a).

According to Pavlidis (1990a), reading disabled children exhibit temporal sequencing problems that are apparent in a wide variety of behaviors. They are slow to learn automatic sequential tasks such as putting on clothes or tying shoelaces. They tend to reverse the order of letters of the alphabet, days of the week or months of the

year. They reverse the order of letters within syllables (on for no), of syllables within words (cilpen for pencil), and of words within a sentence, and they have problems remembering the above-mentioned tasks in the reverse order. The sequencing problem is also evident in tasks requiring short term memory for temporal order, as in remembering directions and reciting poems or songs. Reading disabled children also show directional confusion in the form of right-left discrimination errors, and have difficulty following verbal directions. However, they frequently have superior abilities in visuo-spatial tasks.

History

Reading disorders in children has been an area of study since the late 1800's. The term "congenital word blindness" was coined by Morgan in 1896 (cited in Hynd & Cohen, 1983) to describe a case of a 14 year old boy who was of high intelligence but was unable to read or write. He manifested no visual disturbances and had received many hours of additional reading instruction outside of school. Morgan proposed that this case represented an example of congenital word blindness and speculated that it might be due to a defect in the region of the left angular gyrus, as acquired dyslexia was already known to result from a lesion in this area. Bastian (1898) described a similar case and agreed with Morgan's formulation (cited in Hynd & Cohen, 1983).

Hinshelwood (1917) reported on several similar cases and established that the children had no oculomotor or refractive visual problems. He suggested that many children had reading difficulties, but that congenital word blindness was rare and was characterized by extreme difficulty in learning to read despite attempts to teach the child to read.

Studies conducted in the early 1900's focused on identifying the cognitive characteristics of children with severe reading problems. Hynd and Cohen (1983) cited several studies in which deficits were reported in visual discrimination, orientation, and memory (Fildes, 1922; Hincks, 1926) as well as in expressive language (Voss, 1914) and written language (Schmitt, 1918).

Orton (1937) suggested that an alteration in cerebral dominance might be responsible for reading disability. He observed that children with reading difficulty frequently showed mirror-image confusions of letters or words, including mirror writing. He proposed the term "strephosymbolia" (twisted symbols) to replace the term congenital word blindness. To explain the reversal errors, Orton argued that visual images are processed in both cerebral hemispheres in a mirror image relationship, being recorded in the proper orientation in the dominant (left) visual cortex and in the reversed orientation in the nondominant visual cortex. In normal children, reading would involve suppression of the nondominant image by the

dominant hemisphere. In reading disabled children, however, dominance is incomplete so that the image in the nondominant hemisphere is not suppressed. Thus, images from the two hemispheres compete, producing mirror image confusions. Furthermore, Orton proposed that inconsistent hand preference (mixed laterality) or consistent use of one hand and the contralateral eye (crossed laterality) were signs of incomplete hemispheric specialization, and were the precursors of reading disability.

Other investigators attributed reading disability to malfunctioning of the left hemisphere. Reading was conceptualized as a language-related, left hemisphere process (e.g., Marshall & Newcombe, 1981). The nature of the left hemisphere "abnormality", however, remained unknown. First, the neuroanatomical evidence was conflicting. For example, Drake (1968) reported a postmortem analysis of the brain of an individual with reading disability which revealed excessive numbers of neurons in the subcortical white matter, which was thought to result from a disorder of neuronal migration. He did not report significant lateral differences. Galaburda and Kemper (1979) also found anomalous cellular migrations; however, they were unilateral, occurring in the left posterior temporal lobe.

Geschwind and Galaburda (1985a, 1985b, 1985c, 1987) formulated a neurobiological theory of reading disability. According to the theory, reading disability is due to an

excess of testosterone during prenatal development, which slows the development of the left hemisphere, leading to abnormal cell migration and organization. These left hemisphere abnormalities result in developmental reading disorder and associated left hemisphere-related cognitive deficits. Further, certain compensatory mechanisms in the right hemisphere are activated, leading to left-handedness and superior visuo-spatial abilities. The theory also states that testosterone affects the thymus gland, leading to an increased incidence of autoimmune diseases. Thus, an association was postulated between developmental reading disorder, left-handedness, and autoimmune diseases.

Etiology of Reading Disability

The etiology of developmental reading disorder has been a subject of controversy. Three major approaches to the study of reading disability correspond to the major theories in the area. One approach has been to study differences in hemispheric specialization between reading disabled children and normal readers. Investigators adhering to this approach have used such techniques as dichotic listening (e.g., Witelson & Rabinovitch, 1972), tachistoscopic presentation of lateralized visual stimuli (e.g., Marcel, Katz, & Smith, 1974), dichhaptic stimulus presentations (e.g., Witelson, 1976) and, more recently, neuroimaging (see reviews by Hynd & Semrud-Clikeman, 1989; and Hynd, Semrud-Clikeman, &

Lyytinen, 1991). A second approach has been to examine linguistic and verbal processing differences (e.g., Vellutino, 1978; 1979). A third approach has been to study neuropsychological or cognitive correlates of developmental reading disorder. Using this last approach, researchers have examined such functions as intersensory integrative ability (e.g., Birch & Belmont, 1964; 1965), visuo-spatial ability (e.g., Gordon, 1988b; Symmes & Rapoport, 1972), and temporal sequencing ability (e.g., Bakker, 1972; Gould & Glencross, 1990). Some of the major hypotheses and findings regarding each of these approaches will be described below; however, the following points should be noted. First, the three approaches are not mutually exclusive, so that those who postulate, for example, that certain cognitive skills are deficient in reading disabled individuals also may agree that cerebral dominance is altered in some way (e.g., Geschwind & Galaburda, 1987). Second, the above noted approaches to the study of reading disability include only the major theories which are most relevant to the present study. For a comprehensive review of the etiology of reading disability, see Pavlidis (1990b; 1990c) and Benton and Pearl (1978).

Abnormal Cerebral Lateralization

Many investigators (e.g., Corballis & Beale, 1983; Dalby & Gibson, 1981; Leong, 1984) have argued that incomplete or reversed cerebral lateralization is associated

with reading disorders. These workers have proposed that the pattern of incomplete or reversed lateralization is a stable one and does not change with age. The evidence in support of this view comes primarily from studies in which groups that differ in reading ability are compared to determine if they differ in functional cerebral lateralization. Most of these studies have employed dichotic listening tasks and lateralized tachistoscopic presentation of verbal or nonverbal stimuli to assess lateralization. Using tachistoscopically presented stimuli, Marcel, Katz, and Smith (1974), for instance, found a significant right visual field (left hemisphere) superiority for recall of single words in 8 year old good readers; however, the right visual field superiority was significantly attenuated in 8 year old poor readers. Using a similar task with 10 year old children, Kershner (1977) found a large right visual field superiority for gifted and good readers, and a smaller right field superiority for poor readers. Several other investigators (e.g., Marcel & Rajan, 1975; Pirozzolo & Rayner, 1979) have reported either a reduced right visual field superiority, or no visual field superiority for laterally presented verbal stimuli in poor readers.

Several studies employing dichotic listening techniques have also reported less asymmetry in reading disabled children than in normal readers. Thomson (1976), for example, found that dyslexic children did not show the

normal right ear (left hemisphere) advantage for recall of lists of words, and Leong (1976) found a smaller right ear advantage for verbal material in dyslexics than in normal readers. Witelson and Rabinovitch (1972) also reported that poor readers failed to show the normal right ear advantage for verbal material.

On the other hand, a number of studies have either failed to provide evidence of differences in functional asymmetry between disabled and normal readers, or have found evidence of greater asymmetry in those with reading disability than in normals. Using lateralized tachistoscopic presentations of verbal stimuli, several workers (Marcel & Rajan, 1975; McKeever & Huling, 1970; McKeever & Van Deventer, 1975) found no differences between those with reading disability and good readers. Similarly, several studies using dichotic listening techniques with verbal stimuli failed to provide evidence of differences in the size of the right ear effect between normal and reading disabled children (e.g., Abigail & Johnson, 1976; Yeni-Komshian, Isenberg, & Goldberg, 1975). Thus, in both the visual and auditory modalities, the findings regarding functional asymmetry differences between reading disabled children and normal readers are conflicting.

There is some direct neuroanatomical evidence of aberrant cerebral lateralization in reading disabled subjects. Hier, LeMay, Rosenberger, and Perlo (1978) analyzed computerized brain tomograms of 24 reading disabled

subjects (aged 14 to 47 years) and found that 10 of the 24 brains (42%) were wider in the right parieto-occipital region than in the left, eight were wider on the left (33.3%), and six (25%) were approximately symmetrical. In three of six left-handed subjects, the parieto-occipital region was wider on the left and in the other three, this area was wider on the right. Although the study by Hier and co-workers did not include a control group, it should be noted that, in 120 children and adults who were right-handed normal readers, the brains of 77% showed wider left occipital regions, 12% showed wider right occipital regions, and 11% showed symmetry (LeMay, 1977). In a group of 120 left-handed normal readers, the brains of 36% showed wider left occipital regions, 35% showed wider right occipital regions, and 29% showed symmetry (LeMay, 1977). Thus, Hier, LeMay, Rosenberger, and Perlo (1978) suggested that reversal of cerebral asymmetry may prove to be an important risk factor for reading disability.

One variant of the hypothesis of abnormal cerebral lateralization in reading disabled children is that these children are suffering from a delay in the development of speech lateralization (Bakker, 1973; Satz & Sparrow, 1970). According to this model, all young children have poorly established cerebral lateralization and, therefore, there are no differences in asymmetry between good readers and disabled readers. In older children, however, there should be a difference, with good readers showing more complete

lateralization than poor readers for verbal functions. Furthermore, the theory predicts that if cerebral asymmetry is not established by puberty, reading disabled children would never develop complete lateralization and reading difficulties would persist beyond childhood.

Studies using dichotic listening techniques have provided inconsistent support for Satz and Sparrow's (1970) model. In support of the model, Satz, Rardin and Ross (1971), for example, found a significant right ear advantage in 11 to 12 year old dyslexic children and normal readers, but the magnitude of the right ear advantage was greater in the normal readers. Further support was provided by Darby (1974, cited in Hynd & Cohen, 1983), who used a dichotic digit task with disabled and good readers, aged 5, 7, and 12, and found that the magnitude of ear asymmetry increased with age for good readers, with a significant right ear advantage evident only in the oldest group. For disabled readers, however, there was no significant right ear advantage in any age group, supporting the notion of a developmental lag in asymmetry in poor readers.

In contrast, several dichotic listening studies failed to provide support for the developmental lag theory. Some indicated no asymmetry differences between good and poor readers at any age (e.g., Zurif & Carson, 1970), while Bryden (1970) reported a stronger relationship between asymmetry and reading ability in younger than in older children. In a review of studies employing lateralized

tachistoscopic presentation of visual stimuli in good and poor readers, Satz (1976) concluded that none provided support for the maturational lag theory.

Witelson (1976) conducted a developmental study of cerebral lateralization using dichotic, visual half field, and dichhaptic techniques with normal and reading retarded 6 to 14 year old boys. For the dichotic task, the results indicated a significant right ear advantage for younger and older normal readers, as well as for older, but not younger, retarded readers. On a tachistoscopic face recognition task, a left visual field (right hemisphere) superiority was found for normal readers but no asymmetry for retarded readers. The dichhaptic task involved the palpation of nonsense shapes, or letters. For nonsense shapes, normal readers showed better recognition with the left than with the right hand, whereas no asymmetry was found for the retarded readers. The retarded readers showed better right hand performance than normals, but there were no differences between reading groups for left hand performance. For the letters task, while normal readers showed a right hand superiority and retarded readers showed a left hand superiority, retarded readers showed better left hand performance relative to normals. Based upon these results, Witelson hypothesized that reading disabled boys have left hemisphere superiority for linguistic processing, but their level of processing of verbal information is lower than in normal readers and may reflect a dysfunction in left

hemisphere function. She further suggested that bilateral representation of spatial functions in reading disabled individuals may interfere with processing of language in the left hemisphere. Thus, according to this view, two abnormalities underlie reading disability: (a) lack of right hemisphere specialization for spatial processing; and (b) dysfunction in left hemisphere processing of linguistic information. Although Witelson's study has been criticized on methodological grounds (see Bryden, 1982), the hypothesis of an association between left hemisphere dysfunction and reading disability has received much support (see below).

Linguistic and Verbal Processing

Several investigators have argued that language deficits underlie the problems of reading disabled children (e.g., Mann & Ditunno, 1990; Vellutino, 1978, 1979). Reading is a linguistic skill which requires understanding of visual symbols to convey meaning. It would be expected, therefore, that any general linguistic deficiency would interfere with the reading process. Evidence has been provided indicating general language deficits in children with reading disability. For instance, Belmont and Birch (1966) and Warrington (1967) found a significant association between reading retardation and a lower WISC Verbal IQ than Performance IQ.

More specific evidence of reading-group differences in verbal processing comes from studies which investigated

different aspects of language ability. Several workers have compared good and poor readers on semantic encoding ability. Vellutino, Steger, and Pruzek (1973) varied verbal and nonverbal learning tasks, using different combinations of visual, auditory, and haptic stimuli. Children classified as poor readers were found to be inferior to normal readers on visual verbal learning tasks but were comparable to normals on nonverbal learning tasks. Similar findings were obtained by Rudel, Denckla, and Spalten (1976).

Other workers have reported differences in syntactic ability between good and poor readers. Vogel (1974), for instance, compared reading disabled and normal readers on nine measures of oral syntax, including sentence repetition, recognition of grammaticality, comprehension of syntax, morphology for nonsense words, recognition of missing words, ability to detect melodic variation, as well as the ITPA Grammatical Closure Test and the Northwestern Syntax Screening Test. Reading disabled children were inferior to normals on all measures except recognition of grammaticality and the Northwestern Syntax Screening Test. A review of empirical studies by Vellutino (1978) indicated that poor readers are deficient on tasks evaluating word knowledge, knowledge of syntax, ability to employ words abstractly, and verbal fluency.

Several authors have proposed that phonological processing deficiencies underlie reading problems. According to one version of this view, there are two ways in

which the reader can derive meaning from a written word, a visual route and a phonological route (e.g., Forster & Chambers, 1973; Meyer, Schvaneveldt, & Ruddy, 1975). In the visual route, the visual configuration of a word is converted directly into meaning without any phonological processing, by means of comparing it to an internal store in memory (usually referred to as "whole word recognition"). In contrast, the phonological route involves the use of letter-sound conversion, and the sound of the word is used to retrieve the meaning. According to Stanovich (1988a; 1988b), the phonological route is impaired in reading disabled children. In support of this argument, several studies have indicated that disabled readers are inferior to normal readers in the reading of pseudowords (pronounceable combinations of letters that are not real words) (e.g., Seigel, 1986; Seigel & Ryan, 1988; Waters, Bruck, & Seidenberg, 1985).

Vellutino (1978; 1979) has argued that all observable problems of reading disabled children can be explained in terms of deficits in verbal processing. Thus, difficulties in intersensory integration, temporal sequencing, and visual-perceptual processing are held to be due to a basic verbal processing deficit. One can argue otherwise, however. Apparent difficulties in verbal processing can often be re-interpreted as reflecting impairments in other functions. For example, poor readers' difficulties in reading pseudowords, rather than reflecting phonological

processing problems, could be due to a difficulty in temporal sequencing. Similarly, syntactic deficiencies could also be due to sequencing difficulties.

An additional argument against the view that reading disability is due solely and specifically to a deficit in verbal processing is that the view fails to explain the visuo-spatial deficits demonstrated by poor readers in a variety of tasks and settings (Dodgen & Pavlidis, 1990; see review by Benton, 1984; and see section below). Furthermore, many reading disabled children show a lower WISC Performance IQ relative to Verbal IQ (Kinsbourne & Warrington, 1963), rather than the opposite.

Intersensory Integration

Birch and Belmont (1964; 1965) proposed that some poor readers have difficulty integrating stimuli received through different sense modalities. They suggested that there was a subgroup of poor readers who failed to develop the connections among the sense systems that are necessary for success in reading (i.e., auditory-visual associations). To test their hypothesis, Birch and Belmont (1964) examined the performance of 9 to 10 year old children on a task requiring the matching of auditory rhythmic patterns tapped out with a pencil to visually equivalent dot patterns presented in a multiple choice format. Reading ability was positively correlated with performance on this task. However, IQ was also correlated with reading ability and with performance on

the auditory-visual integration task. In another study (Birch & Belmont, 1965), the auditory-visual matching task was administered to a wider age range of good and poor readers, from kindergarten through sixth grade, with a control for IQ. There was a significant correlation between auditory-visual cross-modal integration task scores and reading ability scores only in first and second graders. However, several other studies indicate that the difficulties faced by poor readers are not confined to cross-modal matching. For example, Blank and Bridger (1966) tested fourth grade retarded and normal readers matched for IQ. The children were administered three tasks: to convert temporal stimuli (patterns of light flashes) into spatial stimuli (dot patterns) within a modality; to perceive the dot patterns; and to report the exact sequence in which the lights were flashed. Retarded readers performed significantly more poorly than normal readers on the first intra-modal transfer task, in that they were unable to convert temporally distributed stimuli into spatially distributed stimuli within a modality. The two reading groups performed equally well on the second task--perceiving dot patterns. On the third task, however, retarded readers performed significantly below normals in reporting the sequence in which the lights were flashed. Blank and Bridger concluded that the deficit exhibited by retarded readers in verbally coding temporal elements might underlie the presumed difficulties in cross-modal tasks.

The results of several other studies have suggested that intermodal integration is not an important factor in reading disability. Senf (1969) used a task in which three pairs of digits were presented, one of each pair in the auditory modality and one in the visual modality. The subjects' task was to recall all six stimuli, either in a free recall format, by pair, or by modality. Reading disabled children (aged 9 to 14 years) made significantly more errors than normals when reproducing the stimuli either by pair or by modality. In particular, disabled readers performed poorly in reproducing the sequence of the digits, whereas they performed as well as controls in the number of digits reproduced correctly. Senf suggested that, rather than being due to a problem with cross-modal integration, reading disability is the result of a specific impairment in the recall of ordered information.

Vande Voort and Senf (1973) reported that reading impaired children also performed poorly on intra-modal tasks involving auditory-auditory and visual-visual matching, as well as on auditory-visual matching tasks. These and other studies (e.g., Vande Voort, Senf, & Benton, 1972) raise doubts about the validity of the intersensory integration view of the etiology of reading disability, and many of the studies (e.g., Senf, 1969) suggest that a deficit in temporal ordering may in fact be a more plausible explanation of the disability.

Temporal Sequencing

Temporal sequencing refers to the experience, perception, and retention of a succession of unidentical events over time (see Bakker, 1972). Temporal ordering is necessary for spoken language, as phonemes must be properly ordered in time. It is also necessary for written language, as graphemes must be properly ordered in a way which corresponds to the sequence of phonemes for that word. The child must be able to perceive and retain temporal sequences in order to learn to read and write as well as to learn to produce and comprehend spoken language.

Bakker and co-workers (1967, 1972, 1981) have proposed that the underlying problem in reading disability is one of temporal sequencing. According to the theory, the sequencing impairment is due to a specific deficit in left hemisphere functioning. Geschwind and Galaburda's (1985a, 1987) theory also suggests that reading disabled children have impaired sequencing skills. According to these workers, children with reading disability show impaired left hemisphere-mediated cognitive functions due to delayed growth of the left hemisphere as a result of excess testosterone prenatally. As sequencing has been shown to depend primarily on the left hemisphere (Efron, 1963; Kim, 1976), it would be expected to be impaired in those with reading disability.

Various researchers have found that children who have difficulty learning to read show deficits in temporal

sequencing. Stamback (1951, cited in Bakker, 1972), for instance, required subjects to reproduce rhythmic patterns tapped out by the experimenter. He found that 7 to 14 year old reading disabled children performed more poorly on this task than did normal readers. Moreover, older reading disabled children did not do better than younger reading disabled children, in contrast to normal readers, in which the performance of the older children was better than that of the younger children.

Another demonstration of a sequencing impairment in poor readers was provided by Belmont and Birch (1966), who found that the Digit Span subtest of the WISC, in which the subject hears a number of digits and is asked to orally reproduce them in the sequence of presentation, was one of the discriminators between normal and reading disabled 9 to 10 year old boys.

A number of studies have reported reading group differences on some temporal sequencing tasks but not on others. Blank and Bridger (1966), for instance, administered three different tasks to 9 year old reading disabled children and normal readers. The reading disabled children performed poorly when they were shown sequences of light flashes and then were asked to either choose a matching dot pattern or describe the pattern verbally. When asked to match two dot patterns, however, they performed as well as normal readers. In another study of 6 year old children, Blank, Weider, and Bridger (1968) found that

reading disabled children performed more poorly than normal readers when asked to describe verbally a sequence of light flashes. When asked to replicate rhythmic beats, however, the two reading groups performed similarly. The authors suggested that reading disabled children have difficulty in perceiving and/or remembering temporal patterns only when a verbal medium is used.

Based on Blank and Bridger's results, Bakker and co-workers (1967, 1972, 1981) proposed that poor readers have a specific disturbance in temporal sequencing of verbal/linguistic material. The results of several studies (Bakker, 1967; 1972; Groenendaal & Bakker, 1971) indicate that reading disabled children are impaired on tasks requiring the sequencing of verbal or verbally codifiable stimuli (for example, letters, digits, or meaningful figures) but not on tasks requiring the sequencing of non-verbal and non-verbally codifiable stimuli (for example, nonsense or meaningless figures). Furthermore, Bakker's findings indicate that poor readers are impaired on tasks requiring the sequencing of auditory stimuli but are only slightly impaired on tasks requiring the sequencing of visual stimuli. Bakker's interpretation of these findings is that auditory stimuli are easier to label verbally than are visual stimuli; i.e., the subject is forced to process the verbal label to a greater extent with an auditory input than with a visual input. Therefore, sensory modality is

important only because it may modify the strength of the verbal processing component.

To provide support for his theory, Bakker conducted a series of studies of children in different types of schools. For example, Bakker (1967) studied fifty four 9 to 15 year old boys who attended a school for children with learning problems. The children were classified either as "better readers," defined as those who scored approximately 2 years below grade level on a standardized reading test, or "worse readers," defined as those who scored about 4 years below grade level. The two reading groups were matched for age and general intelligence. The children were shown sequences of four tachistoscopically presented items consisting of four types of material: digits, letters, meaningful figures, and meaningless figures. Following presentation of each sequence, the children were shown the same items arranged randomly on a card, and asked to report the correct order of prior presentation. The "worse readers" made more errors than the "better readers" when all types of material were combined. However, when type of material was considered, reading group differences favoring the "better readers" were obtained for letters, meaningful figures, and digits, but not for meaningless figures. Bakker concluded that his findings were consistent with those of Blank and Bridger (1966), and proposed that poor readers cannot make use of the inherent verbal labels, which would have helped with temporal order recall of verbally labelable materials.

Groenendaal and Bakker (1971) provided a further test of Bakker's theory, using children in a public school. Using a similar temporal ordering task, they presented sequences of meaningful or meaningless figures to 7 and 10 year old children who were either above average or below average readers, matched for IQ. The 7 year old below average readers showed poorer sequencing performance when meaningful figures were used, but did not differ from above average readers when the figures had no verbally codifiable meaning. However, the 10 year old below average readers performed similarly to the above average readers when meaningful figures were used. Further, when meaningless figures were used, below average readers showed a non-significant trend ($p < .10$) towards poorer performance than above average readers. Thus, whereas the findings for the 7-year-olds are supportive of Bakker's theory, the results for the 10-year-olds are not.

More recently, Bakker and Schroots (1981) tested 411 Dutch children for temporal order perception when they were in nursery school (5 to 6 years old), and for reading ability at the end of first grade of primary school. The tasks included: Knox Cubes, in which several series of blocks are tapped by the experimenter and must be reproduced by the child in the correct order; Wordspan, in which sequences of nouns are spoken by the examiner and must be reproduced in the order of presentation; Picture Matching, in which the child must point to a sequence of pictures

corresponding to the order of nouns previously spoken (in Wordspan); and a sentence imitation task. They found that sentence imitation and Picture Matching showed the highest correlation with first grade reading ability, followed by Knox Cubes and Wordspan. Knox Cubes, Picture Matching, and sentence imitation all contributed significantly to the multiple correlation, with only Wordspan being statistically non-significant. The authors suggested that poor temporal order perception causes poor reading, and not the reverse. They stated that the results support their previous conclusion that temporal order processing of verbal and verbally codifiable information is a predictive as well as an explanatory factor in reading problems. It should be noted that, in this study, reading disabled children performed more poorly than normal readers on Knox Cubes, in which the stimuli are largely nonverbal (see Lezak, 1983).

In agreement with Bakker's theory of the causal relationship between temporal sequencing and reading disability, other workers have also reported that reading disabled children exhibit impairments in auditory/verbal but not in visual/non-verbal sequencing ability. Gould and Glencross (1990) studied 20 reading disabled elementary school children who scored at least 2 years below chronological age on the Neale Analysis of Reading Accuracy Test. The children had at least average Verbal, Performance or Full Scale WISC-R IQ scores. They were matched for age and IQ with normal readers from the same classes. Two

sequencing tasks were administered: Hebb's Digits, in which the subject must repeat each of 32 sequences of digits with every third one being the same; and Corsi Blocks, in which the subject must tap out each of 32 block tapping sequences, again with every third one being the same. The poor readers performed significantly worse than the good readers on Hebb's Digits, but there were no reading group differences on Corsi Blocks. When order of report was excluded and only percent of items correctly recalled was considered, there were no differences between normal and disabled readers. Further, the good readers did better on Hebb's Digits than on Corsi Blocks, but the poor readers performed similarly on both tasks. The authors concluded that while disabled readers do not have a general impairment in serial organization, they do show a specific deficit in verbal sequencing.

In several other studies in which auditory and visual or verbal and non-verbal sequencing tasks have been administered to the same reading disabled subjects, the findings fail to support Bakker's argument that the deficit underlying reading disability is specific to auditory/verbal sequencing. For instance, Corkin (1974) found that 6 to 11 year old inferior readers (boys) performed more poorly than did age-matched boys who were average readers on a digit span test (verbal sequencing), and on the Knox Cubes task (primarily nonverbal sequencing). It was concluded that

reading disorders arise from a general impairment in temporal sequencing that cuts across sensory modalities.

Gordon (1980) found Israeli reading disabled children to be impaired on both verbal and nonverbal sequencing tasks. Disabled readers over 7 years of age performed more poorly than normal readers on the WISC Digit Span subtest, and on a sequential reading test in which they were required to read Hebrew words according to the temporal rather than the spatial ordering of flashed letters. Furthermore, the disabled readers performed poorly on the Serial Sounds test, in which they were required to identify the temporal order in which sequences of environmental sounds were presented.

Zurif and Carson (1970) also reported results that are in opposition to Bakker's theory. Fourth grade boys who were either dyslexic or normal readers were administered the Rhythm subtest of the Seashore Measures of Musical Talents in which they were asked to judge whether two tapped out rhythmic patterns were the same or different, and a visual task in which they were asked to match temporal sequences of light flashes. In comparison to the normal subjects, the dyslexics were significantly inferior on both tasks.

Another study whose results were not consistent with Bakker's hypothesis was conducted by Denckla, Rudel, and Broman (1981). Eight to 10 year old boys who were dyslexic (performing at least 1.5 years below expectation on the Gray Oral Reading Test, based upon IQ score) were found to be impaired relative to non-dyslexic learning disabled boys

(performing between 5 months below expectation and above average on the Gray Oral Reading Test) on a task of matching temporal sequences of light flashes. The investigators concluded that dyslexics were better suited to simultaneous processing than sequential processing and seemed to have a left hemisphere deficit.

The studies described above were all concerned with the sequencing of input in various sensory modalities. The possibility exists that reading disabled children also have an impairment involving the sequencing of motor output. In fact, Denckla (1985) and Rudel (1985) have suggested that reading disabled children are deficient in a left hemisphere-dependent motor analyzer that is important for timed, sequential movements. In support of this hypothesis, Denckla (as described in Rudel, 1985) compared 6 to 14 year old dyslexics with 5 to 11 year old controls using rapid, timed, alternating movements of the feet, hand and fingers, as well as toe taps, hand pats, finger taps, heel toe alternation, and finger-thumb opposition sequences. On all measures except heel-toe alternation, the dyslexics were slower than controls. In another study, however, Denckla (1985) found that dyslexic children were slower than controls only at ages 7 and 8 years on the toe tap alternation task, and were slower than controls only at age 8 on finger-thumb opposition sequences.

There are several methodological issues which complicate interpretation of the studies described above.

First, different populations were compared in different studies. Whereas Bakker (1967) compared better readers with worse readers from a learning disabled population, Groenendaal and Bakker (1971) used only average readers, and other workers (e.g., Corkin, 1974; Gordon, 1980) compared inferior or disabled readers with normal readers. It would be expected that greater differences would be found between disabled and normal readers than within either of the two reading groups.

Second, the ages of the subjects varied across studies. Zurif and Carson (1970), for example, used only fourth graders, and Gordon (1980) used children 7 years old and above with no separate analysis for the different age levels. As Bakker (1972) reported a relationship between temporal order perception and chronological age, with better performance at older ages, comparisons among studies using different age groups are difficult.

Third, many studies have failed to adequately define reading disability and to use standardized, uniform criteria for the selection of subjects. For instance, Corkin's (1974) "inferior readers" were children who read consistently below grade level according to their teachers, excluding those with emotional disorders, general retardation or diagnosed brain lesions. However, no standardized reading test was administered to the children, as is required by the American Psychiatric Association criteria. Bakker (1967, 1972) defined reading groups

according to a reading test but failed to screen subjects for visual and auditory acuity, which could have confounded the results. Since children in the various studies were selected on the basis of different criteria as being reading disabled, the results of these studies cannot be compared nor any definitive conclusions drawn.

It should be noted that there is evidence from a different perspective that is suggestive of sequencing deficits in some reading disabled children. Kinsbourne and Warrington (1963) studied a group of reading disturbed children who showed evidence of the Gerstmann syndrome: they had poor performance on tests of finger differentiation and order, impairment in right-left orientation and in mechanical arithmetic, as well as constructional difficulty. They also showed impairments in writing, in that they were unable to form and copy letters properly. According to Kinsbourne and Warrington (1963), the difficulty in each of these tasks is essentially one of sequential ordering, and they postulated that the basis of the reading problem in a particular subgroup of reading disturbed children is a deficit in sequential ordering. These children also scored at least 20 points lower on the WISC Performance scale than on the Verbal scale.

The findings of this study raise several questions. As these children were not tested directly for sequencing ability, it is not clear whether sequencing difficulties were the basis of the reading problem or of the impairments

on the various tasks. In addition, it is not clear whether the deficits described by Kinsbourne and Warrington have any relationship to the sequencing deficits described by other investigators (see above); these authors may be describing a different subtype of dyslexia. Also, the finding of a lower Performance IQ than Verbal IQ, and the finding of very low scores on Block Design and Object Assembly subtests, suggests that these reading disabled children are likely to have had visuo-spatial deficits.

Visuo-Spatial Ability

Orton (1937) noted the frequent occurrence of right-left and upside-down errors in the reading of disabled readers and postulated that the basis for reading disorder was an orientation disability that stemmed from a delay in the establishment of cerebral dominance. Bender (1956) also proposed that a delay in the development of functional lateralization, resulting in impaired figure-ground organization, was associated with reading disability, and Hermann (1959) argued that faulty visuo-spatial processing was the cause of reading disability and was the result of a genetic predisposition toward directional confusion. Hermann further suggested that dyslexia might be a type of developmental Gerstmann syndrome, characterized by impaired right-left orientation and finger agnosia.

The findings regarding the question of whether reading disabled children show visuo-spatial deficits are

conflicting. Various investigators have noted impaired right-left orientation in disabled readers. Shankweiler (1963), for example, found that among 11 severely reading disabled children, 6 showed defective right-left discrimination as well as right-left reversals in reading. Of the 5 children with adequate right-left discrimination, only 2 showed reversals in reading. It has been suggested (Benton, 1984) that impairment in right-left orientation may be translated in some poor readers into a corresponding impairment in directional orientation in reading. Supportive evidence was provided by Benton and Kemble (1960), who found that 8 to 10 year old reading disabled children made errors in identifying lateral body parts of their own body (e.g., right and left hands) and those of another person. Harris (1957) also compared the performances of reading disabled and unselected children on a three-item test involving identification of single lateral body parts (e.g., right hand, left ear). Thirty-eight percent of 7-year-olds with reading disability made one or more errors, whereas only 5% of age-matched controls made one or more errors. However, only 10% of the 8-year-olds and 6% of the 9-year-olds with reading disability showed evidence of directional confusion, suggesting that directional confusion plays a role in reading disability only at younger ages (before 8 years of age). According to the findings of Hermann and Norrie (1958), however, 9 to 11 year olds with reading disability do not perform as well as

controls on a two item crossed commands task (right hand on left ear; left hand on right knee). Specifically, only 25% of the reading disabled children performed perfectly, whereas 57% of controls performed perfectly, suggesting that if reading disabled children do show deficits in right-left orientation, the impairment may in fact play a role after, as well as before, age 9. Benton (1984), however, has pointed out that impaired right-left orientation is not an important factor in many cases of reading disability.

Other investigators have argued that other aspects of spatial skills are impaired in those with reading disability. Pontius (1981) has reported that reading disabled children show a specific impairment on rotational tasks which require accurate spatial orientation. She compared dyslexics (aged 8 to 15 years) with normal readers (aged 8 to 12 years) on a task in which standard Bender-Gestalt figures were presented to the subject and had to be reproduced from memory at a 90 degree rotation to each side. The dyslexics made significantly more errors than normal readers in the rotation of appendage parts of the figures. In contrast, the dyslexic children's performance did not differ from that of normal readers on such variables as form reproduction and rotations of entire figures. Therefore, the errors made by the dyslexics were not due to motor impairment. According to Pontius, these errors reflect a deficit in visuo-spatial ability and, more specifically, a deficit in relationally specific

representation without any impairment in global spatial representation.

In contrast to these findings, there have been reports of superior or above average visuo-spatial ability in reading disabled children. Symmes and Rapoport (1972) found that 7 to 13 year old reading disabled children showed superior performance on tasks involving visual recognition and three-dimensional spatial visualization (e.g., Hiskey Spatial Relations and Visual Analogies subtests, ITPA Visual Reception and Visual Closure). The authors suggested that superior spatial visualization may lead to reading difficulty because of the tendency to relate forms to each other three dimensionally; for example, b and d are seen as the same three dimensional form and are therefore confused.

Superior visuo-spatial ability among poor readers was also reported by Gordon (1980), who found that reading disabled children over 7 years of age performed better than average on spatial tasks, including the Wechsler Block Design subtest, a form completion test, and a model orientation task in which the subject had to match photographs of three-dimensional models rotated with respect to each other. The same subjects exhibited below average performance on tests of verbal and nonverbal sequencing. In another study, Gordon and co-workers (Harness, Epstein, & Gordon, 1984) found that of 100 children referred to a clinic for reading disabilities, 97% performed better on visuo-spatial than on verbo-sequential tests. Performance

on visuo-spatial tests was an average of .5 standard deviations above the mean, whereas performance on verbo-sequential tests was an average of .5 standard deviations below the mean. Gordon (1984) claimed that a cognitive profile favoring visuo-spatial abilities is a necessary but not sufficient condition for reading disability.

In a later series of studies, Gordon (1988a, 1988b) administered a test battery consisting of the following types of visuo-spatial tasks: (a) a two-dimensional spatial orientation test in which the subject had to identify which two patterns were of similar orientation; (b) a localization test in which, after viewing an "x" within a rectangular space, the subject had to identify the position of the "x" on another, blank rectangle; (c) a block counting task in which the subject had to indicate how many blocks were touching a given block in a construction; and (d) a form completion test in which a pictured object had to be identified. The following types of verbo-sequential tasks were also administered: (a) Serial Sounds, in which the subject heard a series of environmental sounds and was required to write down the names of the sounds in their proper order; (b) Digit Span; (c) verbal fluency using letters; and (d) verbal fluency using semantic categories. For fourth and fifth grade children in mainstream classes, those who scored higher on the visuo-spatial tasks than on the verbo-sequential tasks performed more poorly on reading

and, to a lesser extent, language tests, relative to children who had the opposite cognitive profile (scoring higher on verbo-sequential than on visuo-spatial tasks). The groups did not differ in their performance on math tests. These results were obtained for children in a metropolitan and also in a non-metropolitan population. Gordon speculated that the results may relate to the relative efficiency with which the neurosystems subserving the two hemispheres contribute to problem solving.

The studies described above have several methodological problems. First, as was the case in temporal sequencing studies, reading disability was defined differently by different investigators. In addition, the criteria used for the selection of subjects differ across studies, and many of the criteria used are inadequate. Pontius (1981), for instance, defined reading disability as "difficulties in reading or writing in the presence of at least average intelligence" (p. 610), with no mention of how reading or writing difficulties were ascertained. In such studies, it is impossible to draw firm conclusions or to compare the results to those of any other study.

Second, the visuo-spatial tasks on which reading disabled children perform poorly might tap different abilities from those on which reading disabled children perform well. There is evidence that visuo-spatial ability is not a unitary phenomenon, and factor analytic studies have revealed at least two spatial factors (McGee, 1979).

For instance, spatial orientation has been described as either the ability to perceive spatial patterns or the ability to maintain orientation with respect to objects in space. It has been suggested (McGee, 1979; Sanders, Wilson & Vandenberg, 1982) that spatial orientation may be mediated by areas of the right hemisphere. Ratcliff (1979) demonstrated that men with right posterior lesions performed more poorly than men with left posterior lesions only when the spatial task required a mental re-orientation of the stimulus. On trials with the same stimuli which did not require rotation, the group with right hemisphere lesions was superior.

On the other hand, right-left orientation is considered to be a spatial function which is distinct from spatial orientation (see Lezak, 1983). Unlike spatial orientation, right-left orientation is disrupted in adults by left posterior lesions (see Lezak, 1983). This dissociation of various aspects of visuo-spatial ability may be partly responsible for the conflicting findings regarding the performance of reading disabled children on visuo-spatial tasks. Specifically, it appears that, with a few exceptions, most of the studies of right-left orientation found poor performance by disabled readers, whereas most of the studies of spatial orientation revealed superior performance by reading disabled subjects. It should be noted that these findings are consistent with the hypothesis of Geschwind and Galaburda (1987), who postulated that right

hemisphere mediated functions are enhanced among reading disabled subjects, whereas left hemisphere mediated functions are impaired. Thus, reading disabled children may in fact have poor right-left discrimination (left hemisphere mediated) but above average spatial orientation (right hemisphere mediated); however, none of the studies investigated these separate abilities in the same subject groups.

Summary

Various factors have been implicated in the etiology of reading disability, including alterations in cerebral dominance and/or functional lateralization, impaired verbal processing, deficient intersensory integration, impaired temporal sequencing, and poor visuo-spatial processing. There is much current controversy regarding the roles of temporal sequencing and of different aspects of visuo-spatial ability in the etiology of developmental reading disorder. The evidence presented above suggests that reading disabled children and normal readers perform differently on tests of temporal sequencing and visuo-spatial ability; however, the nature of these differences is not clear. A number of methodological problems, such as the use of different criteria for defining reading disability in different studies, contribute to the confusion in the literature and make comparisons across studies difficult. An additional problem is that, in the

studies described above, the subjects' hand preference was either not reported or only right handed subjects were used. As visuo-spatial and possibly sequencing abilities may vary according to hand preference (e.g., Levy, 1969), handedness should be considered in studies of reading disabled groups.

Handedness: General Considerations

Assessment and Classification

In studies of handedness in children, the method used to assess hand preference must be considered because the findings may vary as a function of the means of assessment. In most studies, one of five methods has been used. In one of these, the child or the child's teacher or relative is asked which hand the child prefers or which hand the child uses for writing. This allows classification that is either dichotomous (right-handed or left-handed) or trichotomous (right-, left-, or mixed-handed). The use of writing-hand to assess preference is of dubious reliability because at times there has been societal pressure, and even coercion, to write with the right hand (Porac, Coren & Searleman, 1986; and see review by Hardyck & Petrinovich, 1977). The use of self-report measures is also undesirable, as several workers have argued that self-reported left-handers tend to be a very variable group, which often includes right- and mixed-handed individuals (Benton, Meyers, & Polder, 1962; Satz, Achenbach, & Fennell, 1967). As a result, there have

been attempts to develop more systematic and objective ways of measuring hand preference.

One commonly used objective method is to assess the relative skill of the two hands on any of a variety of motor tasks. This method involves observation of the actual hand skill of the subject on tasks involving the relative speed or coordination of some controlled movement, such as peg moving (Annett, 1976; Barnsley & Rabinovitch, 1970). A continuously graded measure of handedness is generally provided, in which the degree of superiority of one hand over the other is indicated. Alternatively, a dichotomous or trichotomous classification may be used. It should be noted, however, that the hand that is found to be faster or better coordinated may not correspond to the one which is preferred by the subject. Thus, this method assesses hand skill, but not necessarily hand preference.

To better address the question of hand preference, several questionnaires have been devised (e.g., Annett, 1970; Harris, 1975; Oldfield, 1971). In the questionnaire (verbal report) method, the subject is presented with a list of activities ordinarily performed with one hand, and asked which hand he/she prefers for each of the activities. The subject is usually told that acceptable responses include "right", "left", or "both". A problem associated with hand preference questionnaires is that subjects' responses may not correspond to their actual performance, particularly in children. Therefore, some investigators have required

subjects to demonstrate behaviorally the activities listed in questionnaires (e.g., Subirana, 1961, cited in Hardyck & Petrinovich, 1977; Tan, 1985). This performance method would appear to be the most desirable one, especially when children are used as subjects.

The results of the questionnaire (verbal report) or performance methods allow classification of subjects into left-handed, right-handed and, possibly, mixed-handed and ambidextrous. Classification as left-handed generally requires the individual to meet a specified criterion; for example, when 6 of 10 activities are performed (or said to be performed) with the left hand. The investigator may require that certain activities, such as writing, be one of the six performed with the left hand. Classification as right-handed generally requires the individual to meet a specified criterion for right-handedness; for example, when 8 or 9 of 10 activities are performed with the right hand. Again, the investigator may specify that writing be one of the activities performed with that hand. Some investigators include three other categories in addition to the left-right dichotomy: ambidexterity, defined as having equal skill with the right and the left hands, in that many or most tasks are performed equally well with both hands; ambiguous handedness, defined as the lack of established hand preference; and mixed handedness, referring to mixed preference such that some tasks are routinely performed by

the right hand and some are routinely performed by the left hand.

It is important to note that, in many studies which utilize the questionnaire method, the number of tasks required to be performed with the preferred hand may be different for right- and left-handers. In general, the criterion for right-handedness is often stricter than that for left-handedness. The primary reason for this is that, depending on the area of research, it may not be clear whether strong left-handers (e.g., those performing 10 out of 10 tasks with the left hand) or weak left-handers (e.g., those performing 6 out of 10 tasks with the left hand) are the ones that differ from the right-handers. By using a less stringent criterion such as 6 of 10 activities, neither group would be excluded from the left-handed sample. In contrast, there would be no need to use such a lenient criterion for right-handed subjects.

Incidence of Left-Handedness

Incidence in the general population. The incidence of left-handedness is generally reported to be between 5% and 12% (Bryden, 1982), with a range of from 1% to 30% (according to a review by Hecaen & Ajuriaguerra, 1964). The specific figures vary depending upon the procedure used to assess handedness. Hardyck and Petrinovich (1977) classified the studies reviewed by Hecaen and Ajuriaguerra according to the methods used to determine handedness, and

concluded that the extremely high and extremely low estimates were based upon indirect determinations of handedness (such as eye dominance or strength of grip) or were unsupported by data. When performance measures were used to determine handedness, the results were more consistent, with the incidence of left-handedness being around 9 to 10% (see review by Hardyck & Petrinovich, 1977).

The incidence of left-handedness does not appear to have changed over the centuries. Coren and Porac (1977) have pointed out that the incidence, as evidenced in early works of art, has been 7 to 8% since 3000 B.C. However, there have been changes in the reported incidence of left-handedness from the earlier to the later part of the twentieth century, with an increase from about 5% to 9 or 10% in the United Kingdom and North America (see review by Bryden, 1982). However, this change can probably be accounted for by the fact that early studies were based upon self-reports of hand preference, and that children in the early part of the century were often pressured to write with their right hand.

There are cross-cultural differences in the incidence of left-handedness in children. For instance, Teng, Lee, Yang, and Chang (1976) found an incidence of only 1.5% among schoolchildren in Taiwan, where there is a strong pressure for left-handers to switch to the right hand. Hardyck, Goldman, and Petrinovich (1975) reported that, in California, 6.5% of Asiatic schoolchildren were left-handed,

compared to 9.9% for the total sample of California schoolchildren. This finding has been interpreted to reflect social pressure among Asiatics to use the right hand (Bryden, 1982). Dawson (1977) reported that in some fishing and hunting societies, such as that of the Alaskan Eskimo, the incidence of left-handedness is 10%. However, in agricultural societies, such as the Hong Kong Hakka, the incidence was 1 to 3%.

The incidence of left-handedness has also been reported to vary between the sexes. Most reports indicate a higher incidence in males than in females. For example, Hardyck, Goldman, and Petrinovich (1975) found that, in a large sample of California schoolchildren (n = 3960), the incidence of left-handedness in boys was 10.5% whereas that in girls was 8.7%. Based on a survey of almost 6500 schoolchildren in Britain, McManus (1981) found a 12.8% incidence of left-handedness in boys and a 10.6% incidence in girls. When small sample sizes are used, however, a sex difference may not be found, or there may be a difference in the opposite direction (according to a review by Annett, 1985). Annett (1985) concluded that "there can be no reasonable doubt that males are more likely to be left-handed than females, but by a small margin (p. 77)."

Incidence in the reading disabled. There have been numerous reports of a higher incidence of left-handedness in children with reading disability than in normal readers. For example, Rutter, Tizard, and Whitmore (1970) studied 86

children with reading disability and found 8 (9.3%) to be left-handed, whereas only 7 (4.8%) of 147 normal readers were left-handed. However, although the incidence of left-handedness was about twice as high for the reading disabled group as for the normal group, the difference was not statistically significant, possibly because of the relatively small sample size.

For larger samples, significant differences between reading groups have been obtained, again with the incidence of left-handedness being about twice as high in reading disabled children as in normal readers. Naidoo (1972) found an 18% incidence of left-handedness among children attending a clinic for reading disability in England, and only a 9% incidence among control children. Hallgren (1950) also found an 18% incidence among reading disabled children in Sweden, but a 9% incidence in controls. Granjon-Galifret and Ajuriaguerra (1951) found significantly more reading disabled 7 to 10 year old, but not 11 to 13 year old, French children who had mixed laterality than was true for controls. In the United States, Harris (1957) found that reading disabled children were more often mixed-handed than were control children.

In some studies, however, when left- and right-handers have been compared on reading achievement, no differences have been found (e.g., Hartlage & Green, 1971; Lyle & Johnson, 1976). For example, Heydorn (1984) reported no differences in reading achievement, measured by performance

on the Gates MacGinitie Reading Test, between left- and right-handed 6 to 7 year old children. Clark (1970, cited in Annett, 1985) compared the reading test scores of 1544 left-, right-, and mixed-handed Scottish children at 7 years of age, and found no differences in reading scores between handedness groups. However, when 19 retarded readers with normal IQ were tested 2 years later, 15.8% of them were found to be left-handed, compared with 8.8% for all children in the original sample.

Similar findings were reported by Annett and Turner (1974), who tested 100 right-handed and 100 left-handed children. The groups did not differ in performance on a reading test. However, those children whose reading test standard scores were at least 30 points below their IQ comprised 15% of the left-handers but only 6.1% of the right-handers. Annett's (1985) interpretation was that "one cannot argue from laterality to reading skill--but one can argue from poor reading skill to laterality" (p. 87).

Other studies, however, have started with hand preference and then investigated history of reading difficulties and have found differences. In particular, Geschwind and Behan (1982; 1984) reported that the incidence of reading difficulties was 10 times higher among strong left-handers than among strong right-handers. According to Geschwind and Galaburda (1985a), even a minor deviation from strong right-handedness was associated with a sharp rise in the frequency of dyslexia. Thus, a more likely

interpretation of the studies investigating the association between reading ability and handedness is that overall reading ability does not differ between left- and right-handed individuals. However, the reading disorder described previously, whether it is labeled as developmental reading disorder, specific reading disability, or dyslexia, is associated with left-handedness, regardless of whether one argues from reading ability to handedness or from handedness to reading ability.

Cognitive Correlates of Handedness

Left-handedness has long been associated with cognitive deficits, even in populations of normal readers in which few cognitive deficits would be expected (see Harris, 1980). The question of cognitive differences between right- and left-handers has been of particular interest because of a hypothesis, advanced by Levy (1969, 1974), that verbal and spatial processes are in competition with each other. That is, optimal cognitive functioning occurs when linguistic and sequential functions are represented in the left hemisphere and visuo-spatial functions are represented in the right hemisphere. If either of these abilities is represented bilaterally, it is hypothesized to interfere with the other type of cognitive ability. For instance, if language is represented in the right as well as the left hemisphere, competition between linguistic and spatial functions will

occur in the right hemisphere, and its ability to process visuo-spatial information will be compromised. Thus, individuals who perform both functions in the same hemisphere would be expected to be deficient in one or the other function relative to more completely lateralized individuals. As bilateral representation of language and possibly of spatial functions occurs more frequently in left-handed than in right-handed individuals (Goodglass & Quadfasel, 1954; Hecaen & Sauguet, 1971), it would be expected, according to Levy's hypothesis, that left-handers would be deficient in one or the other ability relative to right-handers.

Temporal Sequencing

Temporal sequencing skills have not generally been assessed in studies of handedness in populations of normal readers. There are reasons to expect, however, that left- and right-handers might differ in sequencing ability. It has been well established that left-handers are more likely to possess bilateral and right hemisphere language representation than are right-handers (Goodglass & Quadfasel, 1954; Hecaen & Sauguet, 1971). There are data which indicate that individuals with right hemisphere speech representation do not process verbal sequential material as well as those who have left hemisphere speech representation (see Zaidel, 1978). It would therefore be expected that

left-handers as a group might be deficient in sequencing skills compared to right-handers.

Some investigators have hypothesized that, among left-handed subjects, left-hemisphere mediated cognitive functions (e.g., language) are weaker due to delayed growth of the left hemisphere, possibly as a result of excess testosterone prenatally (e.g., Geschwind & Galaburda, 1987). As sequencing has been demonstrated to depend primarily on the left cerebral hemisphere (Efron, 1963; Kim, 1976), it would be expected to be impaired in left-handed subjects.

Furthermore, several studies have indicated that left-handed subjects have poorer language and syntactic skills than do right-handers (Briggs, Nebes, & Kinsbourne, 1976; Heim & Watts, 1976), presumably because there is competition between the cerebral hemispheres in left-handers during linguistic activities (Moscovitch, 1977). As sequencing is an important component of language, it would be of interest to determine whether left- and right-handed children differ in temporal sequencing abilities.

Visuo-Spatial Ability

The cognitive ability most frequently studied in relation to handedness has been spatial ability. Levy (1969) offered evidence that left-handed adults have poor visuo-spatial ability but normal verbal ability. She found that male science graduate students who classified themselves as left-handed performed more poorly on the WAIS

Performance scale (mean IQ = 117) than did students who classified themselves as right-handed (mean IQ = 130), whereas the performance of the two groups on the WAIS Verbal scale did not differ (mean IQ = 142 for left-handers, mean IQ = 138 for right-handers).

In a study of undergraduate students, Bradshaw, Nettleton, and Taylor (1981) found significantly lower scores on the WAIS Performance scale among left-handers (mean IQ = 115.5) than among right-handers (mean IQ = 120). Left-handers have also been reported to score lower than right-handers on the NIIP Form Relations Test (Miller, 1971), on Cattell's Culture Fair Intelligence Test (Hicks & Beveridge, 1978), and on the DAT Space Relations subtest (Sherman, 1979).

In contrast, a superiority of visuo-spatial skills in left-handed adults was reported by Herrmann and Van Dyke (1978), who required self-reported left- and right-handers to judge visual patterns as the same or different when they were presented in different orientations. Left-handers were faster than right-handers in matching the pattern as well as the orientation of the figures, contradicting the hypothesis that left-handers have impaired spatial skills. Similarly, Porac and Coren (1981) found that left-handed university students performed better than right-handers on a test of mental rotation of three dimensional patterns, while Sanders, Wilson, and Vandenberg (1982) found that left-handed men performed better than right-handed men on a

task involving imagining the rotations of figures. Geschwind and Galaburda (1985a; 1987) have argued that some left-handed individuals may have superior spatial talents as evidenced by the high incidence of left-handedness in certain professions requiring spatial skills (Peterson & Lansky, 1980), including visual artists (Peterson, 1979), architects (Peterson & Lansky, 1974), and mathematicians (Annett & Kilshaw, 1972).

Numerous other studies have failed to find any handedness-related differences in visuo-spatial abilities. For example, Gibson (1973) found no differences between the performances of left- and right-handed graduate science students and academic scientists on the WAIS Performance Scale. Other studies have also failed to find differences between left- and right-handers on the WAIS (Newcombe & Ratcliff, 1973), as well as on Raven's Standard Progressive Matrices Test (Chattopadhyay, Mazumder, & Biswas, 1983).

Studies of children have generally failed to support the hypothesis of spatial deficits in left-handers. For instance, Roberts and Engle (1974) reported no differences between left- and right-handed 6- to 11-year-olds on the WISC Block Design subtest, and Fagan-Dubin (1974) found no differences between left- and right-handed 5- to 6-year-olds on the WISC Performance Scale.

Several methodological problems complicate interpretation of the studies of visuo-spatial ability in left-handers. First, some investigators used self-report or

observation of the hand used for writing (e.g., Herrmann & Van Dyke, 1978) to identify left- and right-handers. The difficulties with these methods to assess handedness have been noted earlier, and may be responsible for some of the failures to find differences in cognitive ability between handedness groups.

Second, Bemporad and Kinsbourne (1983) have noted that, in studies which do use verbal report questionnaires or performance measures to assess handedness, some use a very narrow definition of left-handedness so that those showing a cognitive deficit may be excluded from the study. For example, Newcombe and Ratcliff (1973) required that left-handers routinely perform all items of a seven item questionnaire with the left hand, and no differences were found on the WAIS Performance scale. However, there is some evidence indicating that those who are weakly left-handed or mixed-handed may be the ones who show cognitive deficits (Swanson, Kinsbourne, & Horn, 1980).

Third, whereas some investigators classify handedness solely on the basis of the subjects' hand preference, others consider familial handedness as well (Briggs, Nebes, & Kinsbourne, 1976). In fact, difference in cognitive functions between those with and those without a family history of left hand preference have been found (see Bryden, 1982). These differences may be especially pronounced for left-handed individuals (Bradshaw, Nettleton, & Taylor, 1981). However, the relationship between familial

handedness and cognitive functioning has not been studied systematically in children.

Another difficulty in studies of the relationship between spatial ability and handedness is that, as noted above in relation to reading disability, a wide variety of tasks are used to assess spatial ability; however, there is evidence that visuo-spatial ability is not a unitary phenomenon (McGee, 1979). It is possible that left-handers may be deficient in some aspects of spatial processing but not in others, and therefore may perform poorly on only certain visuo-spatial tasks. In this regard, Johnson and Harley (1980) found that left-handers performed more poorly than right-handers on certain spatial tests but not on others. According to Geschwind and co-workers (Geschwind & Behan, 1982; Geschwind & Galaburda, 1985a, 1987), because there is slowed left hemisphere development in left-handers, left-handers exhibit poor left hemisphere skills and enhanced right hemisphere skills. As spatial orientation is mediated by areas of the right hemisphere, and right-left orientation is mediated by the left hemisphere, one would expect that these two aspects of visuo-spatial ability would be dissociated in studies of handedness. Hermann and Van Dyke (1978) did, in fact, find that left-handed adults were faster than right-handers on a task of spatial orientation, whereas Elze (1924a, 1924b, cited in Benton & Kemble, 1960) found that adults who report confusion in right-left orientation are often ambidextrous. However, it is not

clear whether this is the case in children, or if the findings would be similar if the two types of tasks were administered to the same groups of subjects.

Summary

There is evidence that suggests that left-handed individuals may exhibit either deficits or superiority in visuo-spatial functions compared to right-handers, and that impairment or superiority may be limited to certain aspects of visuo-spatial function. It is possible that left-handers have difficulty with right-left orientation but perform well on spatial orientation tasks. Although temporal sequencing ability has not generally been assessed in relation to handedness, there is evidence that suggests that left-handers as a group might exhibit sequencing impairments.

It is possible that, even if differences in cognitive function are not consistently found between right- and left-handers in the general population, there might be differences in certain abilities between right- and left-handed reading disabled children.

Reading Disability, Handedness, and Cognitive Ability

Reading Disability, Handedness, and Temporal Sequencing

Few studies have investigated whether left- and right-handed reading disabled children differ in sequential

processing, but there are some suggestions that they do. Badian and Wolff (1977) compared the performance of left- and right-handed dyslexic and normal boys (aged 8 to 15 years) on motor sequencing tasks in which the subjects were required to tap two keys in time to the beat of a metronome, either with the left or right hand alone or alternating hands. Left- but not right-handed dyslexics were more impaired on single hand trials than on alternating hand trials. However, left- and right-handed dyslexics were not reported to differ in their overall level of sequencing ability.

There have been other suggestions of a relationship between reading disability, handedness, and sequencing ability. Bemporad and Kinsbourne (1983) proposed that the dyslexic subtype characterized by a difficulty with sequential ordering (Kinsbourne & Warrington, 1963) may be associated with a high incidence of left-handedness. The basis for this suggestion is unclear, as Kinsbourne and Warrington (1963) noted a high incidence of left-handedness in their reading disabled subjects who showed sequential ordering deficits and in those who showed language deficits. The authors did not, however, indicate the number of left-handers in the sample.

Healey (personal communication) offered preliminary evidence indicating that left-handed children with developmental reading disorder are impaired in a particular aspect of motor sequencing. She administered a variety of

cognitive tests to left- and right-handed reading disabled children matched for age and IQ and found that the left-handed children were most impaired in copying sequences of words and sentences and were completely unable to write to dictation. Only one of seven left-handed reading disabled children showed evidence of a language impairment, whereas six of seven right-handed children had language deficits. The small sample size and the absence of a control group of normal readers renders these findings inconclusive; clearly, further investigation of motor sequencing ability in left- and right-handed reading disabled children is warranted.

It should be noted that Geschwind and Galaburda's (1985a; 1987) hypothesis predicts an interaction between reading ability, handedness, and temporal sequencing. According to their theory, reading disabled children and left-handers are at risk for left hemisphere syndromes. As sequencing has been shown to depend primarily on the left hemisphere (Efron, 1963; Kim, 1976), one would expect both left- and right-handed reading disabled children, as well as left-handed normal readers, to have poorer temporal sequencing abilities than right-handed normal readers. This, however, has never been tested directly.

Reading Disability, Handedness, and Visuo-Spatial Ability

A few workers have noted a possible relationship between reading disability, left-handedness, and

visuo-spatial deficits. In a study of reading disabled children, Doehring (1968) found that when he removed the data of the left-handed subjects, the previously found significant difference between reading disabled children and normal readers on right-left discrimination was no longer obtained. This suggests that the left-handed children had the most difficulty with these tasks, but, again, this was not tested directly.

It should also be noted that, according to Geschwind and Galaburda's (1985a; 1987) hypothesis, there is a relationship between reading disability, handedness, and visuo-spatial skills. Reading disabled children and left-handers should exhibit superior right-hemisphere skills, including visuo-spatial ability. Thus, left- and right-handed reading disabled children and left-handed normal readers should exhibit enhanced visuo-spatial skills compared to right-handed normal readers. However, this aspect of the hypothesis has not been tested directly.

Bemporad (1986) found no evidence of differences between right- and left-handed reading disabled children on the Karnovsky Test of Mental Rotation or on a variety of other spatial tests including the Wechsler Performance IQ and the Wechsler Performance scale subtests. However, a wide age range (7 to 21 years of age) was used and no control group of normal readers was included.

Summary

In sum, no adequate study has been conducted to determine whether interactions exist between reading ability, handedness and temporal sequencing ability, nor between reading ability, handedness and visuo-spatial skills. The few studies which have dealt with these questions either failed to control for age of subjects, failed to include a comparison group of normal readers, or have other methodological flaws which render the findings inconclusive. Should such interactions exist, they may have implications for classifying reading disabled children into subtypes based upon whether the children are right- or left-handed. Although subtypes of reading disability have not usually been based upon hand preference, right- and left-handedness have been associated with different patterns of brain organization (e.g., Bryden, 1982). It is possible that the differences in brain organization could provide the basis of reading disability subtypes.

Hypotheses and Questions

The purpose of the present study was to examine certain aspects of cognitive functioning in children who were poor and average readers, and who were left-handers as well as right-handers. More specifically, the present study examined temporal sequencing skills and visuo-spatial skills in left- and right-handed poor and average readers. The

hypotheses and questions which were addressed are described below.

Reading Ability and Temporal Sequencing

Because it has been argued that reading disability results from a deficit in temporal sequencing skills (e.g., Bakker, 1972) and because reading disabled children have been found to perform less well on sequencing tasks than normal readers (e.g., Corkin, 1974; Denckla, Rudel, & Broman, 1981; Gordon, 1980; Gould & Glencross, 1990), poor readers in the present study were expected to perform more poorly than average readers on a variety of temporal sequencing tasks, including verbal and nonverbal, auditory and visual, and motor sequencing tasks. Specifically, it was hypothesized that poor readers would perform more poorly than average readers on tasks of auditory verbal sequencing, visual verbal sequencing, visual nonverbal sequencing, and motor sequencing.

Handedness and Temporal Sequencing

As left-handers may have weak left-hemisphere functioning (e.g., Geschwind & Galaburda, 1987), and as temporal sequencing has been demonstrated to depend primarily on the left cerebral hemisphere (Efron, 1963; Kim, 1976), children who are left-handed were expected to perform more poorly on tasks of temporal sequencing than children who are right-handed.

Reading Ability, Handedness, and Temporal Sequencing

Some workers have suggested a relationship between reading ability, handedness, and temporal sequencing (Bemporad & Kinsbourne, 1983; Healey, personal communication). However, the evidence is conflicting with respect to the nature of a possible interaction between reading ability and hand preference. Thus, although specific predictions cannot be made, the question of whether poor and average readers differ in temporal sequencing task performances depending upon whether the children are left- or right-handed was addressed in the present study.

Reading Ability and Visuo-Spatial Ability

Because directional confusion has been thought to be a cause or at least a correlate of reading disability (e.g., Hermann, 1959), because right-left reversals in reading have been found among reading disabled children (Shankweiler, 1963), and because reading disabled children have been found to exhibit impairments in right-left orientation (Benton & Kemble, 1960; Harris, 1957), children who are poor readers were expected to show poorer performance on a task of right-left orientation than children who are average readers.

In contrast, conflicting evidence exists with regard to reading group differences in spatial orientation (see earlier section). Thus, although a specific prediction cannot be made, the question of the relationship between

reading disability and spatial orientation skills, as measured by performance on a spatial orientation memory task, was examined in the present study.

Handedness and Visuo-Spatial Ability

As it has been proposed that left-handers exhibit poor left hemisphere cognitive skills (Geschwind & Galaburda, 1987), and as right-left orientation has been found to be mediated primarily by the left cerebral hemisphere (see Lezak, 1983), left-handed children were expected to exhibit poorer performance the right-left orientation task than right-handers.

In contrast, as it has been proposed that left-handers show enhanced right hemisphere cognitive skills (Geschwind & Galaburda, 1987), and as spatial orientation has been found to be mediated by areas of the right cerebral hemisphere (Ratcliff, 1979; Sanders, Wilson, & Vandenberg, 1982), left-handed children were expected to perform better the spatial orientation task than right-handed children.

Reading Ability, Handedness, and Visuo-Spatial Ability

As there are some suggestions that left-handed reading disabled children have particular difficulty on tasks of right-left discrimination (Doehring, 1968), left-handed poor readers were expected to perform more poorly on a task of right-left orientation than both right-handed poor readers and right- and left-handed average readers.

In contrast, as it has been hypothesized that left-handed individuals and reading disabled individuals have enhanced right hemisphere functioning, including visuo-spatial skills (Geschwind & Galaburda, 1987), and as spatial orientation has been demonstrated to depend on areas of the right cerebral hemisphere (Ratcliff, 1979; Sanders, Wilson, & Vandenberg, 1982), left- and right-handed poor readers and left-handed average readers were expected to perform better on the spatial orientation task than right-handed average readers.

Method

Subjects

The subjects were forty six 7.5 to 11.5 year old boys who attended one of six elementary schools in a middle class public school district in Queens, New York. The rationale for the use of boys only was that both reading disability and left-handedness have been found to be more common in boys than in girls (Benton, 1975; Bettman, Stern, Whitsell, & Gofman, 1967; and see Introduction section). The children were all students in regular classes and, according to the children and their teachers, were all fluent in English. Permission for the children to participate in the study was granted by the District Superintendent, the school Principal, and the child's teacher; informed consent was given by each child's parent or guardian (see Appendix A). In addition, oral agreement to participate in the study was obtained from each child. As an incentive to volunteer, each child was promised and given an inexpensive, 5 and 10 cent store variety digital watch upon completion of the testing session.

Subject groups were established according to reading ability and hand preference. There were 23 poor readers ($n = 12$ right-handed and $n = 11$ left-handed) and 23 average readers ($n = 12$ right-handed and $n = 11$ left-handed). Reading ability was determined by performance on a standardized, individually administered reading test

relative to performance on a standardized, individually administered test of nonverbal intelligence. This criterion was based on studies which indicate that children with specific reading disability perform poorly on reading tests/tasks relative to performance on nonverbal intelligence tests, whereas normal readers show no discrepancy between reading and nonverbal intelligence test scores (Rutter & Yule, 1976).

Hand preference was determined by performance of 10 activities listed in a standardized handedness questionnaire. The criterion for right-handedness was more strict (at least 9 of 10 items performed with the right hand) than the criterion for left-handedness (at least 6 of 10 items performed with the left hand). This difference in criterion was based upon findings that indicate that whereas most right-handers are strongly right-handed, left-handers are frequently mixed handed or ambidextrous (see Hardyck & Petrinovich, 1977; and see Introduction section).

All subjects were required to show at least average nonverbal intelligence test performance, and to demonstrate normal visual and auditory acuity. Children with evidence of gross neurological disorders, serious emotional problems, or attention deficit hyperactivity disorder were not included in the sample. An attempt was made to obtain city wide reading scores and familial handedness history for each subject; however, as this information could be obtained for

fewer than one third of the subjects, these variables were not taken into consideration in the selection of subjects.

Procedure for Subject Selection

The procedure for selection of subjects involved the following steps:

1. In each of the six schools, boys in regular second through fifth grade classes were considered potential subjects and, whenever possible, a preliminary screening to identify potential subjects by handedness and reading skill was carried out. This involved questioning both the children and their teachers regarding the hand preferences of the children. Teachers were also asked to identify boys who were either average or poor readers. Those boys reported to be right- or left-handed, and to be average or poor readers were given informed consent forms to have signed by their parent or guardian. In two of the six schools, this initial screening was not possible and therefore, informed consent forms were distributed to as many boys as possible in the second through fifth grades without regard to handedness or reading ability. In these cases, a question was included on the form asking the parent whether his/her child was right- or left-handed.

2. For those children who received parental permission to participate in the study, the files containing physicians and teachers reports were screened, if available. Children with documentation of gross neurological disorder, serious

emotional problems, Attention Deficit Hyperactivity Disorder, a history of school absenteeism, or uncorrected visual or auditory defects were excluded. When records were unavailable, this information was obtained from the teachers, the Principal, or from the parent.

3. Each child who received parental permission and who himself agreed to participate in the study was then examined individually in one 40 to 45 minute screening session. The screening was conducted in a quiet room in the school building with only the child and an examiner present. The following tests were administered, in the order listed, for all children, with a 2 to 4 minute break provided between tests.

a) Coloured Progressive Matrices Test (Raven, Court, & Raven, 1986). This test was designed as a measure of nonverbal general intellectual ability in children, and it has been normed on children between 7 and 11 years of age. It was specifically chosen for this study because it requires no reading or other verbal responses and it correlates significantly with the Wechsler Intelligence Scale for Children (Performance IQ score) ($r = .70$; Birkemeyer, 1965) and with the Stanford-Binet ($r = .68$; Phillips & Bannon, 1968). For each of the 36 test items, the subject is shown a picture with a piece cut out of it, and six choices below it, one of which correctly completes the stimulus pattern. The subject's task is to point to the one choice which correctly completes the pattern. The score

on the test is the number of correct items out of 36, which is then standardized according to the child's age.

b) Gray Oral Reading Test-Revised, Form B (Wiederholt & Bryant, 1986). This is a widely used test of oral reading and comprehension in children, which has been standardized on large numbers of children within the age range used in the present study and is considered to be among the best available reading tests. The subject is required to read aloud a series of increasingly difficult paragraphs, and to answer five multiple choice comprehension questions following each paragraph. The starting paragraph varies depending on the age of the child, and it is necessary that the child answer all five questions correctly following the simplest paragraph read, and that he answer no more than two out of five correctly following the most difficult paragraph read. Thus, a different number of paragraphs are read by each child depending on his age and comprehension score. A total reading quotient is based on the speed and accuracy of oral reading, as well as on the total number of comprehension questions answered correctly.

c) Harris Tests of Lateral Dominance, Test 2: Hand Preferences (Harris, 1975). This test was chosen as it is one of the few handedness questionnaires that has been standardized and normed on children of the age range used in the present study. The test assesses the subject's hand preference by the hand used to perform 10 unimanual activities, as follows: writing one's name, throwing a ball,

using a toothbrush, using a comb, using an eraser, cutting with a knife, using a scissor, winding a watch, hammering a nail, and turning a doorknob. Each of the items to be used was placed in front of the child, at the midline, and the child was asked to show the examiner how he performed each of the activities.

d) Visual Acuity screening measure. Twenty letters, half upper- and half lower-case, were printed on a single page which was shown to the child. The letters were identical in size and typeface to the printing used in the stories of the Gray Oral Reading Test-Revised (see Appendix B). As the examiner pointed to each letter in turn, the child was asked to orally identify the letter. A child was included in the sample only if he correctly identified at least 18 of the 20 letters; all children screened met this criterion.

e) Auditory Acuity screening measure. Twenty words were read aloud to the child (see Appendix C). The child was asked to repeat each word immediately after hearing it. The words were taken from a second grade reading text and were pretested on three second graders, who were able to repeat the words. A child was included in the sample only if he correctly identified at least 18 of the 20 words; all children screened met this criterion.

Scores on the screening tests were used in forming four groups of subjects: right-handed average readers,

right-handed poor readers, left-handed average readers, left-handed poor readers.

Poor readers were defined by a significant discrepancy between reading test scores and nonverbal intelligence test scores, with the standard score on the Gray Oral Reading Test-Revised at least 1.5 standard deviations (22 points) below the standard score on the Coloured Progressive Matrices Test. Additionally, no poor reader scored above 91 on the Gray Oral Reading Test-Revised, or below 84 on the Coloured Progressive Matrices Test. Thus, in addition to a discrepancy between reading test performance and nonverbal intelligence test performance, normal intelligence was a criterion for inclusion in the sample. Other workers have used IQ cutoffs ranging from 80 (Mattis, French, & Rapin, 1975) to 85 (Pavlidis, 1990a). It should be noted that the children selected as poor readers had not been diagnosed as such, but rather were classified, for purposes of this study, on the basis of the criteria described above.

Average readers were defined by the absence of a performance discrepancy between reading test score and nonverbal intelligence test score. Specifically, average readers had standard scores on the Gray Oral Reading Test-Revised which were no more than five points below their standard scores on the Coloured Progressive Matrices Test. In addition, no average reader scored below 84 on the Coloured Progressive Matrices Test.

In order to be considered left-handed, a child was required to perform at least 6 of the 10 unimanual activities on the Harris Test of Lateral Dominance with the left hand. It was necessary that writing be one of those activities. In order to be considered right-handed, a child was required to perform at least 9 of the 10 activities with the right hand, including writing. As there was no information on familial handedness history, it is likely that the groups of both right- and left-handed children consisted of some with and some without familial left-handedness. Further, there were no measures of either the strength or the consistency of hand preference.

Description of the Sample. The screening tests were administered to a total of 108 children. Of these, 46 children (12 right-handed average readers, 12 right-handed poor readers, 11 left-handed average readers, 11 left-handed poor readers) met all of the criteria described above and were used as subjects.

The ages of the four groups of subjects are presented in Table 1. A 2 (Reading Group) x 2 (Handedness) Analysis of Variance was performed on the age variable. There were no statistically significant age differences between reading groups ($F(1, 42) = .03, n.s.$), between handedness groups ($F(1, 42) = .08, n.s.$), or in their interaction ($F(1, 42) = .01, n.s.$).

Table 2 shows the scores on the Gray Oral Reading Test-Revised for the four groups of subjects. A 2 (Reading

Table 1

Ages (Years) of Handedness and Reading Groups

Group	n	Mean	SD	Range
Right-handed				
Average Readers	12	9.6	1.36	7.6 to 11.4
Right-handed				
Poor Readers	12	9.5	1.32	7.8 to 11.3
Left-handed				
Average Readers	11	9.5	1.09	7.5 to 11.0
Left-handed				
Poor Readers	11	9.4	1.21	8.1 to 11.5
Marginals				
Right-handers	24	9.6	1.31	7.6 to 11.4
Left-handers	22	9.4	1.12	7.5 to 11.5
Average Readers	23	9.5	1.22	7.5 to 11.4
Poor Readers	23	9.5	1.24	7.8 to 11.5
Total	46	9.5	1.21	7.5 to 11.5

Table 2

Standard Scores on the Gray Oral Reading Test-Revised (Form B) of Handedness and Reading Groups

Group	n	Mean	SD	Range
Right-handed				
Average Readers	12	108.2	12.93	91 to 136
Right-handed				
Poor Readers	12	75.1	10.11	50 to 88
Left-handed				
Average Readers	11	106.0	9.10	91 to 118
Left-handed				
Poor Readers	11	75.4	11.53	52 to 91
<u>Marginals</u>				
Right-handers	24	91.7	20.39	50 to 136
Left-handers	22	90.7	18.63	52 to 118
Average Readers	23	107.2	11.07	91 to 136
Poor Readers	23	75.3	10.56	50 to 91
<u>Total</u>	46	91.2	19.36	50 to 136

Group) x 2 (Handedness) Analysis of Variance was applied to the GORT-R scores. As expected, there was a highly significant main effect of reading group ($F(1, 42) = 95.55$, $p < .001$), with average readers scoring higher than poor readers. The GORT-R scores of the left- and right-handed children did not differ significantly ($F(1, 42) = .08$, n.s.), and the interaction between reading group and handedness ($F(1, 42) = .16$, n.s.) was not statistically significant.

The standard scores on the Coloured Progressive Matrices Test are presented in Table 3. A 2 (Reading Group) x 2 (Handedness) Analysis of Variance failed to reveal a difference in test scores between reading groups ($F(1, 42) = 2.33$, n.s.), between handedness groups ($F(1, 42) = .02$, n.s.), or in their interaction ($F(1, 42) = 1.66$, n.s.). However, as there was a seven point difference between the mean score of the left-handed average readers ($M = 100.2$) and the left-handed poor readers ($M = 107.2$), a one-way Analysis of Variance was performed for these two groups. The higher score of the poor readers was statistically significant ($F(1, 42) = 5.58$, $p = .03$); therefore, score on the Coloured Progressive Matrices Test was used as a covariate in all analyses of the dependent measures.

The difference scores between the Gray Oral Reading Test-Revised and the Coloured Progressive Matrices Test (GORT-R score minus CPMT score) are shown in Table 4. A 2 (Reading Group) x 2 (Handedness) Analysis of Variance was

Table 3

Standard Scores on the Coloured Progressive Matrices Test of Handedness and Reading Groups

Group	n	Mean	SD	Range
Right-handed				
Average Readers	12	103.1	11.42	89 to 123
Right-handed				
Poor Readers	12	103.7	7.26	90 to 113
Left-handed				
Average Readers	11	100.2	7.39	84 to 110
Left-handed				
Poor Readers	11	107.2	6.48	99 to 117
Marginals				
Right-handers	24	103.4	9.37	89 to 123
Left-handers	22	103.7	7.67	84 to 117
Average Readers	23	101.7	9.60	84 to 123
Poor Readers	23	105.4	6.98	90 to 117
Total	46	103.5	8.50	84 to 123

Table 4

Difference Between Reading and Nonverbal Intelligence Test Scores (GORT-R minus CPMT scores) of Handedness and Reading Groups

Group	n	Mean	SD	Range
Right-handed				
Average Readers	12	5.2	8.27	-5 to 24
Right-handed				
Poor Readers	12	-28.6	6.05	-40 to -22
Left-handed				
Average Readers	11	5.8	6.88	-3 to 18
Left-handed				
Poor Readers	11	-31.7	13.51	-64 to -22
<u>Marginals</u>				
Right-handers	24	-11.7	18.64	-40 to 24
Left-handers	22	-12.9	21.88	-64 to 18
Average Readers	23	5.5	7.47	-5 to 24
Poor Readers	23	-30.1	10.19	-64 to -22
<u>Total</u>	46	-12.3	20.03	-64 to 24

performed on the difference scores. As reading groups were chosen on the basis of a 22 point (1.5 SD) discrepancy between GORT-R and CPMT scores, the statistically significant difference between average and poor readers was expected ($F(1, 42) = 177.45, p = .001$), with poor readers showing a significantly greater discrepancy than average readers. There was no evidence of a difference in discrepancy of scores between the left- and right-handers ($F(1, 42) = .22, n.s.$) and no significant interaction between handedness and reading group ($F(1, 42) = .50, n.s.$).

Table 5 shows the number of items (out of 10) which were performed with the preferred hand (right or left) on the Handedness portion of the Harris Test of Lateral Dominance. A 2 (Reading Group) x 2 (Handedness) Analysis of Variance revealed a significant effect of handedness ($F(1, 42) = 43.94, p < .001$), with right-handers performing more items with the preferred right hand than left-handers performed with the preferred left hand. However, on average, the difference between the right- and left-handers was only 1.4 items. There was no difference in the number of items performed with the preferred (right or left) hand between reading groups ($F(1, 42) = .67, n.s.$) and no significant interaction between handedness and reading group ($F(1, 42) = .67, n.s.$).

Table 5

Number of Items Performed With The Preferred (Right or Left) Hand on the Harris Test of Lateral Dominance for Handedness and Reading Groups

Group	n	Mean	SD	Range
Right-handed				
Average Readers	12	9.8	.39	9 to 10
Right-handed				
Poor Readers	12	9.8	.39	9 to 10
Left-handed				
Average Readers	11	8.2	1.17	6 to 10
Left-handed				
Poor Readers	11	8.6	.82	7 to 10
Marginals				
Right-handers	24	9.8	.38	9 to 10
Left-handers	22	8.4	1.00	6 to 10
Average Readers	23	9.0	1.19	6 to 10
Poor Readers	23	9.2	.90	7 to 10
Total	46	9.1	1.05	6 to 10

Experimental Tasks and Testing Procedure

Five temporal sequencing tasks and two visuo-spatial ability tasks were administered to each of the 46 subjects. For each of the five sequencing tasks, the child was required to reproduce sequences ranging in length from two through eight items, presented in an ascending series, with three different sequences (trials) of each length. For each task, testing began with a sequence length of two for all subjects and was discontinued when a child made sequence errors on all three trials of a given length. The tasks were as follows:

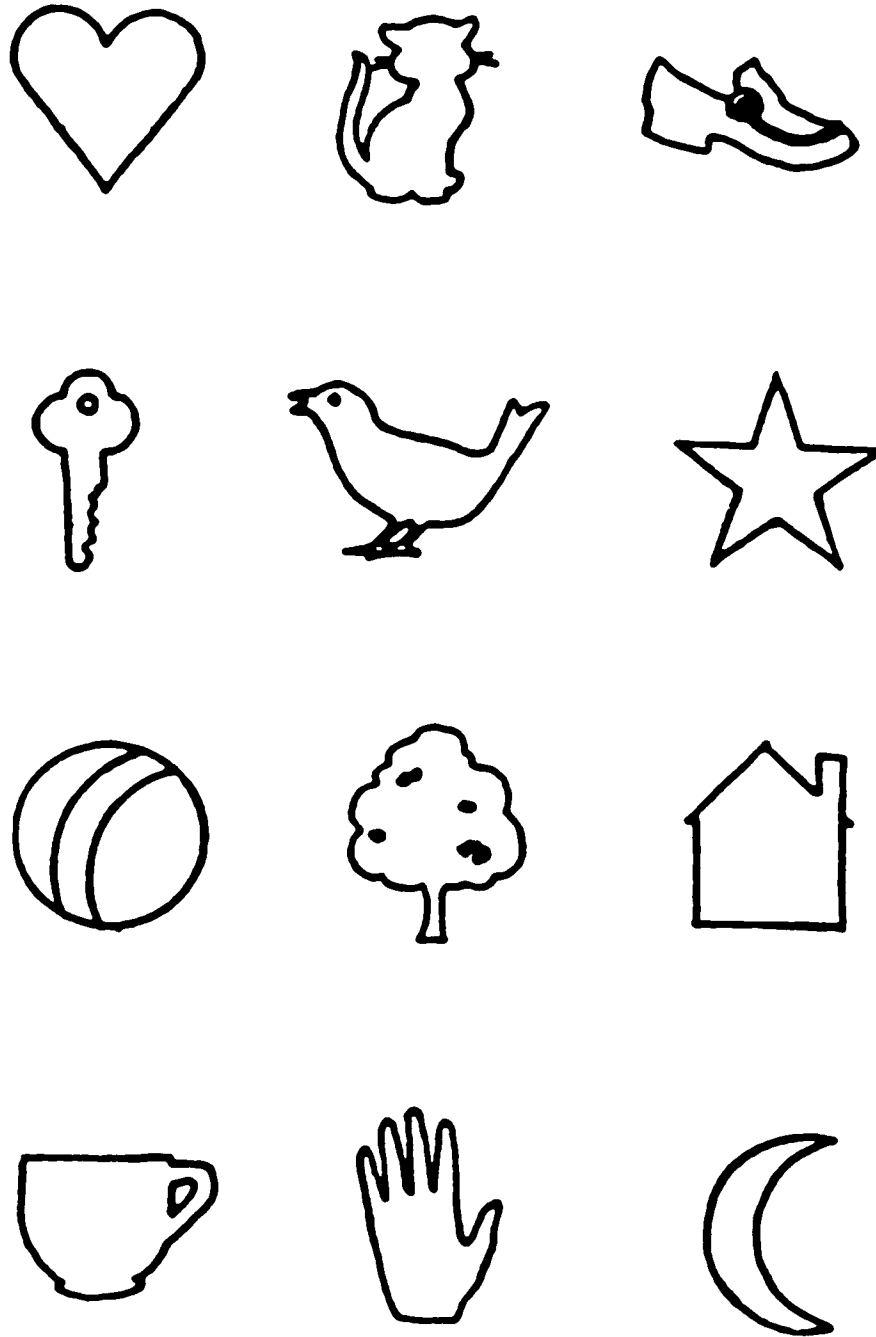
1. Auditory Verbal Sequencing (Digits): This task was largely based on the Number Recall subtest of the Assessment Battery for Children (Kaufman & Kaufman, 1983), which is widely used and has been standardized on large numbers of children. The test requires the subject to repeat sequences of digits spoken by the examiner. Digits are presented at a rate of one per second. In order for the timing to be as exact as possible and still be consistent with the standardized procedure for administration, the examiner followed the timing of a stopwatch while administering each sequence to the subject. The Number Recall subtest was modified in the following ways in order to match the other sequencing tasks used in this study: (a) two eight-digit sequences were added so that there were three trials of each length, from two through eight, and (b) testing began with a sequence length of two for all subjects and was discontinued

when a child made sequence errors on all three trials of a given length.

2. Auditory Verbal Sequencing (Words): This task required the subject to repeat sequences of words heard on an audio tape. The following 12 words were used: cat, house, shoe, tree, moon, key, heart, ball, bird, hand, cup, star. These words were taken from the Word Order subtest of the Assessment Battery for Children (Kaufman & Kaufman, 1983). The words were pre-tested with three second grade children, who were able to correctly match each word with a corresponding picture (see below). It should also be noted that each word is from a different semantic category. A female voice was used to record the words on tape. Before testing the children used as subjects in the study, two adults verified that all the words were clearly audible on the tape. The words were presented at a rate of one every 2 seconds, with the timing checked against a stopwatch.

3. Visual Verbal Sequencing: This task required the subject to reproduce, by pointing to pictures, the order of prior slide presentations of a sequence of line drawings of familiar objects, which were outlines of the figures used in the Word Order subtest of the Assessment Battery for Children (Kaufman & Kaufman, 1983). The following 12 pictures (line drawings) were used: cat, house, shoe, tree, moon, key, heart, ball, bird, hand, cup, star (see Figure 1). These items were the same as those used in the Auditory Verbal Sequencing (Words) task. Three second grade children

Figure 1. Stimuli used in the Visual Verbal Sequencing Task



were pretested with these stimuli, and all of them easily identified the pictures as the objects which they represented; two adults also correctly identified (named) the pictures.

The apparatus for projection of the slides consisted of a Kodak Carousel 800 projector with a Lafayette (Model 43016) shutter. The slide projector was connected to a timer (Lafayette Model 43011/16 shutter control), a power supply (International Power, 1HB5, 3 amps), and a counter. The timer allowed the duration of the stimulus as well as the length of the interstimulus interval to be controlled exactly. The number of slides to be shown in any given sequence was set manually prior to showing that sequence.

Each stimulus within each trial sequence was shown for a duration of 1 second, with an interstimulus interval of 1 second. The order of the items in each sequence was similar for the Visual Verbal and Auditory Verbal (Words) Sequencing tasks, although the sequences were presented in a different order. (It should be noted that the Visual Verbal and Auditory Verbal (Words) Sequencing tasks were separated from each other by other tests during the testing session in order to minimize intertask facilitation).

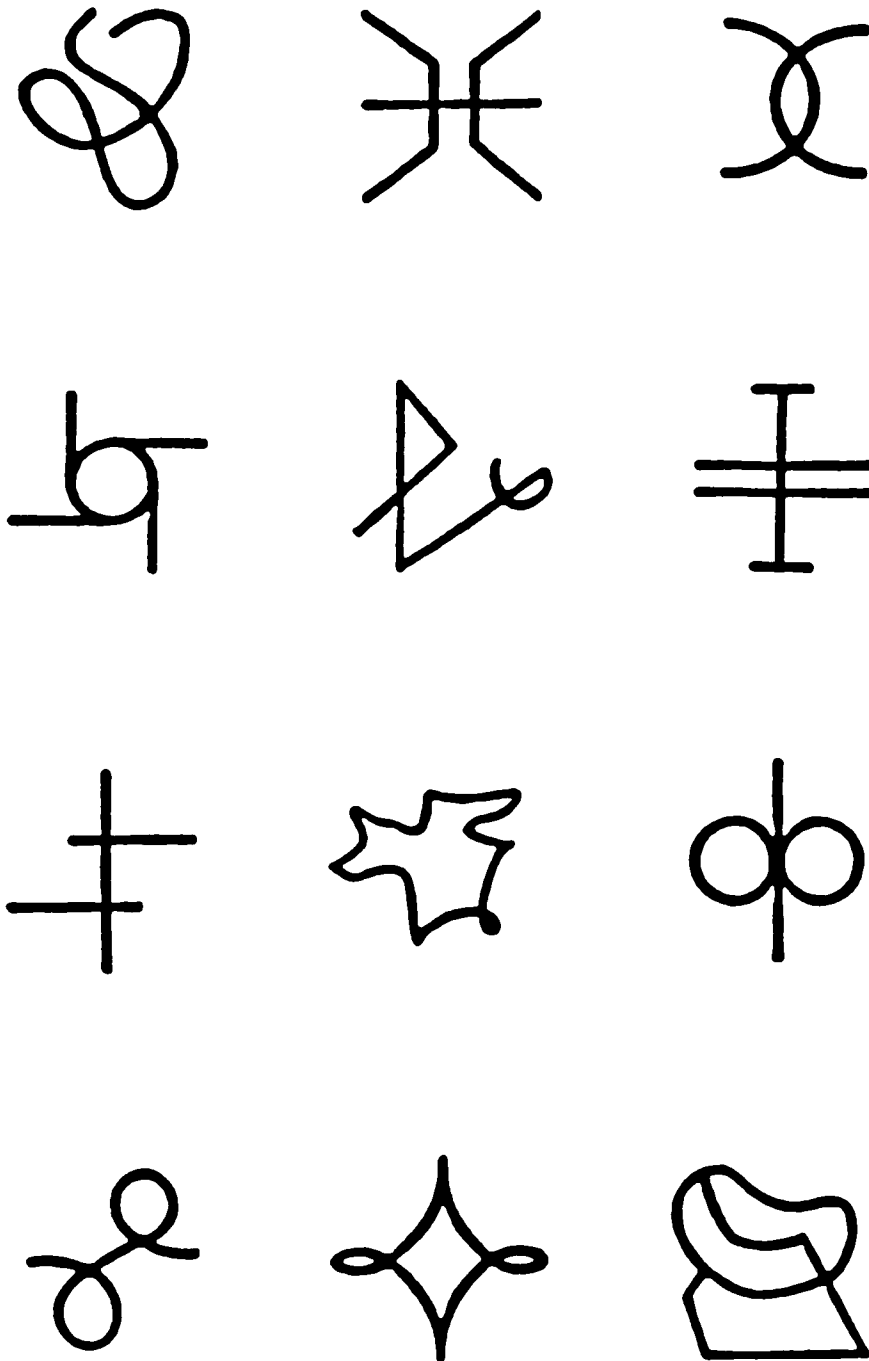
The drawings were projected in black outline, at a size of approximately 11 inches in height by 11 inches in width, onto a white screen which was 22 inches in height by 28 inches in width. The subject was seated at a distance of 6 feet from the screen, with the center of the screen at eye level.

The response consisted of identification of the stimulus sequences by pointing, as follows: after presentation of each sequence of slides, the examiner exposed a page on a desk in front of the child on which the same line drawings were shown. The pictures were arranged in a horizontal row in pseudo-random order, with no picture following another on the page if it followed the other in the stimulus sequence. The child was told to point to the pictures on the page in the same order in which he had seen them on the screen. After the child pointed to the pictures, a blank page was then exposed while the next sequence was shown on the screen.

4. Visual Nonverbal Sequencing. This task required the child to reproduce, by pointing, the order of prior slide presentation of line drawings of nonsense shapes. The 12 figures (see Figure 2) were taken from two sources: the Visual Paired Associates subtest of the Wechsler Memory Scale-Revised (Wechsler, 1987), and the Visual Sequential Memory subtest of the Illinois Test of Psycholinguistic Abilities (Kirk, McCarthy, & Kirk, 1974). Prior to testing the children, five adults were pre-tested; none verbally labeled any of the nonsense shapes. The stimuli were matched with those of the Visual Verbal Sequencing task on the basis of size and approximate thickness of the lines in the drawings.

The apparatus and the procedure for administration of the Visual Nonverbal Sequencing task was identical to that

Figure 2. Stimuli used in the Visual Nonverbal Sequencing Task



of the Visual Verbal Sequencing task. The two tasks were matched on the basis of the position of correct responses on paper for each trial.

5. Motor Sequencing. This task required the subject to copy finger opposition sequences demonstrated by the examiner. While sitting opposite the child, the examiner demonstrated each finger opposition sequence (thumb to finger) using the hand on the same side as the subjects' preferred hand. For example, the examiner's right hand was on the same side of space as the child's left hand, so for a left-handed child, the examiner used his/her right hand. The sequences were presented at a rate of one finger movement every 1.5 seconds, and the timing was monitored continuously by a stopwatch. After viewing the sequence, the child was required to copy the sequence using his preferred hand.

6. Right-Left Orientation Test (Benton, Hamsher, Varney, & Spreen, 1983). This 20 item test assesses the subject's knowledge of right and left body parts, both his own and those of the examiner (see Figure 3). This particular test was chosen because it does not require an oral response by the subject, thereby minimizing the role of expressive language in performance on the test. The subject is asked to identify different body parts either on the right or left side. Four types of identifications are tested: (a) own body parts, ipsilaterally (e.g., "Show me your right hand"); (b) own body parts, crossing the midline

Figure 3. Items used in the Right-Left Orientation Test

Own Body

1. Show me your left hand.
2. Show me your right eye.
3. Show me your left ear.
4. Show me your right hand.
5. Touch your left ear with your left hand.
6. Touch your right eye with your left hand.
7. Touch your right knee with your right hand.
8. Touch your left eye with your left hand.
9. Touch your right ear with your left hand.
10. Touch your left knee with your right hand.
11. Touch your right ear with your right hand.
12. Touch your left eye with your right hand.

Examiner's Body

13. Point to my right eye.
14. Point to my left leg.
15. Point to my left ear.
16. Point to my right hand.
17. Put your right hand on my left ear.
18. Put your left hand on my left eye.
19. Put your left hand on my right shoulder.
20. Put your right hand on my right eye.

(e.g., "Touch your right knee with your left hand"); (c) examiner's body parts, ipsilaterally (e.g., "Point to my left hand"); and (d) examiner's body parts, crossing the midline (e.g., "Point to my left ear with your left hand").

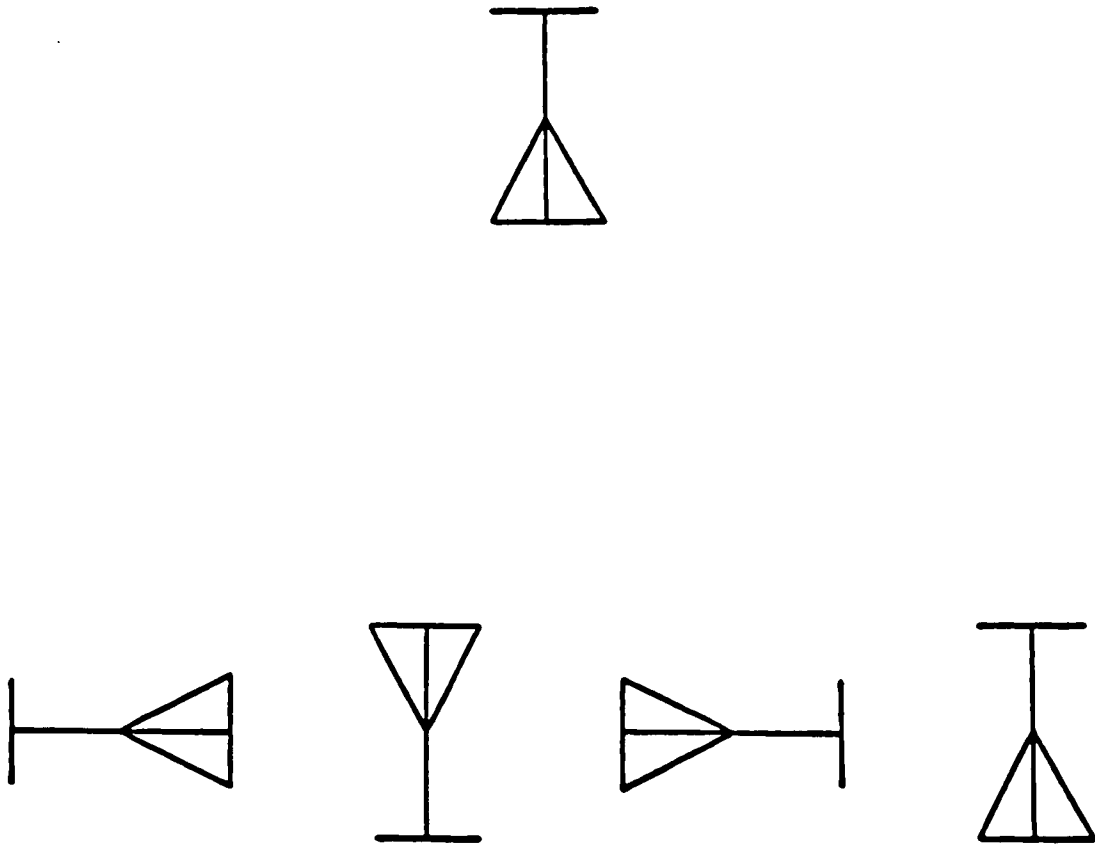
7. Spatial Orientation Memory Test (Wepman & Turaidis, 1975). This 20 item test assesses the child's ability to recall the spatial orientation of forms presented visually and has been extensively normed on children within the age range used in the present study. The test consists of a 5 second presentation of a single visual stimulus (a geometric form) on a page. The child is then shown another page on which there is a multiple choice array of the same form in different orientations, one of which matches the orientation of the original stimulus. The task is for the child to identify the design which is rotated in the identical direction as the stimulus form (see Figure 4).

The seven tasks were administered in the following order for all children: (a) Auditory Verbal Sequencing (Words) Task; (b) Spatial Orientation Memory Test; (c) Visual Verbal Sequencing Task; (d) Right-Left Orientation Test; (e) Visual Nonverbal Sequencing Task; (f) Auditory Verbal Sequencing (Digits) Task; and (g) Motor Sequencing Task. The testing session lasted approximately 45 minutes, with 2 to 4 minute breaks between tests.

Response Measures

For each of the five sequencing tasks, the response

Figure 4. Sample item from the Spatial Orientation Memory Test



measure used was the number of sequences reproduced or identified correctly. For the Right-Left Orientation Test, the response measure was the number of items responded to correctly, with one half point being given for an initial error with a quick, spontaneous change to a correct response. For the Spatial Orientation Memory Test, the response measure was the number of correct items.

Data Analyses

As scores on the Coloured Progressive Matrices Test differed significantly between left-handed average and poor readers (see Page 81 and Table 3), this score was covaried out in all analyses.

For each of the five sequencing tasks, a 2 (Reading Group) x 2 (Handedness) Analysis of Covariance was performed on the number of sequences reproduced correctly. Additionally, for each child, a mean composite sequencing score was calculated by combining the scores on the five sequencing tests. A 2 (Reading Group) x 2 (Handedness) Analysis of Covariance was then performed on the composite sequencing scores.

For the Right-Left Orientation Test, a 2 (Reading Group) x 2 (Handedness) Analysis of Covariance was performed on the number of correct responses. For the Spatial Orientation Memory Test, another 2 (Reading Group) x 2 (Handedness) Analysis of Covariance was applied to the number of correct items. In addition, a mean composite

spatial score was calculated from the number of correct responses on the Right-Left Orientation Test and on the Spatial Orientation Memory Test for each subject. A 2 (Reading Group) x 2 (Handedness) Analysis of Covariance was then performed on the composite spatial scores.

Because prior empirical evidence strongly supported the prediction that poor readers would show a sequencing deficit (e.g., Bakker, 1967, 1972; Bakker & Schroots, 1981; Gordon, 1988a, 1988b), a one-tailed test was used for assessing the differences in sequencing task scores between average and poor reading groups in the Analyses of Covariance. For all other analyses, two-tailed tests were used. Differences were considered statistically significant if they reached or exceeded the .05 level of confidence.

Results

Temporal Sequencing Tasks (Table 6)

Means and standard deviations were calculated for the number of sequences reproduced correctly for each of the five temporal sequencing tasks as well as for the composite of the five tasks. Scores were subjected to a 2 (Handedness) x 2 (Reading Group) Analysis of Covariance, using the standard score on the Coloured Progressive Matrices Test as the covariate.

Auditory Verbal Sequencing (Digits). Average readers scored significantly higher on Auditory Verbal Sequencing (Digits) than did poor readers ($M = 12.7$ for average readers; $M = 10.8$ for poor readers) ($F(1, 41) = 8.87, p = .003$). There was a non-significant trend ($F(1, 41) = 3.12, p = .085$) for right-handers ($M = 12.3$) to perform better than left-handers ($M = 11.1$). There was no evidence of a significant interaction between handedness and reading group ($F(1, 41) = 1.82, n.s.$); that is, the superiority of average over poor readers was similar for left- and right-handers.

Auditory Verbal Sequencing (Words). Right-handers performed significantly better on Auditory Verbal Sequencing (Words) than did left-handers ($M = 10.3$ for right-handers; $M = 8.8$ for left-handers) ($F(1, 41) = 6.39, p = .015$). There was a non-significant trend towards better performance by average readers ($M = 9.9$) than by poor readers ($M = 9.3$)

Table 6

Number of Sequences Reproduced Correctly for Each of Five Sequencing Tasks and for the Five-Task Composite Sequencing Score

Group	n	Sequencing Task					Com- posite Seq. Score	
		Aud. Verb. (Dig)	Aud. Verb. (Word)	Vis. Verb.	Vis. Non- verb.	Motor		
Right-handed Average Readers	12	M SD	12.9 2.11	10.8 2.38	9.2 2.69	7.4 2.11	8.5 2.20	9.8 1.64
Right-handed Poor Readers	12	M SD	11.8 3.25	9.8 2.12	7.5 2.81	5.5 1.24	6.3 1.97	8.2 1.44
Left-handed Average Readers	11	M SD	12.4 2.21	9.0 1.61	9.3 2.87	6.0 2.00	6.4 1.97	8.6 1.33
Left-handed Poor Readers	11	M SD	9.7 1.95	8.6 2.11	7.7 1.90	6.3 2.15	6.1 2.91	7.7 1.78
<u>Marginals</u>								
Right-handers	24	M SD	12.3 2.74	10.3 2.26	8.3 2.82	6.5 1.96	7.4 2.32	9.0 1.71
Left-handers	22	M SD	11.1 2.47	8.8 1.84	8.5 2.50	6.1 2.03	6.3 2.43	8.2 1.61
Average Readers	23	M SD	12.7 2.12	9.9 2.19	9.2 2.71	6.7 2.14	7.5 2.29	9.2 1.58
Poor Readers	23	M SD	10.8 2.84	9.3 2.16	7.6 2.37	5.9 1.74	6.2 2.41	7.9 1.59
<u>Total</u>	46	M SD	11.7 2.66	9.6 2.18	8.4 2.65	6.3 1.98	6.9 2.42	8.6 1.70

($F(1, 41) = 2.34, p = .067$). There was no significant interaction between handedness and reading ($F(1, 41) = .00, n.s.$), indicating that the superiority of right- over left-handers was similar for average and poor readers.

Visual Verbal Sequencing. Average readers performed significantly better on the Visual Verbal Sequencing task than did poor readers ($M = 9.2$ for average readers; $M = 7.6$ for poor readers) ($F(1, 41) = 5.82, p = .01$). Right- and left-handers did not differ significantly ($F(1, 41) = .04, n.s.$). There was no evidence of a significant interaction between handedness and reading group ($F(1, 41) = .05, n.s.$).

Visual Nonverbal Sequencing. Average readers obtained significantly higher mean scores than poor readers on the Visual Nonverbal Sequencing task ($M = 6.7$ for average readers; $M = 5.9$ for poor readers) ($F(1, 41) = 5.59, p = .01$). There was no evidence of a difference between the scores of right- and left-handers ($F(1, 41) = .50, n.s.$), and no evidence of an interaction between handedness and reading group ($F(1, 41) = 2.18, n.s.$).

Motor Sequencing. Average readers scored significantly higher on the motor sequencing task ($M = 7.5$) than did the poor readers ($M = 6.2$) ($F(1, 41) = 3.46, p = .04$). There was a non-significant tendency toward better performance by right-handers ($M = 7.4$) than by left-handers ($M = 6.3$) ($F(1, 41) = 2.83, p = .10$), but no evidence of a significant

interaction between handedness and reading group ($F(1, 41) = 1.56, n.s.$).

Composite Sequencing. Average readers correctly reproduced or identified significantly more sequences, overall, than did the poor readers ($M = 9.2$ and $M = 7.9$ for the average and poor readers, respectively) ($F(1, 41) = 11.39, p = .001$). There was a tendency towards better performance by right-handers ($M = 9.0$) than by left-handers ($M = 8.2$) ($F(1, 41) = 3.65, p = .06$) but no evidence of an interaction between handedness and reading group ($F(1, 41) = .04, n.s.$).

Summary of Results: Sequencing Tasks. Average readers performed significantly better than poor readers on four of the five sequencing tasks; specifically, on Auditory Verbal Sequencing (Digits), Visual Verbal Sequencing, Visual Nonverbal Sequencing, and Motor Sequencing tasks. On the Auditory Verbal (Words), there was a non-significant trend ($p = .067$) for average readers to obtain higher scores than poor readers. On the Composite Sequencing measure, average readers scored significantly higher than poor readers.

Right-handers performed significantly better than left-handers on only one of the five sequencing tests, the Auditory Verbal (Words) task. However, there was a trend towards better performance by right- than by left-handers on both the Auditory Verbal (Digits) task ($p = .085$) and on the motor sequencing task ($p = .10$). There were no differences in performance between the right- and left-handers on either

of the two visual sequencing tasks. On the composite sequencing measure, right-handers showed a non-significant tendency to score better than left-handers ($p = .06$).

There were no interactions between handedness and reading group for any sequencing task nor for the composite sequencing measure.

Visuo-Spatial Tasks (Table 7)

Means and standard deviations were calculated for the number of correct items on each of the two spatial tasks as well as for a composite of the two tasks. Scores were subjected to a 2 (Handedness) x 2 (Reading Group) Analysis of Covariance, using the standard score on the Coloured Progressive Matrices Test as the covariate.

Right-Left Orientation Test. Left-handers scored significantly higher ($M = 16.7$) than right-handers ($M = 14.5$) on the Right-Left Orientation Test ($F(1, 41) = 4.58$, $p = .04$). Average readers and poor readers did not differ significantly ($F(1, 41) = 2.69$, n.s.). The superiority of left-handers over right-handers was similar for average and poor readers, as shown by the lack of a significant interaction between handedness and reading group ($F(1, 41) = .13$, n.s.).

Spatial Orientation Memory Test. On the Spatial Orientation Memory Test, there was no evidence of a difference in performance between average and poor readers ($F(1, 41) = .99$, n.s.) or between the performances of

Table 7

Number of Correct Responses for Each of Two Visuo-Spatial Tests and for the Two-Test Composite Spatial Measure

Group Score	n	Visuo-Spatial Task			
		Right-Left Orientation	Spatial Orientation	Composite Spatial	
Right-handed Average Readers	12	<u>M</u> <u>SD</u>	15.7 4.00	12.1 3.80	13.9 3.08
Right-handed Poor Readers	12	<u>M</u> <u>SD</u>	13.2 4.49	10.9 3.06	12.1 3.10
Left-handed Average Readers	11	<u>M</u> <u>SD</u>	16.9 2.78	12.6 2.94	14.8 2.33
Left-handed Poor Readers	11	<u>M</u> <u>SD</u>	16.5 2.30	13.1 3.21	14.8 2.29
<u>Marginals</u>					
Right-handers	24	<u>M</u> <u>SD</u>	14.5 4.34	11.5 3.43	13.0 3.15
Left-handers	22	<u>M</u> <u>SD</u>	16.7 2.50	12.9 3.01	14.8 2.26
Average Readers	23	<u>M</u> <u>SD</u>	16.3 3.45	12.4 3.35	14.3 2.72
Poor Readers	23	<u>M</u> <u>SD</u>	14.8 3.90	12.0 3.25	13.4 3.01
<u>Total</u>	46	<u>M</u> <u>SD</u>	15.5 3.72	12.2 3.27	13.8 2.87

right- and left-handers ($F(1, 41) = 2.12, n.s.$). In addition, there was no evidence of a significant interaction between handedness and reading group ($F(1, 41) = .13, n.s.$).

Composite Spatial Measure. Overall, left-handers obtained a significantly higher composite score on the two spatial ability tests than did right-handers ($M = 14.8$ for left-handers; $M = 13.0$ for right-handers, as shown in Table 7) ($F(1, 41) = 5.20, p = .03$). Average readers showed a trend towards higher scores compared to poor readers ($M = 14.3$ for average readers; $M = 13.4$ for poor readers ($F(1, 41) = 2.81, p = .10$). There was no evidence of a significant interaction between reading ability and handedness ($F(1, 41) = .42, n.s.$).

Summary of Results: Visuo-Spatial Tasks. Left-handers performed significantly better than right-handers on the Right-Left Orientation Test, but there was no handedness group difference on the Spatial Orientation Memory Test. On the Composite Spatial Measure, the performance of left-handers was significantly superior to that of right-handers. There was no evidence of differences between poor and average readers on either of the spatial tests, nor was there evidence of a significant interaction between handedness and reading group for either spatial task.

Discussion

The results of the present study provide evidence of a relationship between reading ability and cognitive functioning and between handedness and cognitive functioning in 7.5 to 11.5 year old boys. The findings are reviewed and discussed below in relation to the questions posed and hypotheses advanced in the Introduction, first with respect to temporal sequencing and then with respect to visuo-spatial ability.

Reading Ability and Temporal Sequencing

In the present study, it was expected that children who are poor readers would perform more poorly on verbal sequencing tasks than children who are average readers. The obtained results are largely supportive of this hypothesis. Poor readers performed significantly worse than average readers on the Auditory Verbal Sequencing (Digits) task, in which sequences of digits had to be reproduced orally, and on the Visual Verbal Sequencing task, in which sequences of pictures had to be reproduced by pointing. The impairment shown by the poor readers on these two verbal tasks is consistent with Bakker's (1967, 1971, 1972) argument and evidence that reading disability results from a deficit in verbal sequencing skills, as well as with a number of other reports of impaired verbal sequencing performance of reading disabled children (e.g., Gould & Glencross, 1990).

Comparison of the performances of the two reading groups on a third verbal sequencing task provided additional support for the hypothesis of verbal sequencing deficits among poor readers. On the Auditory Verbal Sequencing (Words) task, which involved sequences of words rather than digits, the poor readers showed a tendency to perform worse than the average readers ($p = .067$). As this finding did not attain the conventional level of statistical significance (i.e., $p \leq .05$), the Auditory Verbal (Words) task may have been slightly less sensitive to reading group differences than was the Auditory Verbal (Digits) task, because of certain methodological differences between the two tasks. The main differences between the tasks were that, first, the stimuli for the Words task were presented to the children on an audio tape, rather than being spoken by the examiner as in the Digits task; and second, in the case of the Words task, the stimuli were presented at the rate of one every two seconds, whereas for the Digits task, items were presented at the rate of one per second. Although it seems unlikely that the taped stimuli would have rendered the Words task less sensitive to group differences in reading ability, it is possible that the longer interval between stimuli for the words task might have had that effect. It has been suggested, both for patients with left hemisphere lesions (Efron, 1963) as well as for reading disabled children (May, Williams, & Dunlap, 1988; Tallal, 1980), that sequencing problems may stem from subjects

requiring more time to perceive temporal order. If this is in fact the difficulty of the poor readers in this study, then the Auditory Verbal (Words) task might have enhanced the performances of these children by allowing them more time to process the temporal sequence. Whether or not this interpretation is correct, the present results clearly indicate a verbal sequencing impairment among children with reading disability.

In the present study, it was also expected that children who are poor readers would perform more poorly on nonverbal sequencing tasks than children who are average readers. This expectation was supported by the findings: the children who read poorly performed significantly worse than the average readers on both the Visual Nonverbal Sequencing task, in which the stimuli to be reproduced were pictures of nonsense shapes, and on the Motor Sequencing task, in which finger opposition sequences had to be reproduced. These results are in agreement with the impaired nonverbal sequencing performances by reading disabled children reported by several other investigators (e.g., Corkin, 1974; Denckla, Rudel, & Broman, 1981; Gordon, 1980).

The findings of impaired performance on verbal as well as nonverbal sequencing tasks by children with reading disability has implications for understanding the basis of the sequencing impairment of poor readers. They suggest that the sequencing impairment exhibited by these children

is not material specific, i.e., it is present regardless of whether the stimuli are verbal, familiar, and meaningful, or nonverbal, unfamiliar, and meaningless. Thus, contrary to the contention that poor readers have difficulty with certain stimuli (e.g., linguistic or visuo-spatial stimuli), poor readers appear to have difficulty with a certain type of cognitive processing (i.e., sequential processing). Further, if sequential processing is mediated primarily by the left cerebral hemisphere (Efron, 1963; Kim, 1976), and reading disabled children exhibit left hemisphere dysfunction (e.g., Bakker, 1972; Denckla, Rudel, & Broman, 1981), then the present finding of deficient performance of poor readers on the Visual Nonverbal Sequencing task suggests that the notion of left hemisphere processing of meaningful and/or verbal stimuli and right hemisphere processing of meaningless and/or nonverbal stimuli might not be accurate. This general notion has been based, in large part, on evidence that left hemisphere damaged patients perform poorly on tasks involving meaningful, verbal stimuli (DeRenzi, Faglioni, & Previdi, 1977), whereas right hemisphere damaged patients have more difficulty on tasks involving meaningless, nonverbal stimuli (Kimura, 1963). The present findings suggest that each hemisphere, rather than being specialized for the processing of a particular type of material, may be specialized for a type of processing, with the left hemisphere being specialized for sequential processing. According to this hypothesis,

reading disabled children have impaired left hemisphere (sequential) processing of information. Alternatively, it is possible that reading disabled children may have one or more dysfunctions involving both hemispheres, which are manifested in tasks involving temporal order sequencing. If this is the case, then sequential processing of verbal information might be carried out in the left hemisphere and sequential processing of nonverbal material in the right hemisphere. As the present study did not directly address the issue of cerebral lateralization of function, further study would be necessary in order to distinguish between these alternatives.

The present finding of impaired performance of poor readers on tasks of nonverbal sequencing provides evidence against the view of Bakker (1967, 1971, 1972) that the sequencing impairment among reading disabled children is limited to verbal or verbally codifiable stimuli. In Bakker's (1967) study, differences between "better" and "worse" readers were obtained for the sequencing of letters, meaningful figures, and digits, but not for meaningless figures. Gould and Glencross (1990) also reported that poor readers were impaired on verbal sequencing but performed as well as controls on tasks of nonverbal sequencing. Methodological differences between these studies and the present one could be responsible for the differences in results. For example, Bakker (1967) used "better" and "worse" readers from a learning disabled population, with no

control group of normal readers and no control for IQ. In a later study (Groenendaal & Bakker, 1971), a control for IQ was added and, although 7 year old poor readers were impaired on verbal but not nonverbal sequencing tasks, the 10 year old poor readers were impaired on both types of sequencing tasks. In the nonverbal task (Corsi blocks) in Gould and Glencross' (1990) study, temporal order was confounded with spatial order, as the blocks were arranged in a spatial pattern on a board. Since reading disabled subjects have been found to perform as well as or better than normals on spatial memory tasks (e.g., Symmes & Rapoport, 1972, and in the present study), it would appear that the use of spatial strategies might have allowed reading disabled children to perform well on this task. Indeed, studies of patients with right and left hemisphere lesions have indicated that the Corsi blocks task depends upon the functioning of the right rather than the left cerebral hemisphere (see Lezak, 1983). Thus, it might be the case that when the sequencing task can be performed using right hemisphere dependent spatial strategies, poor readers perform as well as normals, but when the task must be solved by temporal rather than spatial strategies (as was attempted in the present study), reading disabled children have difficulty with nonverbal temporal sequencing.

The present findings that the poor readers performed significantly more poorly than the average readers on the Auditory Verbal (Digits) task, and showed a nonsignificant

trend towards poorer performance on the Auditory Verbal (Words) task, support Bakker's (1972) argument that reading disability stems from an impairment in auditory/verbal sequencing. These results are also consistent with numerous studies demonstrating auditory sequencing impairments in reading disabled children (e.g., Bakker, 1972).

The results of the present study support the prediction that children who read poorly would perform worse than average readers on visual sequencing tasks. The poor readers performed significantly worse than the average readers on the Visual Verbal Sequencing task, in which the stimuli were pictures of objects, and on the Visual Nonverbal Sequencing task, in which the stimuli were nonsense shapes. These results are consistent with other reports of visual sequencing impairments among poor readers (e.g., Denckla, Rudel, & Broman, 1981; Gordon, 1980). Thus, the sequencing impairments of reading disabled children do not appear to be limited to auditory stimuli, but are present for visual stimuli as well. The impairment, then, is not modality-specific but is present across modalities. Again, it appears that the type of processing is important in characterizing the deficits of children with reading disability, rather than the modality of the information. However, the question of sequencing deficits in other sensory modalities (e.g., touch) remains to be tested in further studies.

The finding of inferior performance of poor readers on the motor sequencing task, in which finger opposition sequences had to be reproduced, suggests that, although visual sequencing problems cannot be ruled out as the basis of the inferior performance, the sequencing impairment of poor readers may not be limited to sequencing of sensory input but is also present for sequencing of motor output, at least for fine finger movements of the preferred hand. This finding is consistent with the suggestion of Denckla (1985) and Rudel (1985) that reading disabled children are deficient in a left hemisphere-dependent motor system that controls sequential movements. The question of whether poor readers also have difficulty with sequencing of finger movements of the non-preferred hand, and/or of gross movements, can only be resolved in future studies.

Poor readers scored significantly more poorly than average readers on the Composite Sequencing measure. This finding is in agreement with those of other workers (e.g., Denckla, Rudel, & Broman, 1981; Gordon, 1980; Zurif & Carson, 1970), which also indicated a general sequencing impairment among reading disabled children.

The present findings of impaired performance by poor readers on temporal sequencing tasks are strongly suggestive of left hemisphere deficits in reading disabled children. Several studies have indicated that temporal sequencing, whether auditory or visual, verbal or nonverbal, is primarily mediated by the left cerebral hemisphere. Kim

(1976), for instance, compared adult patients with right or left hemisphere lesions and normals on tasks of verbal sequencing (digits, words, and geometric forms) in either the auditory or visual modalities. She found that patients with left hemisphere lesions were more impaired on all sequencing tasks than were both of the other groups.

However, the right hemisphere lesioned patients were also slightly impaired compared to normals, suggesting that the right hemisphere might play a minor role in mediating temporal sequencing skills. Other studies of verbal sequencing have confirmed that deficits occur primarily with left hemisphere lesions, but they do not agree on whether the right hemisphere contributes in some minor way to sequencing ability (Albert, 1972; Weinberg, Diller, Gerstman, & Schulman, 1972).

Several studies have indicated that nonverbal sequencing, like verbal sequencing, is dependent primarily on the left hemisphere, regardless of sensory modality (Carmon & Nachson, 1974; Efron, 1963; Swisher & Hirsch, 1972). Using adult patients with right or left hemisphere damage, these investigators presented sequences of colored lights, or tones of different pitch, and asked the patients to indicate the order in which the stimuli had been presented. Patients with left hemisphere lesions did more poorly than right hemisphere lesioned patients. It was suggested that the process of temporal sequencing per se is carried out in the left hemisphere.

If it is the case that reading disabled children exhibit weak left hemisphere functioning, one would expect linguistic functions as well as sequencing abilities to be impaired. Although language abilities per se were not tested in the present study, the finding, in this and other studies, that poor readers are impaired on tasks of visual nonverbal sequencing challenges the view that all observable deficits of reading disabled children can be explained by impairments in verbal processing, and that deficits in functions such as temporal sequencing and visuo-spatial ability are due to a more basic verbal processing deficit (Vellutino, 1978, 1979). As it is unlikely that the Visual Nonverbal Sequencing task involved verbal processing, the present results are more consistent with the view that, if there are indeed verbal processing deficits among reading disabled children, temporal sequencing impairments might underlie the language problem. Language is, after all, fundamentally dependent upon temporal order sequencing. Both the acoustic aspects of language comprehension as well as the motor components of speech production are primarily sequencing processes (see Kimura & Archibald, 1974; see Lashley, 1951). Thus, an individual with impaired sequencing ability would be likely to have language problems.

It is possible that the impairment in temporal sequencing scores among poor readers in the present study might be due to a short-term memory deficit, as all tasks of

temporal sequencing involved recall of a previously presented sequence. There are a number of arguments against this view. First, the average and poor readers performed similarly on the Spatial Orientation Memory Test (Wepman & Turaids, 1975), which involves memory for the orientation of geometric forms. If poor readers had a general short-term memory impairment, one would expect them to show a deficit on this test. Second, the average and poor readers in this study performed similarly on the Right-Left Orientation Test (Benton, Hamsher, Varney, & Spreen, 1983). Benton (1984) has pointed out that this test has a short term verbal memory component, in that children may have difficulty keeping successive items of verbal information in mind long enough to correctly execute the command. If poor readers had a short term memory deficit, one would expect them to show a deficit on this test. Third, as noted earlier, on the Auditory Verbal Sequencing (Digits) task, the stimuli were presented at a rate of one every second, whereas on the Auditory Verbal Sequencing (Words) task, the stimuli were presented at a rate of one every two seconds. Average readers performed significantly better than poor readers on the Auditory Verbal (Digits) task but only showed a trend towards better performance on the Auditory Verbal (Words) task. If poor readers had a short-term memory impairment that was responsible for their poor performance on sequencing tasks, one would expect that they would have performed particularly poorly on the Auditory Verbal (Words)

task, in which the memory requirements were greater due to the longer interstimulus interval. Thus, although memory was not directly investigated in the present study, it is unlikely that a short-term memory deficit accounts for the poorer performances of the reading disabled children on temporal sequencing tasks.

Another related point is that, while it is clear that the poor readers in the present study showed impaired temporal sequencing ability, one cannot definitively determine whether it is the perception of temporal order or the recall of temporal order that is the primary problem. All of the sequencing tasks involved perception of either verbal or nonverbal stimuli in a particular sequence, followed by replication, either verbal or nonverbal, of the sequence. Several previous studies have demonstrated that the sequencing impairment of poor readers is not limited to the recall of temporal order. For instance, May, Williams, and Dunlap (1988) presented two words tachistoscopically and varied the stimulus onset asynchrony between the words to determine the subjects' threshold for perceiving temporal order. Children who read 1 year below grade level required greater asynchrony between the onset of different stimuli to make accurate temporal judgments, leading the authors to conclude that poor readers exhibited a deficit in temporal order perception. Similar findings have been reported in other studies (Lovegrove & Brown, 1978; Tallal, 1980). Thus, although perception vs. recall of temporal order

cannot be separated in the present study, it is unlikely that the sequencing deficit of poor readers is limited entirely to temporal order recall.

Handedness and Temporal Sequencing

The present findings support the hypothesis that left-handed children perform more poorly on tasks of temporal sequencing than children who are right-handed. The left-handers performed significantly worse than the right-handers on the Auditory Verbal (Words) task, and on both the Auditory Verbal (Digits) task and the Motor Sequencing task there was a trend towards poorer performance by left-handers. On the Composite Sequencing measure, there was a tendency ($p = .06$) for left-handers to perform more poorly than right-handers.

To the extent that temporal sequencing is dependent primarily on left hemisphere functioning (e.g., Efron, 1963; Kim, 1976), the finding of sequencing impairments among left-handed children provides some support for the hypothesis that left-handers have inferior left hemisphere functioning compared to right-handers. These findings are partially consistent with Geschwind and Galaburda's (1985a, 1985b, 1985c, 1987) theory that, among left-handers, left hemisphere mediated cognitive functions are weaker due to delayed growth of the left hemisphere. The present findings do not provide strong support for this hypothesis, however, as there was no evidence of poorer performance by

left-handers than by right-handers on either of the two visual sequencing tasks.

It should be noted that, in view of the fact that information on familial handedness was not obtained, it is possible that the handedness groups were not homogeneous with respect to familial hand preference. This likely resulted in increased intragroup variability, especially for the left-handers, thereby decreasing the likelihood of finding handedness differences in cognitive function. Thus, the possible inclusion of children with different familial handedness histories within the right- and left-handed groups could account, at least in part, for the failure to find a greater number of significant differences between right- and left-handers on temporal sequencing tasks.

Reading Ability, Handedness, and Temporal Sequencing

The present study addressed the question of whether differences between poor and average readers in temporal sequencing skills depends upon whether the children are left- or right-handed. The results indicated that handedness did not interact with reading group on any of the tasks of temporal order sequencing, or on the composite sequencing measure. Thus, although the results showed that children who read poorly had poorer sequencing skills than children who read well, and left-handed children showed a tendency towards poorer sequencing task performance than right-handers, the difference between average and poor

readers in sequencing task performance was similar for left- and right-handers. In other words, the sequencing impairment found among poor readers is present for left-handed as well as right-handed children. Although numerous other studies have reported sequencing deficits among poor readers (e.g., Bakker, 1967, 1972; Bakker & Schroots, 1981; Gordon, 1980; Gould & Glencross, 1990), none have addressed the issue of hand preference nor have they analyzed the data according to handedness. The present finding of the absence of an interaction between reading ability and handedness is particularly important as it extends the previous research on reading disability and temporal sequencing to include left-handed children.

Reading Ability and Visuo-Spatial Ability

The question of visuo-spatial skills among poor readers was examined in the present study. On the Composite Visuo-spatial measure, which consisted of the mean score on two spatial tasks, there was a non-significant tendency ($p = .10$) for average readers to perform better than poor readers. This finding is consistent with other reports of poor visuo-spatial skills among reading disabled children (e.g., Pontius, 1981). However, the findings for each of the spatial tasks separately do not reveal differences between average and poor readers. On neither the Right-Left Orientation Test nor the Spatial Orientation Memory Test did the performances of the average and poor readers differ.

These findings suggest that poor spatial performance is probably not an important factor in most cases of reading disability, at least not for the two types of spatial skills that were examined in the present study.

The absence of evidence of a significant difference between average and poor readers in performance on the Spatial Orientation Memory Test does not support the hypothesis of enhanced spatial orientation skills and, therefore, enhanced right hemisphere functioning in reading disabled children. However, whether reading disabled children show a cognitive profile favoring spatial skills compared to their own sequential skills, as Gordon (1988a, 1988b) suggested, was not tested directly in the present study, since the difficulty of the visuo-spatial tasks was not equated with that of the sequencing tasks.

As the Spatial Orientation Memory Test was used in the present study to assess right hemisphere spatial abilities, it is important to note that the absence of a performance difference between average and poor readers is meaningful. It indicates that the impairment in temporal sequencing found among poor readers relative to average readers in this study does not represent a general deficit in all cognitive abilities, and suggests that the sequencing impairment of poor readers may be specific to that type of cognitive skill. Furthermore, to the degree that sequencing reflects left hemisphere functioning (Efron, 1963; Kim, 1976) and spatial orientation reflects right hemisphere functioning

(Ratcliff, 1979), the present findings are consistent with the possibility that, in reading disabled children, left hemisphere functioning is impaired whereas right hemisphere functioning remains intact.

Further, the absence of a performance difference between average and poor readers on the Spatial Orientation Memory Test has implications for understanding the etiology of reading disability in terms of type of cognitive processing. The stimuli used in the spatial orientation task were nonverbal, meaningless, unfamiliar figures, as were the figures used in the visual nonverbal sequencing task. However, our poor readers performed more poorly than our average readers when sequencing was required but not when discrimination of orientation was required. Although a direct comparison cannot be made between the two tasks, as the visual stimuli were not even similar, the results suggest that the type of cognitive processing rather than the type of stimuli used determines the performance of children with reading disability. That is, poor readers have difficulty with sequential processing tasks but not with discrimination of spatial orientation even if both involve nonverbal, unfamiliar visual stimuli. In future studies, it would be of interest to employ identical stimuli presented both sequentially and in the discrimination format used in the Spatial Orientation Memory Test.

Handedness and Visuo-Spatial Ability

The question of performance differences between handedness groups on visuo-spatial ability tasks was examined in the present study. Left-handers performed better than right-handers on the Composite Visuo-spatial measure, which consisted of the mean score on two visuo-spatial tasks. This is in agreement with Geschwind and Galaburda's (1985a, 1985b, 1985c, 1987) hypothesis of better visuo-spatial ability in left-handers than in right-handers, and challenges Levy's (1969) hypothesis of poor spatial performance among left-handers because of cognitive crowding due to bilateral representation of language in left-handers. However, the findings for each of the spatial tasks separately suggests that left-handers may be superior to right-handers on certain types of visuo-spatial tasks but not on others.

Our hypothesis that left-handed children would perform better than right-handed children on a task of spatial orientation was not supported by the present results, as no difference was found between the performances of left- and right-handed children on the Spatial Orientation Memory Test. However, on the Right-Left Orientation Test, the left-handed children performed significantly better than the right-handers. The direction of this difference was unexpected. It was hypothesized that left-handed children would exhibit poorer right-left orientation ability than right-handers, based on Geschwind and Galaburda's (1985a,

1985b, 1985c, 1987) proposal that left-handers have poor left hemisphere cognitive skills because of delayed left hemisphere development. Right-left orientation performance has been shown to be mediated primarily by the left hemisphere, and disturbances of right-left orientation in adults are usually the result of a lesion in the left temporo-parietal-occipital area (Strub & Geschwind, 1974; and see also Lezak, 1983). However, there is no direct evidence in children.

One possible explanation for the finding that left-handers performed better than right-handers on the Right-Left Orientation Test is that in children, and particularly in left-handed reading disabled children, there may be a greater than usual contribution of the right hemisphere to right-left orientation skills. Certain other cognitive abilities have been hypothesized to shift representation from one hemisphere to another during childhood (e.g., Bakker, 1979). It is not clear, however, if this occurs in the case of right-left orientation. It is also possible that, in populations with anomalous cerebral dominance, such as left-handers and those with reading disability, the right hemisphere may make a greater contribution to right-left orientation skills than is the case for right-handers and average readers, and that this pattern may be stable throughout development. If right-left orientation is mediated largely by the right hemisphere in left-handers, then the present findings would be consistent

with the hypothesis of enhanced right hemisphere mediated spatial skills in left-handers.

Another possible explanation for the superiority of left-handed over right-handed children on the Right-Left Orientation Test is based on the assumption that the left hemisphere is the one which makes a greater contribution to right-left orientation. Geschwind and Galaburda (1985a, 1985b, 1985c, 1987) described a process by which cortical regions could become enlarged if they are located directly adjacent to other cortical areas whose growth is delayed due to prenatal hormonal influences. The individual would then display superiority of the functions subserved by the enlarged region. The specific functions which are enhanced or impaired would depend on when during development the influence was present. Geschwind and Galaburda (1987) suggested that this mechanism accounts for findings that reading disabled individuals sometimes display superiority of the "Gerstmann talents", which include right-left orientation. A similar process could account for superiority in right-left orientation among left-handed children. In order to clarify the relationship between handedness and right-left orientation skills, it would be necessary to study large numbers of left-handers, preferably using direct measures of hemispheric specialization as well as tests of right-left orientation in the same subject groups.

The possibility of a socio-cultural basis for the superiority of left-handers over right-handers on the Right-Left Orientation Test cannot be ruled out. It is possible that for left-handed children, left hand preference may be commented upon more frequently by parents and teachers than is the case for their right-handed peers. This could lead to earlier and/or better learning of right-left differences by left-handers, and superior performance on right-left orientation tasks. This may not have been the case when earlier papers were published, as right-left orientation skills were not as much a part of the school curriculum as they are today (Benton, 1984). Benton (1984) has suggested that increased current emphasis on right-left orientation skills also accounts for the finding that children acquire right-left orientation skills earlier today than they did in the past. Although the possibility of a socio-cultural influence on right-left orientation was not examined in the present study, it would be an interesting question for future investigations.

Reading Ability, Handedness, and Visuo-Spatial Ability

In the present study, we predicted that left-handed poor readers would perform more poorly on a task of right-left orientation than both right-handed poor readers and right- and left-handed average readers. In addition, we predicted that left- and right-handed poor readers and left-handed average readers would perform better on a task

of spatial orientation than right-handed average readers. Neither of these hypotheses were supported, as handedness and reading did not interact in performance on either the Right-Left Orientation Test or the Spatial Orientation Memory Test. Thus, the superiority of left-handers over right-handers in right-left orientation did not differ for average and poor readers.

Although none of the interactions between handedness and reading group were statistically significant, the results of the Coloured Progressive Matrices Test suggests that there may be some tendency for one of the subject groups to differ from the other three in certain aspects of spatial ability. Although this test was used for selection of the children and was not a dependent variable, it is of interest that the left-handed poor readers had a significantly higher score than did the left-handed average readers (107.2 for left-handed poor readers; 100.2 for left-handed average readers). The score on this test was used as a covariate in all analyses of the dependent variable; therefore, the difference did not affect the results of the study. However, to the extent that the Coloured Progressive Matrices Test assesses aspects of visuo-spatial ability, including pattern and numerical relationships, the data are consistent with the hypothesis that left-handed poor readers show superior spatial skills compared to the other reading and handedness groups. Thus, this finding points to the need for future studies to

investigate numerous aspects of visuo-spatial ability with right- and left-handed average and poor readers.

Summary and General Discussion

In summary, the results of the present study are in agreement with previous suggestions and empirical findings that impairments in temporal sequencing are associated with reading disability in children. Further, the results extend previous findings to include left-handed as well as right-handed poor readers. The findings support the view that a general sequencing process is impaired in reading disabled children which is not specific to modality (auditory, visual) or type of material (verbal, nonverbal). The findings are also in agreement with the hypothesis of left hemisphere deficits in children with reading disability, possibly as a result of delays in left hemisphere development during the prenatal or early postnatal period. In addition, the results of the present study partially support the hypothesis that left-handers exhibit poor temporal sequencing skills compared to right-handers, as left-handers performed poorly on only a few tasks. A larger number of left-handers need to be studied in order to conclusively demonstrate poor sequencing abilities in this group of children.

The results of the present study provide no evidence for hypothesized differences in visuo-spatial ability between average and poor readers. The finding that poor

readers performed as well as average readers on the spatial orientation test though markedly worse on temporal sequencing tasks indicates that the sequencing deficit of poor readers cannot be due to a general deficit in all cognitive functions. The finding that left-handers performed better than right-handers on a test of right-left orientation might reflect enhancement of areas of the left (or right) hemisphere resulting from delays in development of adjacent left hemisphere language areas in left-handers.

It should be noted, however, that since only two spatial tasks were used, a thorough examination of spatial ability differences in average and poor readers and in left- and right-handers was not possible, and the conclusions that can be drawn are therefore limited. Future studies should investigate a broader spectrum of spatial functions in these subject groups. In addition, as it has been proposed by some investigators that only one subgroup of individuals with reading disability shows visuo-spatial deficits (Mattis, French, & Rapin, 1975), the question of reading disability subtypes should also be examined in relation to spatial ability and handedness.

One must also question whether the present results can be generalized to all children with reading disability, as children with different subtypes of reading disability might show different patterns of cognitive skills. In the present study, poor readers were not classified according to subtypes; instead all the children were required to meet the

same criteria to be included in the reading disabled group. Thus, either most of the children happened to be of a similar subtype, which might correspond to the sequential subtype described by some investigators (see Mattis, 1978), or reading disabled children tend to have similar cognitive profiles characterized by impaired sequencing skills and adequate visuo-spatial skills, regardless of reading subtype. This latter possibility is consistent with the results of Doehring, Trites, Patel, and Fiedorowicz (1981), who found that three subtypes of poor readers defined by different patterns of performance on reading tests did not differ in their pattern of performance on a battery of neuropsychological tests. For all reading subtypes, sequential skills were below average and visuo-spatial skills were above average. Gordon and co-workers (Harness, Epstein, & Gordon, 1984) also found that most reading disabled children have poor verbosequential skills, reflecting left hemisphere functioning, and high visuo-spatial skills, reflecting right hemisphere functioning. Gordon (1988a) concluded that the similarity of cognitive profile among the majority of reading disabled children does not ignore the presence of subtypes, but that subtype differences in reading pattern are secondary to the more important features of low verbosequential and high visuo-spatial skills in the majority of children with reading disability. The present findings of poor temporal sequencing and adequate visuo-spatial skills among poor

readers are consistent with Gordon's (1988b) conclusions and extend them in two ways: (a) a similar profile may hold not only for verbosequential tasks but also for nonverbal and motor sequencing tasks; and (b) a similar pattern of poor sequential and adequate visuo-spatial ability applies to left-handed as well as right-handed reading disabled children. However, a direct test of sequencing and spatial abilities of left- and right-handed children demonstrated to have different subtypes of reading disability would still be of interest for future studies.

With respect to subtypes of reading disability, it should also be noted that the nature of the reading test used to classify reading groups may have served to limit the selection of subjects. The standardized procedure for administration and scoring of the Gray Oral Reading Test-Revised does not permit independent assessment of oral reading and comprehension, in that the number of paragraphs read aloud, which determines the oral reading score, is contingent upon the comprehension score. To the extent that reading disability subtypes may be manifested in different patterns of oral reading and comprehension (Olson, 1989, cited in Newby & Lyon, 1991), certain subtypes may have been excluded.

Another issue which was not addressed in the present study concerns familial vs. nonfamilial left-handedness. There is evidence that left-handers with and without a family history of left-handedness differ in their pattern of

cerebral organization (see Bryden, 1982; also Hardyck & Petrinovich, 1977) and, further, it has been suggested that subtypes of left-handedness (e.g., left-handed children with and without other left-handers in their family), might relate in some way to subtypes of reading disability (Bemporad & Kinsbourne, 1983). To examine any such relationships, future studies should subdivide hand preference groups in accordance with family handedness history.

This study raises a number of questions about the relationships among reading ability, handedness, and cognitive ability. For instance, how do the present findings relate to neuroanatomical asymmetry; that is, do reading disabled children with more severe sequencing impairments also have smaller left hemispheres or, at least, a smaller extent of certain areas within the left hemisphere which might mediate temporal sequencing? Is there a single sequencing mechanism in the left hemisphere that controls all types of temporal sequencing, or are there several cortical areas involved, all of which are dysfunctional in children with reading disability? Do these areas include frontal regions, occipital regions, parietal regions, or some combination of these? In addition, are poor readers with sequencing deficits the same children who might have been subjected to high prenatal testosterone levels or high receptor sensitivity to testosterone prenatally? Would

similar findings be obtained for girls as were obtained for boys in the present investigation?

The present study also raises questions about the neural substrate of hand preference. As left-handers tend to have better right-left orientation skills and poorer temporal sequencing performance than right-handers, is hand preference a manifestation of a system located in the left cerebral hemisphere (Witelson, 1985) which might be related to possible hemispheric substrates for both right-left orientation and temporal sequencing? Alternatively, if hand preference is the result of asymmetry at the level of the motor cortex (Witelson, 1985), presumably the right motor cortex in left-handers, how might this be related to cognitive ability? Are right-left orientation or sequencing skills represented in the right hemisphere in left-handers, or is left-handedness associated with ipsilateral motor control, as suggested by Levy and Reid (1978)?

Two important questions have practical implications for the identification and treatment of reading disabled children. First, are left-handers at greater risk for reading problems than is the case for right-handed children? This issue was not examined directly in the present study. However, sequencing problems are a primary impairment among reading disabled children, and it may be that left-handers are more prone to such problems, as there was a tendency for left-handers to perform more poorly than right-handers on a few sequencing tasks. Thus, if left-handed children are at

greater risk for sequencing difficulties, it might predispose them to reading disability to a greater extent than right-handed children.

Second, what is the best way to remediate both right- and left-handed reading disabled children? Gordon and Carmon (unpublished data, cited in Gordon, 1980) noted that their standard remediation has been to provide reading drills using sequential techniques; letter by letter, word by word, and so on. They reported that greater improvement in reading was seen in the children who received strictly sequential training than in those for whom less rigid sequential strategies were used, implying that improvement in sequential skills helped the reading disabled children to improve their reading skills. The present results support the notion that training and practice in the use of sequential strategies would help reading disabled children to read and, further, that this would be an appropriate strategy for left-handed as well as right-handed reading disabled children.

What is not clear, however, is the process by which temporal sequencing is impaired, as we still do not know how knowledge of sequencing is coded in the brain. Although it is clear that it is mediated primarily by the left hemisphere, it is not clear what the process is. This issue is of crucial importance in order to better treat children with reading disability. When we develop a better understanding of the substrate(s) as well as the process

underlying sequential processing, we can better understand how to improve these skills and thereby remediate children who have problems learning to read.

Appendix A. Informed consent form signed by parents



Department of Psychology

April 6, 1989

Dear Parent,

I am in the process of conducting a very exciting project using school aged children. This project (my Ph.D. thesis) deals with the relationship between reading and hand preference (right or left handedness). The results of this project could lead to the development of better strategies in teaching children to read. The project has been approved by the District Superintendent, and I have permission from M _____ to observe the children in P.S. _____

I would greatly appreciate your allowing your child to participate in the project. He/she would attend two short interviews in a room in the school building. He/she will be asked to read paragraphs aloud, and to perform activities such as drawing a picture to see which hand he/she uses. Your child will also play a few games with pictures of geometric shapes and familiar objects (cat, house, tree). All of these tasks have proven to be interesting and enjoyable for children.

I am not interested in the performance of any individual child; rather, I am interested in groups of children. Your child's name will never be used; individual results will be completely confidential, and will not be shown to teachers, other children, or anyone else.

If you would like more information, leave your phone number and I will be happy to telephone you. Please fill out the form below and have your child return it to school.

Thank you very much for your cooperation.

Sincerely yours,

Ellen M. Schneider, M.A.

Approved: _____
Principal

*****TEAR AND RETURN*****

PLEASE CHECK ONE BOX and return to M _____ by April 11, 1989.

- Yes, I give permission for my child to participate.
- I would like to speak with you. My phone number is _____.
- No, I do not give permission for my child to participate.

Child's Name _____

Class _____

Date _____

Signature of Parent or Guardian _____

My child is left handed right handed.

Appendix B. Stimuli used in visual acuity screening measure

A y o k H
p t r n e
a s J f d
o g i L e

Appendix C. Stimuli used in auditory acuity screening measure

- | | |
|------------|-----------|
| 1. Cat | 11. Candy |
| 2. Pencil | 12. Radio |
| 3. Tomato | 13. Food |
| 4. Clown | 14. Play |
| 5. Happy | 15. Run |
| 6. Balloon | 16. Toy |
| 7. Dog | 17. Red |
| 8. Coat | 18. Truck |
| 9. Desk | 19. Water |
| 10. Flag | 20. Pen |

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