ABSTRACT

The planum temporale (PT) is a highly lateralized cortical region located within Wernicke’s area which is thought to be involved in auditory processing, phonological processing, and language. Research has linked abnormal morphology of the PT and its parietal extension, the planum parietale (PP), to developmental dyslexia, although results have varied in large part due to methodological inconsistencies in the literature. This study examined the asymmetry of the PT and PP in 29 children who met criteria for dyslexia and 26 children who did not. Leftward asymmetry of the PT was found in the total sample, and this leftward asymmetry was significantly reduced in children with dyslexia. This reduced leftward asymmetry in children with dyslexia was due to a PT that is larger in the right hemisphere. In this sample, leftward PT asymmetry was significantly correlated with right-handedness, but not with verbal intelligence or phonological processing. Furthermore, PT asymmetry did not predict reading achievement. Significant results were not found with regard to PP asymmetry. This study lends support to the idea that PT asymmetry is altered in children with developmental dyslexia.

INDEX WORDS: developmental dyslexia, reading disability, brain morphology, planum temporale, planum parietale.
PLANUM TEMPORALE AND PLANUM PARIETALE MORPHOLOGY IN CHILDREN
WITH DEVELOPMENTAL DYSLEXIA

by

JULIANA SANCHEZ BLOOM
B. A., Emory University, 1998
M.Ed., The University of Georgia, 2001

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by

JULIANA SANCHEZ BLOOM

Major Professor: George W. Hynd
Committee: Jonathan Campbell
           Roy P. Martin
           L. Stephen Miller
           Joseph Wisenbaker

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
May 2006
DEDICATION

This work is dedicated to:

David Weinstein, who believed I was special;

My parents, who believed I could do anything I set my mind to; and,

My dear husband, Rob Bloom, who was there every step of the way. I cannot thank you enough for your love and support.
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CHAPTER I
INTRODUCTION

Developmental dyslexia, also referred to as a learning disability in reading or a reading disability, is defined as a dysfunction of reading that cannot be explained by intelligence, sensory impairment, or environment (American Psychiatric Association, 2000). This disorder is estimated to affect 3-6% of school-age children (Kibby & Hynd, 2001), and is characterized by particular cognitive deficits in addition to a deficiency in reading achievement. These cognitive deficits include phonological processing that is considered by many researchers to be the “core” deficit in developmental dyslexia (Lombardino, Riccio, Hynd, & Pinheiro, 1997; Lyon, 1996; Shaywitz & Shaywitz, 1999; Siegel, 1993). In fact, phonological processing skills in kindergarten are the most predictive factor of word reading achievement in elementary school, with correlations ranging from 0.4 to 0.6 (Torgesen, Wagner, & Rashotte, 1994).

Some researchers, however, have theorized that phonological processing deficits alone are not sufficient to explain dyslexia. Wolf and Bowers (1999) posited that phonological processing and rapid, automatized naming skills can both be deficits in dyslexia. According to their theory, three subtypes can exist: a subtype with deficits in phonological processing, a subtype with deficits in rapid naming, and a more severe combined subtype. This theory is referred to as the double-deficit hypothesis (Wolf & Bowers, 1999).

Research has supported the presence of other cognitive deficits in individuals diagnosed with dyslexia. These include deficits in phonological processing and rapid naming, difficulties in receptive and expressive language (Purvis & Tannock, 1997), verbal memory (Shaywitz et al., 1995), temporal processing (Klein, 2002), and attention (Mayes, Calhoun, & Crowell, 2000). Evidence of impairments in orthographic processing and visual-spatial skills has also been found.
(Eden, VanMeter, Rumsey, & Zeffiro, 1996), which may point to the existence of an orthographic subtype of dyslexia. The phonological subtype of dyslexia, however, is the most common, the most thoroughly researched, and the most accurately identified at this time.

**The Neurobiological Basis of Dyslexia**

For more than a century, scientists have focused their attention on the neurobiological basis of language and reading (Kral, Nielson, & Hynd, 1998). Broca and Wernicke localized language to the left hemisphere of the brain in the late nineteenth century (Kral et al., 1998), leading Hinshelwood to suggest that damage to these cortical areas may be associated with reading problems (Hinshelwood, 1900). Specifically, Hinshelwood suggested that damage to the supramarginal and angular gyri on the left side of the brain may be responsible for difficulties in learning to read (Hinshelwood, 1900; Kibby & Hynd, 2001). These brain areas are still the focus of the majority of research on the neurobiological basis of reading problems, and research linking abnormalities in left hemisphere cortical language areas to developmental dyslexia is copious (Filipek, 1995; Galaburda, 1993; Hynd & Semrud-Clikeman, 1989; Miller, Sanchez, & Hynd, 2003; Morgan & Hynd, 1998). Dyslexia has been linked to neurobiological abnormalities in Broca’s area, the angular gyrus, the planum temporale (PT) and the surrounding perisylvian cortex, the lateral geniculate nucleus of the thalamus, the occipital cortex, and the corpus callosum (Miller et al., 2003). All of these areas are involved in the auditory or visual system, strengthening the link between dyslexia and deficits in language functioning, such as phonological processing, and deficits in visual processing, such as orthographic skills. It is, however, the region of the planum temporale (PT) that has received the most attention from researchers as it is believed to play a pivotal role in the neurolinguistic deficits typically reported in dyslexia. The relationship between reading, dyslexia, and the PT is the focus of this work.
The Planum Temporale

The planum temporale (PT) is a triangular-shaped area of cortex situated on the superior surface of the temporal lobe, adjacent to the Sylvian Fissure (SF). It is bordered anteriorly by Heschl’s gyrus and posteriorly by the termination of the horizontal aspect of the SF (Shapleske, Rossell, Woodruff, & David, 1999). The PT is the largest structure in Wernicke’s area, an area long known to play an important role in language comprehension (Barta et al., 1995). It has long been associated with language lateralization, due to the fact that it is one of the most lateralized structures in the brain and typically shows pronounced leftward asymmetry (Geschwind & Levitsky, 1968; Shapleske et al., 1999).

Cytoarchitectonically, the PT is a part of auditory association cortex (Steinmetz, 1996) or cortex involved in second-order processing of auditory stimuli. In fact, there is a strong correlation between PT asymmetry and the asymmetry of cytoarchitectonic area Tpt, which is considered an important substrate of language (Galaburda, Sanides, & Geschwind, 1978). This finding suggests that PT asymmetry may, in fact, represent an anatomical reflection of language lateralization (Galaburda et al., 1978).

The idea that PT asymmetry is related to language functioning is strengthened by the fact that atypical asymmetry of the PT has been found in a wide variety of disorders in which disturbed language is a core or associated feature. These disorders include schizophrenia (Shapleske et al., 1999), Down’s syndrome (Frangou et al., 1996), autism (Rojas, Bawn, Benkers, Reite, & Rogers, 2002), developmental language disorders (Gauger & Lombardino, 1997), and dyslexia (Morgan & Hynd, 1998). Furthermore, exaggerated leftward asymmetry has been found in musicians with “perfect pitch” which is an unusual ability to name pitches out of
context (Steinmetz, 1996), as well as in professional musicians in comparison to nonmusicians (Schlaug & Jäncke, 1995).

The function of the PT, as demonstrated by functional imaging and lesion studies, may be related to acoustic processing, phonological decoding, and language tasks. Research on subjects with lesions of the PT or near the PT has shown that those individuals are impaired in speech comprehension and auditory discrimination, suggesting the PT plays an important role in those cognitive tasks (Shapleske et al., 1999). Finally, some functional neuroimaging studies have suggested that the PT is activated during phonological decoding and language-related tasks (Shapleske et al., 1999), which would connect the function of the PT to the major cognitive deficit in dyslexia. Other studies, however, have shown that the left PT is activated equally by tones and words, suggesting that the PT is involved in early auditory processing at a level before language (Binder, Frost, Hammeke, Rao, & Cox, 1996). Regardless of the level at which the PT’s involvement occurs, this structure is clearly an important functional part of auditory and language perception.

Recently, a theory regarding the importance of the left temporo-parietal area, which corresponds roughly to the PT, in the development of reading skills has been proposed by Shaywitz and colleagues (Pugh, Mencl, Jenner, Katz et al., 2001; Shaywitz, 2003). In this theory, there are two left-hemisphere brain regions that are important in the development of fluent reading skills: the temporo-parietal area and the occipito-temporal area. The temporo-parietal system, which is thought to link orthographic and phonological processes, dominates as reading skills first develop. As word recognition becomes fluent and automatic, the occipito-temporal system becomes dominant over the temporo-parietal system. In individuals with dyslexia, functional activation is disrupted in both these systems, and increased activation is found in the
Figure 1: An axial view of the PT (the larger, triangular structure) and Heschl’s gyrus of a normal adult. In this picture, the anterior of the brain is at the top and right and left are reversed. Thus, the fact that the left PT is larger is visible. Adapted from Hirayasu et al. (2000).
corresponding right hemisphere posterior brain regions and inferior frontal regions (Pugh, Mencl, Jenner, Lee et al., 2001). The disruption of activation in the left temporo-parietal region, which corresponds roughly to the left PT, and increase in activation in the right temporo-parietal region, which corresponds roughly to the right PT, may reflect the functional consequences of atypical structural asymmetry of the PT.

The Planum Temporale and Developmental Dyslexia

Due to the association between the PT and language, the relationship between the PT and dyslexia has been the subject of considerable research. Abnormalities of the PT at the gross (Filipek, 1995; Hynd & Semrud-Clikeman, 1989; Morgan & Hynd, 1998) and cellular levels (Galaburda & Kemper, 1979; Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1990; Humphreys, Kaufman, & Galaburda, 1990) have been documented in dyslexia, although results have been inconsistent. This inconsistency is likely due to wide variety of methodological issues in measuring the PT, including a lack of consensus in the borders of the area and the limitations of early imaging technology (Barta et al., 1995; Honeycutt, Musick, Barta, & Pearlson, 2000). Furthermore, variables such as gender and handedness have not been well controlled in these studies, two variables that appear to have a relationship with PT asymmetry (Shapleske et al., 1999). A preponderance of the evidence suggests that individuals with dyslexia do not demonstrate the leftward asymmetry of the PT that is typically found in normal populations (Morgan & Hynd, 1998).

What might PT asymmetry have to do with developmental dyslexia? First of all, the PT is one of the most lateralized structures in the brain, which has led many researchers to conclude that it may be a structural representation of left-hemisphere dominance for language. Research has connected anomalous cerebral asymmetry to dyslexia, suggesting that language is not as
strongly lateralized to the left hemisphere in dyslexia (Galaburda, 1995; Kertesz, Black, Polk, & Howell, 1986). Consistent with this theory, anomalous PT asymmetry would be expected in dyslexia. Furthermore, the mechanism for cerebral dominance may lie in the asymmetry of the homologous cortical regions, the larger of which may control its homologue via callosal connections, leading to left-hemisphere dominance for language (Galaburda, 1993). Galaburda and colleagues have found that when symmetry exists it is generally due to a larger than normal right PT rather than a smaller left PT (Galaburda, Corsiglia, Rosen, & Sherman, 1987; Humphreys et al., 1990). They suggest that the larger right PT in dyslexics as compared to controls may be interfering in the normal dominance of the left PT for language processing (Galaburda, 1995). In short, the structural asymmetry of the PT may reflect the functional dominance of the left hemisphere for language, which has been compromised in developmental dyslexia.

Functional imaging studies have also added to the understanding of the role of the PT in reading in general and in individuals with dyslexia in particular. Functional MRI research has demonstrated more activation of temporal cortex during reading in children who are typically developing readers than in children with dyslexia, suggesting that children with dyslexia fail to use brain areas specializing in language during reading tasks (Backes et al., 2002). Similarly, other researchers have found underactivation in the left temporo-parietal region, which corresponds roughly to the PT, in children with developmental dyslexia when compared to normally developing readers (Pugh, Mencl, Jenner, Lee et al., 2001; Shaywitz et al., 2002). Increased activation has been found in other brain areas, such as the left extrastriate cortex (Backes et al., 2002), right temporo-parietal region, and inferior frontal regions (Pugh, Mencl, Jenner, Katz et al., 2001) during reading in children with dyslexia, suggesting that children with
dyslexia are using brain regions that are not specialized for language during reading tasks. This disruption of the activation of area that corresponds to the PT during reading in children with dyslexia is evidence for the link between dyslexia and the PT.

**The Planum Parietale**

In the last decade, some researchers have chosen to distinguish between the horizontal and parietal aspects of the plana (Foster, Hynd, Morgan, & Hugdahl, 2002; Heiervang, Hugdahl, Smievoll, & Steinmetz, 1998; Heiervang et al., 2000; Jäncke, Schluag, Huang, & Steinmetz, 1994; Leonard et al., 1993; Preis, Jäncke, Schmitz-Hillebrecht, & Steinmetz, 1999; Steinmetz, Ebeling, Huang, & Kahn, 1990). The parietal bank of the plana is located on the floor of the posterior ascending ramus (PAR) of the SF, and follows the SF as it extends into the parietal lobe. It is situated within the supramarginal and/or angular gyri association areas, which receive projections from the temporal and frontal lobes (Heiervang et al., 1998). The parietal bank of the plana has been named the planum parietale (PP) by Jäncke and colleagues (Jäncke et al., 1994). The SF is morphologically distinct in the left and right hemispheres, with the PAR (a marker of the PP) of the SF significantly longer in the right hemisphere (Jäncke et al., 1994; Steinmetz, Rademacher et al., 1990). This rightward asymmetry of the PP is thought to counterbalance the smaller PT on the right side (Jäncke et al., 1994). Thus, when both the temporal and parietal banks of the plana are included in the measurements, symmetry is typically found (Steinmetz, Rademacher et al., 1990). Some researchers have found an inverse relationship between the PP and PT (Steinmetz, Rademacher et al., 1990), although other research has failed to find such a relationship (Jäncke et al., 1994). It is important to note that the borders of the PP were different in the two studies.
Figure 2: The PT and PP are outlined in a sagittal image. The horizontal line designates the PT while the vertical line designates the PP.
The Planum Parietale and Developmental Dyslexia

Although no specific functions have yet to be attributed to the PP, there is evidence that suggests that it is also involved in language and dyslexia. According to studies of cytoarchitectonic area Tpt, a cortical area thought to be a substrate of language, Tpt does extend into the PP (Galaburda et al., 1978), suggesting that language functioning occurs in this region. Furthermore, some research has found that significantly fewer dyslexic children show the expected rightward asymmetry of the PP (Heiervang et al., 2000), although other studies have failed to find this relationship (Leonard et al., 1993; Rumsey et al., 1997a). Furthermore, one study did not find a relationship between developmental language disorders and PP asymmetry (Preis, Jäncke, Schittler, Huang, & Steinmetz, 1998). Interestingly, one study investigating handedness found that the PP (as measured by the PAR) is a good predictor of handedness (Foundas, Leonard, & Hanna-Pladdy, 2002). Other researchers have suggested that the parietal bank of the plana may be related to visual-spatial abilities (Leonard et al., 1993). As very few studies have been published on the topic of the PP, further research is needed on the relationship between PP morphology and dyslexia.

Statement of Purpose

The purpose of this study is to explore the relationship between PT and PP morphology, reading ability, and dyslexia diagnosis in children. Specifically, the following questions will be examined:

1. What is the relationship between PT asymmetry and handedness, verbal intelligence, gender, and phonological processing?
2. What is the relationship between PP asymmetry and handedness, verbal intelligence, gender, and phonological processing?
3. What are the unique contributions of PT asymmetry, phonological processing skills, and rapid naming skills in predicting reading fluency?

4. Are there morphological differences in PT interhemispheric asymmetry in children with developmental dyslexia compared to clinic-referred children who did not meet criteria for developmental dyslexia?

5. Are there morphological differences in PP interhemispheric asymmetry in children with developmental dyslexia compared to clinic-referred children who did not meet criteria for developmental dyslexia?

6. Are there morphological differences in intrahemispheric asymmetry of the PT and PP in children with developmental dyslexia compared to clinic-referred children who did not meet criteria for developmental dyslexia?

With this brief introduction in mind, Chapter II provides a critical review of the related literature, Chapter III describes the methods used in this study, Chapter IV reports the results and finally, Chapter V provides the discussion of the results.
CHAPTER II
REVIEW OF THE LITERATURE

Important Findings Regarding Plana Morphology

The relationship between the PT and various disorders, including dyslexia, has been studied extensively. In order to understand the implications of these studies, it is essential to understand PT morphology in normal subjects. This section will discuss normal patterns of symmetry and asymmetry and the relationship between PT asymmetry and language lateralization. Furthermore, the relationships between PT morphology, gender, handedness, age, and verbal intelligence will be discussed with reference to the implications of these findings on methodology.

Normal Asymmetry and Symmetry

In 1968, Geschwind and Levitsky published a seminal study on planum temporale asymmetry in normal subjects (Geschwind & Levitsky, 1968). Of 100 postmortem brains, 65% showed a larger left planum temporale, 11% showed a larger right planum temporale, and the remaining 24% were of equal size. With this study, the link between PT asymmetry and left-hemisphere language lateralization was made, leading many researchers to investigate the possibility that the PT is the structural correlate of functional language lateralization.

Galaburda and colleagues reanalyzed the brains used by Geschwind & Levitsky to determine more specifically the types of symmetry and asymmetry found in the population (Galaburda et al., 1987). As was found in the original study, there was a higher prevalence of leftward asymmetry, although in this more thorough analysis, asymmetry was found to be on a continuum. Of interest, the researchers also found that brains with symmetrical plana differed...
from brains with asymmetrical plana by having two large plana, each of which was as large as the larger plana in the asymmetrical cases (Galaburda et al., 1987).

Steinmetz and colleagues examined 10 cadaver brains, 7 male and 3 female, both by postmortem analysis and magnetic resonance imaging (Steinmetz, Rademacher et al., 1990). Information about handedness and hemispheric language representation was unknown. The PT showed significant leftward asymmetry, while the area yet to be named the PP showed significant rightward asymmetry. The combined plana were symmetrical. Further research has found the same pattern in the PP (Jäncke et al., 1994). Thus, research has been consistent in finding leftward asymmetry of the PT, rightward asymmetry of the PP, and symmetry of the combined plana as the typical pattern in normal subjects.

**PT Asymmetry and Language Lateralization**

Although there is not a great deal of direct evidence associating PT asymmetry with language dominance (Beaton, 1997), two studies were specifically designed to address this question. Foundas and colleagues examined 12 seizure patients for whom language representation had been determined through the Wada procedure. Eleven patients were right-handed and had left hemisphere representation of speech, and one patient was left-handed with language function localized to the left hemisphere. The authors found a significant relationship between hemispheric dominance for language and PT asymmetry in this small sample (Foundas, Leonard, Gilmore, Fennell, & Heilman, 1994).

Moffat and colleagues measured the PT in left- and right-handed males (Moffat, Hampson, & Lee, 1998). The left-handers were divided into those with left and right hemisphere language lateralization as inferred from dichotic listening tasks. Individuals with left hemisphere representation of language showed a strong leftward PT asymmetry, regardless of handedness,
while individuals with right hemisphere representation of language did not show a consistent pattern of PT asymmetry. This is consistent with the fact that the frequency of right hemisphere language lateralization is significantly smaller than the frequency of reversed asymmetry in the population (Beaton, 1997). Further studies have supported the relationship between dichotic listening asymmetry and PT asymmetry (Hugdahl et al., 2003) while other studies have not (Foster et al., 2002; Heiervang et al., 2000).

Research on the relationship between functional language dominance and structural asymmetry has not yielded any clear conclusions. Although studies show that a reversal of language lateralization does not necessarily show a structural correlate in the PT, there is evidence to support the idea that PT asymmetry is associated with functional language dominance, particularly in the left hemisphere.

**Methodological Issues**

Many studies have been criticized for failing to adequately control for variables such as gender, handedness, age, and verbal intelligence when conducting research involving the PT. The relationship between the PT and each of those variables is examined in this section, and implications for methodology are discussed.

**Gender.**

Gender is an important variable to consider in the study of the PT, as there is substantial evidence that there is a relationship between gender and PT asymmetry. This is not surprising considering that a relationship between gender and language lateralization has been known for decades, with females typically showing less lateralization than males (Beaton, 1997). Research has shown that males have significantly larger left plana than females (Foundas et al., 2002;
Shapleske et al., 1999), and that females are more likely than males to show a reversal of the normal asymmetry of the PT (Beaton, 1997).

Not all research has supported the idea that females do not show the leftward asymmetry of the PT to the same degree as males. One study found no relationship between gender and PT asymmetry (Jäncke et al., 1994), while another study, conducted on children, found that girls showed more leftward asymmetry of the PT than boys, although the effect was very small (Preis et al., 1999). Other research has shown that all brain areas measured were significantly larger in boys than in girls (Schultz et al., 1994). Although the relationship between gender and PT asymmetry is unclear at this time, gender must be controlled for in studies of the PT (Honeycutt et al., 2000).

**Handedness.**

There is a great deal of evidence to suggest that handedness and asymmetry of the PT and PP are related. Steinmetz and colleagues examined the relationship between handedness and PT asymmetry in a study of right-handers and left-handers (Steinmetz, Volkmann, Jäncke, & Freund, 1991). Importantly, there were equal numbers of males and females in each group. Laterality coefficients and interhemispheric asymmetry coefficients were determined. The authors found that PT asymmetry is correlated with hand dominance, with left-handers having significantly reduced leftward asymmetry of the PT. As it is known that left-handedness is related to an increased incidence of bilateral or right hemisphere speech representation (Shapleske et al., 1999), the authors concluded that the relationship they found between PT asymmetry and handedness may be reflective of language representation (Steinmetz et al., 1991).

Foundas and colleagues also examined the relationship between handedness and PT asymmetry in two studies (Foundas et al., 2002; Foundas, Leonard, & Heilman, 1995). The first
study examined 8 right-handed and 8 left-handed adults, with equal numbers of men and women in each group (Foundas et al., 1995). The authors found significant PT asymmetry in the right-handed subjects, but no significant asymmetry in the left-handed subjects, suggesting a relationship between handedness and PT asymmetry. Interestingly, among the left-handed group, subjects who used a non-inverted writing posture, which is thought to be related to right-hemisphere language lateralization, showed rightward asymmetry of the PT.

The second study by Foundas and colleagues was somewhat larger in scope. Sixty-seven adults, including 36 men and 31 women, were compared on measures of handedness and PT and PP (called the “PAR” in this study) asymmetry (Foundas et al., 2002). The sample was 55% right-handed, 13% left-handed, and 31% mixed. Seventy-two percent of the sample showed leftward PT asymmetry and 64% showed rightward PP asymmetry, with only 56% showing both patterns of asymmetry as is considered to be the typical pattern. Handedness was not related to the size of asymmetry of the PT or PP; however, left- and mixed-handers were overrepresented among those with reversed asymmetry. Interestingly, the right PP was the best predictor of handedness, and the left PT was the best predictor of the degree of handedness (Foundas et al., 2002).

In conclusion, it appears that handedness has a strong relationship with asymmetry of the PT and PP (Foundas et al., 1995; Steinmetz et al., 1991). In addition, it has been suggested that the degree of handedness has greater effect on the asymmetry of the PT and PP than the direction of the handedness (Foundas et al., 2002). Furthermore, some researchers believe that structural asymmetry may be more related to handedness than to functional language lateralization (Beaton, 1997). For these reasons, it is extremely important to control for handedness, measured as a continuous variable, in any study examining PT and PP asymmetry.
Age.

Evidence suggests that PT asymmetry is apparent as early as 30 weeks gestation (Chi, Dooling, & Gilles, 1977; Witelson & Pallie, 1973). Thus, the development of PT asymmetry is strongly influenced by genetic and intrauterine development. However, these early studies did not determine if the degree of structural lateralization increased with age, or what the role of the environment and the functional specialization of language may have in the development of PT asymmetry. Recently, Preis and colleagues (1999) investigated whether the degree of PT asymmetry changes across development. Results indicated that there was no relationship between age, PT asymmetry, or total brain volume, suggesting that PT asymmetry remains constant across development and functional lateralization follows this structure (Preis et al., 1999). This suggests that age is a variable that does not need to be controlled for when studying the PT.

Verbal intelligence.

Research suggests that PT asymmetry is associated with verbal intelligence (Eckert & Leonard, 2000; Rumsey et al., 1997a). Semrud-Clikeman and colleagues compared children with dyslexia, ADHD, and normal control subjects on PT asymmetry and neurolinguistic measures, and found that the presence of reversed or symmetrical PT was significantly correlated with lower verbal comprehension scores (Semrud-Clikeman, Hynd, Novey, & Eliopoulos, 1991). Leftward PT asymmetry has been associated with higher Verbal Intelligence Quotient (VIQ) in dyslexic and control subjects (Rumsey et al., 1997a). Another study found that reversed asymmetry was associated with lower verbal ability (Hier, LeMay, Rosenberger, & Perlo, 1978). Furthermore, as Eckert and Leonard have pointed out, deviations in normal patterns of asymmetry are more likely in studies in which the dyslexic children have lower IQ than the
control group, while studies that have covaried by IQ have failed to find differences in temporal lobe areas when comparing dyslexics and controls (Eckert & Leonard, 2000). This suggests that differences in VIQ may be a more important factor in structural asymmetry than reading problems. Thus, it is important to control for verbal intelligence when examining the structural relationship of the PT to functional abilities.

**Conclusions on the Normal Morphology of the Planes**

Research on normal subjects has been consistent in finding leftward asymmetry of the PT, rightward asymmetry of the PP, and symmetry of the combined plana. The relationship between functional language dominance and structural asymmetry is unclear at this time, although there is evidence to support the relationship between functional language dominance and PT asymmetry. Evidence supports the existence of relationships between PT asymmetry and gender, handedness, and verbal intelligence, and the relationship between PP asymmetry and handedness. Thus, these variables must be controlled for in studies utilizing PT or PP measurements. Research does not support a relationship between age and PT asymmetry when total brain volume is controlled for; however, this conclusion is based on data from only one study and it may be prudent to control for age despite this evidence.

**Measurement Issues**

Research on the PT has been plagued by a host of methodological issues that have hindered the interpretation of findings. These issues include the relationship between measurements made postmortem and on MRI scans, the influence of the gyrification of the cerebral hemispheres, the definitions of the borders of the PT, and the type of measurement made.
Comparing Postmortem to MRI Measurements

An assumption that needs to be questioned is that measurements made on cadaver brains are comparable to measurements made on live subjects using MRI. To address this issue, Steinmetz and colleagues developed a method for measuring the area of the PT using MRI (Steinmetz et al., 1989; Steinmetz, Rademacher et al., 1990). As a contrast, area measurements on cadaver brains were made by the use of two-dimensional photographical planimetry taken after brain section. The authors compared postmortem asymmetry coefficients to MRI asymmetry coefficients of the same brains and found a weak correlation, with total area being consistently larger using the total surface area technique. They suggested that, while the measurements could be compared, the MRI measurements were more accurate due to their three-dimensional nature, the correction for individual variation in cortical folding, as well as the photographic foreshortening endemic to the postmortem technique (Steinmetz, Rademacher et al., 1990). Studies comparing Computerized Tomography scans with postmortem measurements of the PT have also found significant correlation, suggesting that the two measurement types can be compared (Pieniadz & Naeser, 1984).

Gyrification

Despite being a plane, as its name suggests, the planum temporale is not a flat structure; rather, it is convoluted due to the folding of the cerebral cortex. Not all methods of measuring the plana are able to measure these convolutions, and there has been a concern that cortex buried in the convolutions may be escaping measure, thereby systematically biasing results (Barta et al., 1995; Shapleske et al., 1999). Furthermore, the degree of gyrification may change across individuals or even between hemispheres. To address this concern, Steinmetz and colleagues calculated a gyrification index for their sample of 10 cadaver brains (Steinmetz et al., 1991).
There were no significant differences in the degree of cortical folding between the left and right hemispheres, although a greater degree of variation was found in the right hemisphere. In a larger sample, gyrification index did not change across hemispheres or between the sexes (Zilles, Armstrong, Schleicher, & Kretschmann, 1988), leading some researchers to conclude that measurements of the PT that do not measure the degree of cortical folding are acceptable. This issue, however, continues to be a matter of debate (Shapleske et al., 1999). While this issue has not been addressed with reference to the PP, it is assumed that the same finding would apply due to the similarity in the morphology of the structures.

The Borders of the Planum Temporale

Research on the PT has been compromised by the use of differing borders to identify the region, which makes it difficult to compare results across studies. Although the lateral and medial borders are clear due to obvious boundaries in the brain, the anterior and posterior borders have been the subject of much debate.

Anterior border.

The anterior border of the PT is usually defined as Heschl's transverse gyrus. Despite this simple definition, the location of the anterior border can be unclear due to the fact that there is often more than one Heschl’s gyrus in each hemisphere. Researchers have not always agreed upon whether or not the second Heschl’s gyrus, if present, should be included in the measurement of the PT (Shapleske et al., 1999). In fact, Geschwind & Levitsky’s seminal study has been criticized for measuring the PT from the first Heschl’s gyrus on the left but from the second Heschl’s gyrus on the right, if present, which may bias the results toward finding leftward asymmetry (Beaton, 1997). As the right hemisphere is more likely to have additional
Heschl’s gyri, not using the most anterior Heschl’s gyrus on both sides would create a systematic bias and lead investigators towards finding leftward asymmetry (Shapleske et al., 1999).

Recent reviews of the measurement of the PT have suggested the use of the most anterior Heschl’s gyrus on both sides as the appropriate landmarks for the anterior borders (Barta et al., 1995; Beaton, 1997; Shapleske et al., 1999). This greatly simplifies matters, increases reliability, and would not create the underestimation of the right PT that may occur with other approaches (Shapleske et al., 1999). Furthermore, this notion is supported by research that suggests that when more than one Heschl’s gyrus is present, the first consists of primary auditory cortex and the second consists of auditory association cortex (Shapleske et al., 1999), similar to the cortex found in the PT. Thus, secondary Heschl’s gyri and the PT have similar cytoarchitecture and function when compared to the more anterior, primary Heschl’s gyri.

Posterior border

The posterior border of the PT has been defined by researchers in different ways. Some researchers have considered the posterior border of the PT as the point where the horizontal ramus of the SF bifurcates into the PAR and/or the posterior descending ramus (PDR) (Chi et al., 1977; Foster et al., 2002; Hynd, Semrud-Clikeman, Lorys, Novey, & Eliopulos, 1990; Kulynych, Vlader, Jones, & Weinberger, 1993; Leonard et al., 1993; Rumsey et al., 1997a; Semrud-Clikeman et al., 1991; Steinmetz et al., 1989). Others have included the PAR (Galaburda et al., 1987; Larsen, HØien, Lundberg, & Ødegaard, 1990; Robichon, Levrier, Farnarier, & Habib, 2000a; Schultz et al., 1994; Steinmetz, Rademacher et al., 1990), which by definition would include the PP in the measurement of the PT. Yet others have included the PDR but not the PAR in their measurements of the PT (Heiervang et al., 2000; Hugdahl et al., 2003; Hugdahl et al., 1998; Preis et al., 1999; Steinmetz et al., 1991).
As mentioned previously, when both the PT and PP are included in the measurement of the plana, symmetry is typically found, with the rightward asymmetry of the PP counterbalancing the leftward asymmetry of the PT (Honeycutt et al., 2000; Steinmetz, Rademacher et al., 1990). For this reason, it is extremely important to measure these areas separately; studies that have measured them as a single body have failed to find asymmetry in normal subjects (Steinmetz, Rademacher et al., 1990). Furthermore, some studies have found that planar tissue is shifted to the right parietal bank in dyslexics when compared to controls (Leonard et al., 1993), suggesting that intrahemispheric asymmetry is important to examine in addition to interhemispheric asymmetry (Morgan, 1996).

Type of Measurement

Many methodologies have been used to determine the size of the PT, including length measurements, area measurements, and, most recently, volumetric measurements. The accuracy of each type of measurement in determining the size of the PT has been a source of much debate in the literature (Barta et al., 1995; Honeycutt et al., 2000; Shapleske et al., 1999). In this section, scan acquisition and the dimension of measurement will be discussed as they relate to the methodology of measuring the PT and PP.

Scan acquisition.

The thickness of the slice in MRI scan acquisition is an important factor in the validity of the PT measurement. Slice thickness has ranged from 1.17 mm to 7.5 mm, and some scans have had gaps of unimaged cortex between the slices. Thick slices and slices with gaps have made it difficult to view the boundaries of the PT, making accurate measurement challenging. Furthermore, as previously discussed, the PT is a convoluted structure and thick slices or gaps between slices may be causing investigators to be unable to measure some of the convolutions of
the structure, leading to inaccurate measurement (Honeycutt et al., 2000). It has been suggested that images with a slice thickness of 1.5 mm and no gaps is best, as it allows for good visualization of boundaries, cortical folding, and grey/white matter contrast (Honeycutt et al., 2000; Shapleske et al., 1999).

**Measurement dimension.**

Measurement of a three-dimensional structure buried deep in the cerebral cortex is obviously more difficult when using MRI scans than it is when using cadaver brains. Initial research using MRI scans to investigate the relationship between PT asymmetry and dyslexia used length measurements of the PT on sagittal or coronal scans (Hynd et al., 1990; Larsen et al., 1990; Leonard et al., 1993; Semrud-Clikeman et al., 1991). This method was criticized for measuring the PT as if it were a flat plane (Honeycutt et al., 2000) and because length measurements could not be compared to measurements done on postmortem brains (Morgan & Hynd, 1998).

In an effort to create a measurement technique that takes the convolutions of the PT into account and is more comparable, Steinmetz and colleagues (1989) developed a method for measuring the area of the PT using MRI. The convoluted length of the PT was measured on serial sagittal sections of three-dimensional representations of the brains. The resulting lengths were multiplied by the distances between sections and summed to provide an area measurement that takes the convolutions of the PT into account. As this technique measures the cortical folding of the PT, larger area values were consistently found using this method when compared to the two-dimensional planimetry, or measuring area from photographs taken of cadaver brains, as done in post-mortem studies (Shapleske et al., 1999).
Kulynych and colleagues attempted to improve upon the technique for obtaining area measurements presented by Steinmetz and colleagues (Kulynych et al., 1993). They introduced cortical surface rendering, which presents a three-dimensional view of the cerebral cortex, as a method by which the convolutions and boundaries of the PT would be made more visible. In addition, a slight head tilt of a subject in the scanner can impact the angle of orientation. To correct for this problem, Kulynych and colleagues rotated the slices so that a line connecting the anterior and posterior commissures was centered on the horizontal axis; the stacks of slices were then resliced in this orientation. An additional problem in measuring the PT from a two-dimensional computer image is “foreshortening” of the curved surface of the temporal lobe (Kulynych et al., 1993). Unfortunately, the right temporal lobe slopes at a greater angle than the left (Shapleske et al., 1999), systematically biasing measurements. To correct for this problem, Kulynych and colleagues developed a mathematical formula to determine the amount of surface area reduction due to the foreshortening effect. Furthermore, Kulynych and colleagues suggested that the MRI scans be presented simultaneously in the sagittal, axial, and coronal planes, to ensure visibility of the boundaries of the PT.

When compared to Steinmetz’s serial sagittal slice method for determining area, Kulynych and colleagues found greater inter-rater reliability than reported by Steinmetz and colleagues, although measurements were conducted on only seven brains (Kulynych et al., 1993). Both the Steinmetz method (Heiervang et al., 2000; Hugdahl et al., 2003; Hugdahl et al., 1998; Preis et al., 1999) and the Kulynych method (Rumsey et al., 1997a) continue to be popular in the literature. In addition to area measurements, a technique to make volumetric measurements that take the convolutions of the PT and PP into account has been proposed (Honeycutt et al., 2000). While the authors suggest that this technique may be more reliable than
area measurements, the fact that the technique takes three to four hours per brain makes it
impractical for large studies.

In sum, the combination of measuring the PT using different dimensions and techniques,
varying technologies utilized in image acquisition, and the use of differing boundaries has likely
been responsible for much of the contrasting results found in the research of PT asymmetry and
dyslexia. Attempts have been made to create general guidelines for the measurement of the PT
and PP so that results can be more easily compared (Barta et al., 1995; Honeycutt et al., 2000;
Shapleske et al., 1999).

Conclusions on Measurement Issues in Examining Plana Morphology

Based on research on the measurement of the PT, it appears that postmortem and MRI
measurements are significantly correlated and can be compared. Evidence suggests that
gyrification of the PT is equal across hemispheres, so that measurement techniques that do not
account for cortical folding are acceptable; however, this area continues to be a matter of debate
in the literature. Another matter of debate in the literature is the boundaries of the planum
temporale. Recently, a consensus has been reached that the anterior border of the PT should be
the most anterior Heschl’s gyrus in each hemisphere. The posterior border continues to be yet
another matter of debate, with some researchers considering it to be the termination of the
horizontal aspect of the SF, while others include the PDR or PAR in measurement. The
definition of the PP as a unique area which is adjacent to the PAR may result in researchers
measuring these areas separately. Finally, the methods for measuring the area of the PT as
developed by Steinmetz et al. (1989) and Kulynych et al. (1993) are the most prevalent in the
literature at this time.
Findings Relating Temporal-Parietal Regions to Developmental Dyslexia

Many studies have examined the asymmetry of temporal-parietal regions in dyslexia. These studies examined regions that contain the PT and PP, but were not able to measure them directly due to slice thickness limitations of computerized tomography (CT scans) and early MRI. It must be cautioned that the results of these studies cannot be directly compared to studies of the PT and PP because other brain regions located in the temporal and parietal lobes are included in the measurements. Details of each study, including diagnostic criteria used to define dyslexia, measurement technique utilized, and results are summarized in Table 1.

Studies Supporting Atypical Temporo-Parietal Asymmetry in Dyslexia

One of the first studies to investigate the relationship between cerebral asymmetry and developmental dyslexia examined 24 patients with developmental dyslexia (Hier et al., 1978). The sample consisted of 22 males and 2 females between the ages of 14 and 47 years, 75% of whom were right-handed. Reversed asymmetry of the parieto-occipital region was found in significantly more patients than would have been expected, given the distribution of handedness, and was associated with lower verbal ability. Thus, this study supports a relationship between dyslexia and atypical asymmetry of the parietal region.

Jernigan and colleagues investigated temporo-parietal asymmetry in children with co-occurring language and learning impairments, all of whom had severe reading problems (Jernigan, Hesselink, Sowell, & Tallal, 1991). The average age of the children was nine years old, and there were approximately equal rates of left-handedness and an equal distribution of genders within the groups. While Jernigan et al. did not find atypical asymmetry of the region containing the PT, the left posterior parietal volume was significantly reduced in children with
Table 1: Temporal Lobe Asymmetry and Dyslexia

<table>
<thead>
<tr>
<th>Authors</th>
<th>Participants</th>
<th>Diagnostic Criteria</th>
<th>PT Measurement Technique and Borders</th>
<th>Findings</th>
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</thead>
</table>
| Hier et al., 1978 | • 24 patients with dyslexia, ages 14-47.  
• 22 males, 2 females.  
• 18 right-handers, 6 left-handers. | • Either a score below the fifth grade level on the GORT or a history of reading two years below grade level while in school.  
• IQ was not a function of diagnosis. | • Computerized Brain Tomography.  
• 4 or 6 axial sections.  
• Widths of the posterior portions of the cerebral hemispheres were measured (parietooccipital region), and brain were classified as R>L, L>R, or L=R. | • R>L = 10 patients (1 female, 3 left-handers).  
• L>R = 8 patients (0 females, 3 left-handers).  
• L=R = 6 patients (1 female, no left-handers).  
• Significantly more patients showed R>L asymmetry than would be expected given handedness.  
• R>L was significantly correlated with lower verbal ability. |
| Duara et al., 1991 | • 21 dyslexic (12 males, 9 females) and 29 control (15 male and 14 female) subjects.  
• All subjects were right-handed adults. | • At least average intelligence.  
• 1.5 SD discrepancy between IQ and reading and/or spelling.  
• A history of childhood reading and spelling problems.  
• A family history of dyslexia in at least two generations. | • 1.0 or 1.5 T MRI scanner obtained 7-mm thick transverse (axial) slices with 3.0 mm gaps.  
• The brain was divided into seven sections in each hemisphere and the area of each section was determined. Thus, the PT was not measured directly. | • The region containing most of the planum temporale was found to be symmetrical across both groups.  
• Rightward asymmetry of the angular gyrus was found in the dyslexic group while symmetry was found in the control group. |
<table>
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<tr>
<th>Study</th>
<th>Sample Characteristics</th>
<th>MRI Parameters</th>
<th>Findings</th>
</tr>
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</table>
| Jernigan et al., 1991 | 20 language and learning-impaired (L/LI) children.  
All L/LI children had severe reading problems.  
Average age of 9 years (13, boys, 7 girls, 2 left-handers).  
12 normal control subjects (eight boys, 4 girls, 1 left-hander). | 1.5 T MRI scanner obtained 7-mm thick transverse (axial) slices with 3.0 mm gaps.  
Volumetric measurement of 6 homologous regions in each hemisphere, including the left posterior parietal region which contains the PT. | Left posterior parietal volume, which contains the PT, was significantly smaller in the children with L/LI.  
Did not find aberrant left posterior parietal asymmetry.  
Authors concluded that functional lateralization of language may be atypical in this group. |
| Kushch et al., 1993   | 17 individuals with dyslexia, 9 male, 8 female, ages 11-63 years, handedness quotient .63.  
21 control subjects: 8 males, 13 females, ages 11-63 years; handedness quotient .79. | 1.5 T MRI magnet obtained 5-mm thick contiguous images in the coronal plane.  
Area measurements were made of the superior surface of the temporal lobes (SSTL). This area includes the PT. | Symmetry of SSTL area in dyslexics compared to leftward asymmetry in controls.  
Leftward asymmetry positively correlated with Woodcock-Johnson Passage Comprehension Scores. |
| Dalby et al., 1998    | 17 children with dyslexia, 6 “retarded” readers, and 12 normal controls.  
All subjects were male and right-handed.  
Ages 13-17 years. | 1.5-T MRI scanner obtained contiguous 7 mm thick sagittal and coronal slices.  
On coronal slices, the depth of the Sylvian Fissure and cross-sectional area of the temporal lobe was measured in each hemisphere. | Symmetry or rightward asymmetry was more common in the dyslexic group, while leftward asymmetry was more common in the controls and “retarded” readers.  
Degree of leftward asymmetry positively correlated with reading and phonemic skills. |
language and learning impairments. The authors postulated that functional language lateralization may be aberrant in children with these disorders. Although the authors did not find atypical asymmetry, this study supports the idea that there may be abnormalities of the left PT in individuals with language and learning problems.

In a study of children and adults, Kushch and colleagues made area measurements of the superior surface of the temporal lobe (SSTL), which contains the PT (Kushch et al., 1993). The dyslexic group displayed symmetry of the SSTL area, while the control group displayed leftward asymmetry. The samples differed on handedness, with the dyslexic group displaying greater left-handedness than the control group. Due to the relationship between handedness and PT asymmetry, it is possible that the symmetry of the area containing the PT in the dyslexic group was due in part to left-handedness.

Dalby and colleagues compared adolescents with dyslexia, “retarded readers,” who had low reading and IQ, and control subjects (Dalby, Elbro, & Stødkilde-Jørgensen, 1998). Leftward asymmetry, based on area measurements of coronal slices of the temporal lobe, was found in the “retarded readers” and control subjects, while the dyslexic group displayed significantly more symmetry or rightward asymmetry. Furthermore, leftward asymmetry was correlated with reading and phonemic skills, a result that remained after differences in nonverbal IQ were controlled. It is interesting that this study found morphological differences in two groups of poor readers that were differentiated only by intelligence.

Studies That Do Not Support Atypical Temporo-Parietal Asymmetry in Dyslexia

Duara and colleagues compared 21 dyslexic (12 male, 9 females) and 29 control (15 male, 14 female) subjects on temporal lobe asymmetry (Duara et al., 1991). All subjects were right-handed adult males. The region containing the PT was symmetrical in both groups, which
is an unusual finding in that most studies that have not found group differences found leftward asymmetry of the PT. This suggests that the section containing the PT may also have contained the PP, which together are symmetrical (Jäncke et al., 1994; Steinmetz, 1996).

**Conclusions on the Findings Regarding Temporo-Parietal Asymmetry in Dyslexia**

The bulk of studies on the temporo-parietal asymmetries in dyslexia have found atypical asymmetry or symmetry in dyslexic groups compared to controls. This suggests that morphological differences of the temporal and parietal lobes exist in individuals with dyslexia. Some studies adequately controlled for important variables such as handedness and verbal intelligence (Dalby et al., 1998; Jernigan et al., 1991), while some studies may have had confounded results due to unequal distribution of these variables between groups (Kushch et al., 1993).

**Findings Regarding Plana Morphology and Developmental Dyslexia**

As mentioned previously, results from studies on the relationship between PT asymmetry and developmental dyslexia have varied widely. This disparity has likely occurred due to differences in a wide variety of methodological techniques, mentioned in previous sections. The majority of these studies did not examine PP asymmetry. The diagnostic criteria used to define dyslexia, the measurement techniques, and the results are summarized in Table 2.

**Postmortem Studies**

After Geschwind & Levitsky published their landmark study on normal PT asymmetry in 1968, which linked language lateralization to leftward asymmetry of the PT, many researchers began to investigate atypical PT asymmetry in language-based disorders, including dyslexia.
<table>
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<th>Authors</th>
<th>Participants</th>
<th>Diagnostic Criteria</th>
<th>PT Measurement Technique and Borders</th>
<th>Findings</th>
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</table>
| Galaburda & Kemper, 1979 | • Postmortem case study of a 20-year old man with well-documented developmental dyslexia. | • Average intelligence, significantly below average reading and spelling. | • Postmortem analysis.  
• PT defined as “the region of the superior temporal plane lying posterior to Heschl’s gyrus.” | • Symmetrical PT.  
• Cytoarchitectonic abnormalities, including polymicrogyria, were found and confined to Heschl’s gyrus and the PT on the left side.  
• Polymicrogyria were found mainly in cytoarchitectonic area Tpt. |
| Galaburda et al., 1985   | • Postmortem case study of four dyslexic brains, including the one from the 1979 study.  
• Ages 14-32 years.  
• Non-righthandedness and autoimmune disease were present in the subjects and their families. | • Diagnosis during life.  
• PT defined as “the triangular region lying immediately caudal to the transverse gyrus of Heschl on the dorsal surface of the temporal lobe…”  
• Measurement techniques not described. | • Symmetrical PT in all four subjects.  
• Cytoarchitectonic abnormalities, including neuronal ectopias and dysplasias, found in primarily the left perisylvian region.  
• Larger right PT is the cause of symmetry. |                                                                                                                                               |
| Humphreys et al., 1990   | • Postmortem case study of 3 women with developmental dyslexia.  
• 2 right-handed, 1 left-handed.  
• Ages at death were 36, 88, and 20. | • Diagnosis during life.  
• 1 patient suffered from bulimia and died of complications, another from depression with psychotic symptoms and died from a suicide attempt. | • “The areas of the temporal plana were calculated on computer-assisted reconstructions made from the serial sections.” | • Symmetrical PT.  
• In one brain, glial scarring was present in the left perisylvian region.  
• The authors suggested that a familial tendency to develop dyslexia is expressed through symmetrical plana. |
<table>
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<tr>
<th>Study</th>
<th>Participants</th>
<th>FSIQ ≥ 85.</th>
<th>Imaging</th>
<th>Length was measured on extreme lateral sagittal slices.</th>
<th>Border of PT: Anterior border of PT: the second transverse Heschl’s sulcus.</th>
<th>Border of PT: Posterior border of PT: the posterior end of the sylvian fissure at the temporoparietal juncture.</th>
<th>Asymmetry:</th>
<th>Conclusion</th>
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<tbody>
<tr>
<td>Hynd et al, 1990</td>
<td>10 children with dyslexia, 10 children with ADD/H, and 10 normal age- and sex-matched control subjects.</td>
<td>Reading achievement ≥ 20 points below FSIQ on both Word Attack and Passage Comprehension subtests of the WRMT-R.</td>
<td>0.6-T Technicare MRI Scanner made sequential T₁ sagittal and axial images that were 7.5 mm thick.</td>
<td>Length was measured on extreme lateral sagittal slices.</td>
<td>Anterior border of PT: the second transverse Heschl’s sulcus.</td>
<td>Posterior border of PT: the posterior end of the sylvian fissure at the temporoparietal juncture.</td>
<td>Symmetrical, asymmetrical, or having reversed asymmetry.</td>
<td>Children with dyslexia had a significantly shorter left PT when compared to the other groups.</td>
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<td>3 children with dyslexia were left-handed, while all children in other groups were right-handed.</td>
<td>Positive family history for learning problems, personal history of difficulty learning to read, and no hyperactivity.</td>
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<td>No differences were found in the length of the right PT across groups.</td>
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<td>Significantly higher IQ in controls.</td>
<td>Inattention and impulsivity were permitted.</td>
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<td>90% of the children with dyslexia had either symmetrical or reversed asymmetry of plana length, which is statistically significant compared to ADD/H and control groups, who displayed the typical pattern.</td>
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<tr>
<td>Semrud-Clikeman et al., 1991</td>
<td>10 children with dyslexia, 10 children with ADHD, and 10 normal controls.</td>
<td>Reading achievement ≥ 20 points below FSIQ on both Word Attack and Passage Comprehension.</td>
<td>0.5-T MRI Scanner made sequential sagittal and axial images that were 7.5 mm thick.</td>
<td>Length was measured on extreme lateral sagittal slices.</td>
<td>Anterior border of PT: the second transverse Heschl’s sulcus.</td>
<td>Posterior border of PT: the posterior end of the sylvian fissure at the temporoparietal juncture.</td>
<td>Symmetrical, asymmetrical, or having reversed asymmetry.</td>
<td>Reversed or symmetrical PT length was related to lower verbal comprehension scores.</td>
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<td>Two members of each group were female.</td>
<td>No history of ADHD.</td>
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<td>Individuals with leftward asymmetry of the PT were significantly better on measures of total reading achievement, pseudoword reading, reading comprehension, confrontational naming, and automatized ability.</td>
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<td>Ages 7 to 15 years.</td>
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| Larsen et al., 1990 | - 19 eighth graders with dyslexia.  
- 19 controls matched for age, intelligence, social-cultural factors, and educational environment.  
- Subjects were selected from 1250 eighth graders in the public school system.  
- Poor word recognition on silent and oral measures.  
- Absence of poor intelligence, sensory deficits, gross neurological disturbances, poor education, and language deviation.  
- 1.5 T MRI scanner obtained 5-mm thick axial slices with a 2.5 mm gap between sections.  
- Anterior border of PT: the "ridge" of Heschl’s gyrus.  
- Posterior border of PT: the most caudal slice showing the Sylvian fissure.  
- A high rate of PT symmetry was found among children with dyslexia (70%) when compared with controls (30%).  
- Increased symmetry was the result of a larger than “normal” right plana.  
- All subjects with phonological deficits had symmetrical plana.  
- No clear association between PT symmetry or asymmetry was found with regards to handedness. |
| Leonard et al., 1993 | - Individuals with dyslexia: 7 males and 2 females, ages 15 to 65 years, who were volunteers from professional families.  
- Unaffected first and second-degree relatives: 4 males and 6 females, ages 6 to 63 years.  
- Control subjects: 5 males and 7 females, ages 14 to 52 years.  
- Subjects had been previously diagnosed by a pediatrician, pediatric neurologist, or learning disabilities specialist.  
- 1 T MRI magnet obtained 128 1.25-mm thick sagittal images.  
- Anterior border of PT: the most anterior Heschl’s sulcus.  
- Posterior border of PT: the bifurcation of sylvian fissure into a PAR or PDR.  
- Length was measured for both temporale (PT) and parietal banks (PP).  
- Interhemispheric asymmetry coefficient was determined using (L-R)/(L+R)(0.5)  
- All subjects demonstrated a larger left than right temporale bank (PT) and larger right than left parietal bank (PP).  
- The group with dyslexia had exaggerated leftward asymmetry of the temporale bank (PT).  
- Subjects with dyslexia were more likely to have anomalous gyri in the planum and parietal operculum. |
<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Methods/Findings</th>
</tr>
</thead>
</table>
| Schultz et al., 1994 | 17 children with dyslexia (10 males, 7 females). 14 control children (7 males, 7 females). Ages 7.5-9.7 years. All children right-handed. Groups equated on IQ. | Two definitions used:  
- Discrepancy-based definition: regression-based discrepancy of 1.5 SD between reading achievement and IQ. All 17 dyslexic subjects met this criteria.  
- Low achievement: Reading score below the 25th percentile on real words and pseudowords. 9 dyslexic subjects also met this criteria. |  
- 1.5 T MRI scanner obtained contiguous 5-mm thick coronal slices.  
- Surface area of PT measured.  
- Anterior border of PT: Heschl’s sulcus, which could not be reliably identified in all subjects.  
- Posterior border of PT: the end of the SF (Included PP).  
- Interhemispheric asymmetry coefficient was determined using (L-R)/(L+R)(0.5)  
- Surface area and symmetry of the PT was not significantly different between groups when age and overall brain size controlled for.  
- Leftward asymmetry was found in both groups.  
- All measurements in boys were significantly larger, regardless of age.  
- Age was positively correlated with brain size.  
- Sex, age, handedness, overall brain size, and definition of dyslexia important in studies of the PT in dyslexia. |
| Rumsey et al., 1997 | 16 right-handed dyslexic men, age 18-40 years. Prior PET studies had shown abnormal temporal and parietal activation in these men. 14 matched control subjects. |  
- Wechsler verbal and performance IQ ≥ 90.  
- GORT-3 Passage score of ≤ 90.  
- All but one had a 15-point discrepancy between IQ and reading.  
- Persistent developmental history of reading problems. |  
- 1.5 T Sigma MRI scanner obtained 124 contiguous 1.5 mm thick axial slices.  
- Axial slices were resliced into the sagittal plane.  
- NIH image area measurements using surface rendering techniques to determine surface area of the PT, using the technique adapted by Kulynych et al., 1993.  
- Length measurement for the PP.  
- Interhemispheric asymmetry coefficient was determined using (L-R)/(L+R)(0.5)  
- Anterior border of PT: Heschl’s sulcus at the most anterior Heschl’s gyrus.  
- Posterior border of PT: The origin of the PAR. |  
- Both groups showed equivalent leftward asymmetry of the PT and rightward asymmetry of the PP.  
- Authors suggest that the deviations from normal asymmetry may be due to left-handedness or developmental language disorders in dyslexic groups.  
- Leftward asymmetry was associated with higher verbal IQ. |
<table>
<thead>
<tr>
<th>Hugdahl et al., 1998</th>
<th>Heiervang et al., 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 children with dyslexia (20 males, 5 females, 2 females left-handed).</td>
<td>20 right-handed dyslexic boys.</td>
</tr>
<tr>
<td>25 control children (20 males, 5 females, 2 females left-handed).</td>
<td>20 matched controls.</td>
</tr>
<tr>
<td>Mean age 11.8 years (dyslexics), 11.7 years (controls).</td>
<td>Girls excluded.</td>
</tr>
<tr>
<td>Groups matched on age, gender, and handedness.</td>
<td>Subjects were selected from 950 fourth graders in Norway schools.</td>
</tr>
<tr>
<td>Subjects were selected from 950 fourth graders in Norway schools.</td>
<td>Mean age 11.8 years (dyslexics), 11.7 years (controls).</td>
</tr>
<tr>
<td>VIQ significantly lower in dyslexic group.</td>
<td>VIQ and PIQ significantly lower in dyslexic group.</td>
</tr>
<tr>
<td>Lowest 10\textsuperscript{th} percentile on a group-administered spelling test.</td>
<td>Lowest 10\textsuperscript{th} percentile on a group-administered spelling test.</td>
</tr>
<tr>
<td>Reading score $\geq$ 2 SD below age mean.</td>
<td>Reading score $\geq$ 2 SD below age mean.</td>
</tr>
<tr>
<td>FSIQ $\geq$ 85.</td>
<td>FSIQ $\geq$ 85.</td>
</tr>
<tr>
<td>1.5 T MRI scanner obtained 128 sagittal slices with 1.25mm-slice thickness.</td>
<td>1 T MRI scanner obtained 128 contiguous sagittal slices with 1.25-mm thickness.</td>
</tr>
<tr>
<td>Area of PT determined according to methodology of Steinmetz et al., 1989, which measures entire folded cortical surface of the PT.</td>
<td>Area of PT and PP determined according to methodology of Steinmetz et al., 1989, which measures entire folded cortical surface of the PT.</td>
</tr>
<tr>
<td>Included PDR in PT.</td>
<td>Included PDR in PT.</td>
</tr>
<tr>
<td>Anterior border of PT: first (most anterior) Heschl’s transverse gyrus.</td>
<td>Anterior border of PT: first (most anterior) Heschl’s transverse gyrus.</td>
</tr>
<tr>
<td>Posterior border of PT: end of the horizontal SF.</td>
<td>Posterior border of PT: transition of the posterior wall of the descending into the ascending ramus of the SF.</td>
</tr>
<tr>
<td>Leftward PT asymmetry in both groups.</td>
<td>Leftward PT asymmetry in both groups.</td>
</tr>
<tr>
<td>Reduced PT asymmetry in dyslexic group.</td>
<td>Smaller left PT in dyslexic group.</td>
</tr>
<tr>
<td>Left Pt area was smaller in dyslexic group.</td>
<td>Rightward asymmetry of the PP was found in significantly fewer dyslexic children than controls.</td>
</tr>
<tr>
<td>Significant correlation between PT asymmetry and reading in control group only.</td>
<td>Significant correlation between PT asymmetry and dichotic listening asymmetry.</td>
</tr>
</tbody>
</table>
| No correlation between PT asymmetry and dichotic listening asymmetry. | }
<table>
<thead>
<tr>
<th>Study</th>
<th>Sample Description</th>
<th>Methods</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robichon et al., 2000</td>
<td>16 adult males with dyslexia, mean age 21 years. 9 right-handed, 7 left-handed.</td>
<td>1.5 T MRI scanner obtained 124 contiguous axial slices with 1.17-mm thickness.</td>
<td>No difference in PT asymmetry between the two groups, but PP included in analyses.</td>
</tr>
<tr>
<td></td>
<td>14 age-matched male controls, mean age 23.6 years. 10 right-handed, 4 left-handed.</td>
<td>Area measurements made in the sagittal plane.</td>
<td>Parietal ribbon had greater leftward asymmetry in dyslexics than controls.</td>
</tr>
<tr>
<td></td>
<td>Reading age of dyslexics: 10.9. Reading age of controls: 14.3.</td>
<td>Anterior border of PT: \textit{first (most anterior) Heschl’s transverse gyrus}.</td>
<td>Suggests phonological segmentation is a frontal lobe skills, while phonological memory is related to parietal lobe morphology.</td>
</tr>
<tr>
<td></td>
<td>Childhood history of $\geq$ 2 years of school learning problems.</td>
<td>Posterior border of PT: \textit{Posterior endpoint of lateral sulcus (includes PP)}.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Family history of dyslexia in at least one first-degree relative.</td>
<td>Interhemispheric asymmetry coefficient was determined using $(L-R)/(L+R)(0.5)$.</td>
<td></td>
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<tr>
<td></td>
<td>Previous diagnosis of dyslexia and past speech therapy.</td>
<td></td>
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<tr>
<td></td>
<td>IQ $&gt; 90$.</td>
<td>No correlation between PT asymmetry and dichotic listening asymmetry.</td>
<td></td>
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<tr>
<td></td>
<td>Exclusions: neurological or psychiatric impairments and hyperactivity.</td>
<td>Subjects with the atypical left ear advantage had larger right PTs.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Subjects with weaker linguistic skills tended to have atypical asymmetry tended to have larger right PTs.</td>
<td></td>
</tr>
<tr>
<td>Foster et al., 2002</td>
<td>19 children with dyslexia, 10 with comorbid diagnoses of ADHD (15 males, 4 females, 18 right-handers, 1 left-hander).</td>
<td>0.6 T MRI scanner obtained gapless sagittal slices with 3.1-mm thickness.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23 children with ADHD (17 males, 6 females, 18 right-handers, 5 left-handers).</td>
<td>Anterior border of PT: \textit{the most anterior Heschl’s sulcus}.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 normal controls (5 males, 7 females, 8 right-handers, 2 left-handers, 2 of unknown handedness).</td>
<td>Posterior border of PT: \textit{the bifurcation of sylvian fissure into a PAR or PDR}.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>All subjects 8-12 years of age.</td>
<td>Direct distance measured on the “best-view” slice and two slices medial and lateral to this slice.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20-point discrepancy between FSIQ and reading achievement as measured by the WRAT reading subtest and WRMT-R Word Attack and Passage Comprehension subtests.</td>
<td>The average measurement was then used.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interhemispheric asymmetry coefficient was determined using $(L-R)/(L+R)(0.5)$.</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Hugdahl et al., 2003</td>
<td>23 children with dyslexia (20 males, 3 females, 1 left-hander). 23 control children (19 males, 4 females, 1 left-hander). All subjects 8-12 years of age. Subjects were selected from 950 fourth graders in Norway schools. VIQ lower in dyslexic group, but not at a significant level.</td>
<td>Lowest 10\textsuperscript{th} percentile on a group-administered spelling test. Reading score $\geq$ 2 SD below age mean. FSIQ $\geq$ 85.</td>
<td>1.0 T MRI scanner obtained 128 sagittal slices with 1.25mm-slice thickness. Area of PT determined according to methodology of Steinmetz et al., 1989, which measures entire folded cortical surface of the PT. Included PDR in PT. Anterior border of PT: first (most anterior) Heschl’s transverse gyrus. Posterior border of PT: end of the horizontal SF, including the cortex in the PDR. Interhemispheric asymmetry coefficient was determined using $(L-R)/(L+R)100$. Both groups had statistically larger left than right PTs. Left Pt area was significantly smaller in dyslexic group, and the right PT was similar in size across groups. Significant positive relationship between PT and dichotic listening asymmetry in the dyslexic but not control group. Suggests a relationship between PT area and perception of phonetic stimuli. Overall brain size not controlled for.</td>
</tr>
</tbody>
</table>
First, Galaburda and Kemper investigated the morphology of the PT in a postmortem case study of a 20-year old man with a documented history of dyslexia (Galaburda & Kemper, 1979). The subject had symmetrical plana and cortical abnormalities, such as polymicrogyria, in the left Heschl’s gyrus and PT. In addition, these abnormalities were found mainly in cytoarchitectonic area Tpt.

In 1985, Galaburda and colleagues examined postmortem four brains of individuals with developmental dyslexia, one of whom was the subject of the 1979 Galaburda & Kemper study (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985). The subjects ranged in age from 14 to 32 years and had a family history of autoimmune disorders and left-handedness. All four subjects had symmetrical plana and cortical abnormalities in the left perisylvian region, which includes the PT. This laboratory also examined postmortem the brains of three females with documented histories of developmental dyslexia (Humphreys et al., 1990). These subjects also showed symmetry of the PT. All three subjects had cortical anomalies such as ectopias, dysplasias, and brain warts, although only one patient showed these anomalies in the left perisylvian region. One patient was left-handed. This study provided evidence that the neurobiological correlates of developmental dyslexia may be the same in males as in females (Morgan, 1996).

Galaburda observed that it is extremely unlikely that symmetrical plana would occur in these dyslexic subjects by chance alone; rather, the familial risk for developmental dyslexia may be expressed through symmetrical plana (Galaburda et al., 1985). Furthermore, it was noted that in brains with symmetrical plana, the right plana is larger than in brains with typical leftward asymmetry, so there are symmetrically large plana. Galaburda and colleagues suggest that the larger right PT is due to insufficient pruning during corticogenesis. Thus, individuals with
symmetrical plana have excess language cortex on the right side that may interfere with language processing (Galaburda, 1993). The work by this lab also notes that neither symmetrical plana nor cortical anomalies alone are likely to account for developmental dyslexia. Instead, it may be that only in cases where both neuroanatomical abnormalities are present that developmental dyslexia is found (Galaburda et al., 1985).

**Structural Magnetic Resonance Imaging**

Studies that support a relationship between atypical PT asymmetry and dyslexia.

Hynd and colleagues were the first to examine the relationship between PT asymmetry and dyslexia using structural MRI (Hynd et al., 1990). They examined 10 children with dyslexia, 10 children with Attention-Deficit Disorder without Hyperactivity, and 10 control subjects matched for gender and age. Each group was composed of 8 males and 2 females. Subjects were categorized as either having leftward asymmetry of the PT, rightward asymmetry of the PT, or symmetrical PTs based on the PT length. Ninety percent of children with dyslexia displayed symmetry or reversed asymmetry of the PT, which is a significant difference when compared to the typical pattern of 70% showing $L > R$ and 30% $L \leq R$ found in the ADD/H and control subjects. In addition, the children with dyslexia had significantly smaller left PTs compared to the other groups. This study has been criticized because the dyslexic group had significantly lower Full Scale IQ and a higher degree of left-handedness (Shapleske et al., 1999). It is possible that the decreased incidence of typical leftward asymmetry in the dyslexic group is due to these factors rather than the presence of dyslexia.

Larsen and colleagues selected 19 children with dyslexia and 19 control subjects matched for age, intelligence, socio-economic status, and educational environment from 1250 eighth graders in the public school system (Larsen et al., 1990). The length of the PT, which was
defined as extending to the end of the SF and thus included the PP, was measured on coronal slices. Subjects were categorized into groups based on PT asymmetry. A significantly higher rate of PT symmetry was found in the children with dyslexia as compared to control subjects. A higher rate of left-handedness was found in the dyslexic subjects, which may have biased the results due to the relationship between handedness and PT asymmetry. However, there was no discernable relationship between PT asymmetry and handedness in this sample, possibly due to the inclusion of the PP in the measurement of the PT.

In a study of 25 children with dyslexia and 25 control children carefully matched for age, gender, and handedness, Hugdahl and colleagues found that both groups had statistically larger left than right PT areas (Hugdahl et al., 1998). There was a significant difference, however, in the degree of PT asymmetry between the groups, with the children with dyslexia having significantly reduced leftward asymmetry. This reduction in leftward PT asymmetry was due to the smaller area of the left PT in children with dyslexia. This study has the advantage that subjects were not clinic-referred but instead were chosen from 950 fourth graders. Verbal intelligence was significantly lower in the dyslexic group, a factor that may have influenced the results. However, Hugdahl found similar results in a later study (Hugdahl et al., 2003). This study eliminated subjects, presumably for low verbal intelligence, which in this sample was lower in the dyslexic group but not at a statistically significant level.

Using the same sample of children as Hugdahl but eliminating the five females from each group, Heiervang and colleagues examined the relationship between dyslexia and PT/PP asymmetry (Heiervang et al., 2000). Heiervang’s sample was now completely male and right-handed. As in the study by Hugdahl and colleagues (1998), leftward asymmetry of the PT was found in both groups. The degree of leftward PT asymmetry, however, was significantly reduced
in the group of children with dyslexia due to a smaller left PT. This study also examined the asymmetry of the PP, and found that the rightward asymmetry of the PP was found in significantly fewer of the children with dyslexia than control children. Interestingly, there was no relationship found between PT asymmetry and reading achievement in the dyslexic group, but this relationship was found in the control group. The dyslexic sample had significantly lower VIQ and PIQ in this study.

Studies that do not support a relationship between atypical PT asymmetry and dyslexia.

Leonard and colleagues examined individuals with dyslexia, seven males and two females ages 15-65 years, and similar numbers of unaffected first- and second-degree relatives and control subjects (Leonard et al., 1993). All subjects were right-handed, with the exception of one unaffected relative. The length of the PT and PP were measured and interhemispheric asymmetry coefficients were determined. All subjects demonstrated the normal pattern of asymmetry of the PT and PP, regardless of group membership. Contrary to previous results in this field, the dyslexic group had exaggerated leftward asymmetry of the PT. Dyslexic subjects demonstrated anomalous intrahemispheric asymmetry due to a shift of temporal tissue from the temporal bank to the parietal bank in the right hemisphere, suggesting deviations in the PP in individuals with dyslexia. It should be noted that the dyslexic participants in this study were chosen on the basis of a historical diagnosis, rather than a full neuropsychological evaluation, which may have confounded the results.

In their 1994 study, Schultz and colleagues compared 17 children with dyslexia (ten males and seven females) to 14 control children (seven males and seven females) (Schultz et al., 1994). All children were right-handed, and the groups were matched on intelligence. Leftward PT asymmetry was found in both groups, and PT asymmetry and area were not significantly
different between groups when age and total brain size were controlled for. The authors suggested that previous studies that found an association between PT asymmetry and dyslexia did not adequately control for sex, age, handedness, and total brain size.

Rumsey and colleagues examined 16 right-handed adult men with dyslexia and 14 matched control subjects. Prior research indicated that the dyslexic men displayed abnormal temporal and parietal activation on language tasks compared to controls. Surface area measurements of the PT and length measurements of the PP were taken. Both groups showed equivalent leftward asymmetry of the PT and rightward asymmetry of the PP, as is the typical pattern of asymmetry. The authors suggested that atypical asymmetry patterns in dyslexia may be due to co-occurring left-handedness or language disorders.

Another study of adult males did not find a relationship between dyslexics and control subjects on PT asymmetry (Robichon et al., 2000a). In this case, 7 of the 16 dyslexic males were left-handed, which was a higher incidence than the 4 left-handers out of the 14 control subjects. It is possible that asymmetry was not found despite the unequal degree of left-handedness between the two groups due to the fact that the PP was included in the measurement of PT area. When the PT and PP are combined, plana are symmetrical in typical populations (Jäncke et al., 1994; Steinmetz, Rademacher et al., 1990).

Foster and colleagues examined 19 children with dyslexia (10 of who had comorbid diagnoses of ADHD), 23 children with solely ADHD, and 12 normal control subjects. Using length measurements, interhemispheric asymmetry coefficients were determined. Typical leftward PT asymmetry was not found in any group, although typical rightward asymmetry of the PP was found. Fewer children with dyslexia and ADHD displayed this typical pattern of
rightward asymmetry of the PP. Weaker neurolinguistic skills were related to atypical asymmetry, which was caused by larger right PTs.

Conclusions on the Relationship Between Plana Asymmetry and Dyslexia

As mentioned previously, research on the relationship between PT asymmetry and dyslexia has yielded inconsistent results. These differences are likely due to the methodological problems and differences in measurement techniques described in previous sections. Postmortem studies have clearly demonstrated the presence of PT symmetry in individuals with dyslexia, due to the presence of a large right PT. MRI studies on dyslexia and PT asymmetry have been more inconsistent, with equal numbers of the 10 studies reviewed here finding and not finding a significant relationship between PT asymmetry and dyslexia.

It has been suggested that the MRI studies that have found a reduced, symmetrical, or reversed asymmetry did not adequately control for handedness and verbal intelligence. However, it is possible that handedness and verbal intelligence in these samples is, in fact, representative of dyslexic populations. Evidence suggests that there is an increased incidence of left-handedness among individuals with dyslexia (Hynd, 1992), although findings have not been consistent. In addition, research has shown that individuals with low reading skills tend to learn less material in the classroom and seek out fewer academic and intellectual tasks of their own volition, which then may cause their intellectual functioning to decrease, particularly in the verbal domain. This cycle has been referred to as “The Matthew Effect” (Stanovich, 1989), and may explain the lower VIQs typically found in dyslexic samples in the MRI investigations.

Research on the relationship between PP asymmetry and dyslexia is still in its infancy. At this time, the evidence suggests that the typical leftward asymmetry of the PT may be reduced in dyslexia. The relationship between the PT and PP within hemispheres has been demonstrated,
suggesting that research on the PP is necessary to the understanding of how total plana
morphology relates to dyslexia.

**Hypotheses**

This study examines six questions in three areas that will help to clarify the relationship between PT and PP asymmetry and dyslexia. Table 3 summarizes the hypotheses of the study and the variables, subtest, test, and planned analysis for each hypothesis.

The first area to be investigated in this study is the relationship between PT asymmetry, neuropsychological test performance, and demographic variables. Previous research has demonstrated a relationship between PT asymmetry and phonological processing, verbal intelligence, handedness, and gender. Thus, the first hypothesis is that leftward PT asymmetry will be positively correlated with performance on tests of phonological processing and verbal intelligence, right-handedness, and male gender, regardless of diagnostic group. Studies of the PP suggest that its cytoarchitecture is similar to that of the PT, suggesting the two structures may have similar language functions. In addition, PP asymmetry has been correlated with handedness in previous studies. Therefore, the second hypothesis is that rightward PP asymmetry will be positively correlated with performance on tests of phonological processing and verbal intelligence, right-handedness, and male gender, regardless of diagnostic group.

The second issue addressed by this study is the relationship between PT asymmetry, neurolinguistic skills, and reading achievement in children. Research has demonstrated a relationship between phonological processing, rapid naming, and reading, as well as a relationship between PT asymmetry and phonological processing. This study will investigate the unique contribution of PT asymmetry to reading. Thus, the third hypothesis is that leftward PT
Table 3: Hypotheses and Planned Analyses

<table>
<thead>
<tr>
<th>Hypotheses</th>
<th>Variables</th>
<th>Subtests</th>
<th>Test</th>
<th>Planned Analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Leftward PT asymmetry will be positively correlated with performance on tests of phonological processing, verbal intelligence, and right-handedness, regardless of diagnostic group. In addition, leftward PT asymmetry will be systematically larger in males than in females.</td>
<td>A. Phonological processing</td>
<td>A composite of the Phoneme Reversal and Elision subtests</td>
<td>CTOPP</td>
<td>Correlation, with directional testing</td>
</tr>
<tr>
<td></td>
<td>B. Verbal Intelligence</td>
<td>Verbal Intelligence Quotient</td>
<td>WASI</td>
<td>Correlation, with directional testing</td>
</tr>
<tr>
<td></td>
<td>C. Handedness</td>
<td>Laterality Quotient</td>
<td>Edinburgh Handedness Inventory</td>
<td>Correlation, with directional testing</td>
</tr>
<tr>
<td></td>
<td>D. Gender</td>
<td></td>
<td>Self/parent report</td>
<td>Directional t-test</td>
</tr>
<tr>
<td>2. Rightward PP asymmetry will be positively correlated with performance on tests of phonological processing, verbal intelligence, and right-handedness, regardless of diagnostic group. In addition, rightward PP asymmetry will be systematically larger in males than in females.</td>
<td>A. Phonological processing</td>
<td>A composite of the Phoneme Reversal and Elision subtests</td>
<td>CTOPP</td>
<td>Correlation, with directional testing</td>
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<td>D. Gender</td>
<td></td>
<td>Self/parent report</td>
<td>Directional t-test</td>
</tr>
<tr>
<td>3. Leftward PT asymmetry, phonological processing skills, and rapid naming skills will predict reading achievement.</td>
<td>Phonological processing</td>
<td>A composite of the Phoneme Reversal and Elision subtests</td>
<td>CTOPP</td>
<td>Multiple regression with an assessment testing for gender differences that may be present in the models.</td>
</tr>
<tr>
<td></td>
<td>Rapid Naming</td>
<td>Alt. Rapid Naming Composite</td>
<td>CTOPP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reading achievement</td>
<td>Passage Composite Score</td>
<td>GORT-3</td>
<td></td>
</tr>
</tbody>
</table>
4. Children identified as having dyslexia will show less leftward asymmetry of the PT than children who did not meet criteria for dyslexia. Handedness, verbal intelligence, supertentorial area will be used as covariates to determine the individual contribution of PT asymmetry to dyslexia diagnosis.

Dyslexia Diagnosis: Average intelligence, below average reading, intelligence 1 standard deviation higher than reading. FSIQ – Reading score (passage) > 15.

<table>
<thead>
<tr>
<th>FSIQ ≥ 86</th>
<th>WASI</th>
<th>Analysis of Covariance (one-tailed).</th>
</tr>
</thead>
<tbody>
<tr>
<td>passage score ≤ 85</td>
<td>GORT-3</td>
<td></td>
</tr>
</tbody>
</table>

5. Children identified as having dyslexia will show less rightward asymmetry of the PP than children who did not meet criteria for dyslexia. Handedness, verbal intelligence, and supertentorial area will be used as covariates to determine the individual contribution of PT asymmetry to dyslexia diagnosis.

Dyslexia Diagnosis: Average intelligence, below average reading, intelligence 1 standard deviation higher than reading. FSIQ – Reading score (passage) > 15.

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<tbody>
<tr>
<td>passage score ≤ 85</td>
<td>GORT-3</td>
<td></td>
</tr>
</tbody>
</table>

6. Children with dyslexia will show differences in intrahemispheric asymmetry when compared to children who did not meet criteria for dyslexia. Handedness, verbal intelligence, and supertentorial area will be used as covariates to determine the individual contribution of intrahemispheric asymmetry to dyslexia diagnosis.

Dyslexia Diagnosis: Average intelligence, below average reading, intelligence 1 standard deviation higher than reading. FSIQ – Reading score (passage) > 15.

<table>
<thead>
<tr>
<th>FSIQ ≥ 86</th>
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</thead>
<tbody>
<tr>
<td>passage score ≤ 85</td>
<td>GORT-3</td>
<td></td>
</tr>
</tbody>
</table>
asymmetry, phonological processing skills, and rapid naming skills will predict reading achievement as measured by reading fluency. As this relationship may be different in boys than in girls, the regression models will be compared to assess for gender differences.

The third area this study examines is whether children with dyslexia show different patterns of PT and PP asymmetry when compared to clinic-referred controls. It is hypothesized that children identified as having dyslexia will show less leftward asymmetry of the PT than children who do not meet criteria for dyslexia (Hypothesis 4). In addition, the fifth hypothesis is that children identified as having dyslexia will show less rightward asymmetry of the PP than children who do not meet criteria for dyslexia. Finally, it is hypothesized that children with dyslexia will show a different pattern of intrahemispheric asymmetry than clinic-referred controls as a result of deviations in PT and PP asymmetry across hemispheres in children with dyslexia (Hypothesis 6). The fourth, fifth, and sixth hypotheses will be tested using Analysis of Covariance. Due to previous findings correlating handedness, verbal intelligence, and gender to PT asymmetry, those three variables will be used as covariates in those analyses.
CHAPTER III

METHOD

Participants

Participants were children referred to the Center for Clinical and Developmental Neuropsychology at the University of Georgia to participate in a research grant. The study, funded by the National Institutes of Health (NIH), was designed to research variation in brain morphology and its relationship to neurolinguistic ability in developmental dyslexia. Families with at least one child who was experiencing serious reading problems or who had been previously diagnosed with developmental dyslexia were referred to the study through schools, local organizations, and advertisements. Both biological parents were required to participate in the testing, with the exception of African-American families, for whom only one biological parent was required to participate. This exception was made in an attempt to recruit more African-American families. The target child was required to be between 8 and 12 years of age and without a history of psychiatric disorders, neurological disorders, severe pre- or peri-natal complications, or traumatic brain injury. In exchange for their participation, parents received a comprehensive neuropsychological report on their children with results reported in a manner useful to school systems for making special education eligibility determinations. All children received a free t-shirt.

Attention problems and previous diagnoses of Attention-Deficit/Hyperactivity Disorder (ADHD) were permitted. Prior research has demonstrated that the cognitive deficits found ADHD and RD are distinct (August & Garfinkel, 1990; Shaywitz et al., 1995) and thus the presence or absence of ADHD was unlikely to influence the results of the present study. Although symptoms of inattention are present in both groups, children with ADHD are
characterized by having additional difficulties with behavioral disinhibition and/or hyperactivity, while children with RD show impairments in phonological processing (Sanchez, Miller, Garcia, & Hynd, in press). Furthermore, children with solely ADHD do not show the atypical asymmetry of the left perisylvian cortex found in children with RD (Hynd et al., 1990). Excluding children with ADHD would have severely limited the available subjects and would have reduced the generalizability of the results, as these two disorders are frequently comorbid (Barkley, 1998).

Seventy families, including 96 children, participated in the data collection, which included both neuropsychological assessment and Magnetic Resonance Imaging (MRI) scans. For the purposes of this study, eleven children were eliminated from data analysis due to Full Scale Intelligence Quotient (FSIQ) scores in the below average or significantly below average range (i.e. less than 85 standard score points). Six additional subjects who met the cut score criteria but not discrepancy criteria for dyslexia diagnosis were excluded from the study to insure that no children were included in the control group who might meet alternate criteria for dyslexia diagnosis. In addition, age was restricted to the range of 8 to 14 years, eliminating six subjects. In nine children, the MRI scans were unreadable due to excess movement. In an additional nine children, there was no scan due to technical difficulties or anxiety regarding the MRI scanner. Elimination of participants for the above reasons left 55 children.

Procedure

Families came to the University of Georgia’s Center for Clinical and Developmental Neuropsychology to participate in the research study. The parents provided informed, written consent for their and their child’s participation in the assessment and MRI scan. In addition, the child provided written assent witnessed by their parents. Neuropsychological assessment was
completed during the day, with a one-hour lunch break and additional breaks as needed.

Following the evaluation, each child underwent a structural MRI scan at Health South Imaging Center in Athens, GA. The scan took approximately 20-25 minutes. All structural MRI scans were reviewed by a board-certified neurologist to screen for neurological conditions and the subject’s parent was informed in the case of the presence of neurological condition. All procedures were approved by the University of Georgia Institutional Review Board, Human Subjects Office.

Neuropsychological Assessment

The target child and participating siblings participated in a comprehensive neuropsychological assessment. The test battery consisted of measures designed to assess intelligence, academic achievement, receptive and expressive language, phonological processing, memory, visual-spatial ability, orthographic skills, executive functioning, handedness, exposure to print, and social-emotional functioning. Variables for the present study include the Wechsler Abbreviated Scale of Intelligence (The Psychological Corporation, 1999), a brief, norm-referenced, individually administered test of intellectual ability. The WASI is composed of four subtests: Vocabulary and Similarities create a Verbal Intelligence Quotient (VIQ), and Block Design and Matrices create a Performance (nonverbal) Intelligence Quotient (PIQ). Together, the four subtests form the Full Scale Intelligence Quotient (FSIQ).

In addition, this study used the Gray Oral Reading Test – Third Edition (Pro-Ed, 1995) as a variable. The GORT-3 is a measure of oral reading fluency and combines both reading rate and reading accuracy into a composite score. A measure of reading fluency was chosen since many of the children in the study had received extensive intervention and thus had improved scores on measures of word identification and pseudoword reading. However, these children continued to
show impairments in reading fluency, which is one of the last reading skills to develop and the most resistant to intervention (Wolf & Katzir-Cohen, 2001). Furthermore, reading fluency is necessary for reading comprehension (Nathan & Stanovich, 1991). Reading fluency measures have been used in other studies in individuals with developmental dyslexia due to their increased sensitivity to reading problems (Rumsey et al., 1997a).

Phonological processing, considered by most researchers to be the core deficit in developmental dyslexia (Siegel, 1993), was assessed using the Comprehensive Test of Phonological Processing (CTOPP; (Wagner, Torgesen, & Rashotte, 1999). The subtests Elision and Phoneme Reversal were averaged to create a composite that was used as a measure of phonological awareness. These subtests were chosen to create the composite because previous research has demonstrated that they discriminate individuals with dyslexia from individuals without dyslexia (Lombardino et al., 1997). In addition, the Alternate Rapid Naming Composite Score, which is composed of Rapid Color Naming and Rapid Object Naming, was used as a measure of naming ability.

The Edinburgh Handedness Inventory was used to assess handedness. This task consists of 10 motor activities, such as writing, eating, and brushing teeth, which are demonstrated by the participant. Scores are continuous and scored as a percentile of right-handedness, with a score of 100 indicating that the subject is completely right-handed and a score of 0 indicating that the subject is completely left-handed.

There has been a great deal of controversy in recent years regarding the appropriate criteria for diagnosing reading disabilities, with many researchers arguing that the traditional IQ/achievement discrepancy model underrepresents children with lower IQ when, in fact, the cognitive deficits found in poor readers are the same regardless of IQ (Siegel, 1988; Stanovich &
Siegel, 1994) as are the responses to intervention (Vellutino et al., 1996). A cut score model, which would advocate the diagnosis of children who perform below average, typically defined as 85 standard score points or lower on a reading measure, has been proposed (Siegel, 1999). Despite its scientific support, this proposed criteria has not been widely accepted at the present time. In an effort to use the most stringent criteria for diagnosis, a diagnosis was made if the children met the following criteria: 1) reading achievement at or below 85 standard score points, as determined by a measure of oral reading fluency, and 2) FSIQ above 85 standard score points, and 3) a discrepancy of at least 15 standard score points between FSIQ and reading achievement. Control subjects were children referred to the study that failed to meet this criteria but had FSIQs in the average range, i.e. greater than or equal to 85 standard score points. To insure that no children were included in the control group who might meet alternate criteria for dyslexia diagnosis, the six subjects who met the cut score criteria but not discrepancy criteria were excluded from the study.

MRI Acquisition and Analysis

A 1.5 Tesla GE Sigma scanner was used to obtain three-dimensional structural MRI scans. Slices were gapless, collected in the sagittal plane, and 1.5 millimeters thick (TE = Min Full; flip angle = 30; Field of view = 24; frequency & phase = 256, frequency direction = S/I). Raw image (*.MERGE) data was compiled using Matlab, a Linux-supported software program. The images were then converted to individual sequential Tagged Image Format (TIF) pictures using MRicro software (freeware found at http://www.psychology.nottingham.ac.uk/staff/cr1/linux.html), and then compiled into a single TIF file using Scion Image (another free program found at [http://www.scioncorp.com/]).
Measurement of the Planum Temporale and Planum Parietale

The measurement of the PT and PP followed the technique proposed by Steinmetz (1989) and subsequently used in many other investigations (Foundas et al., 2002; Heiervang et al., 1998; Heiervang et al., 2000; Hugdahl et al., 2003; Hugdahl et al., 1998; Preis et al., 1999; Steinmetz et al., 1991). In this technique, the folded cortical surface is traced on each sagittal slice in which the PT and PP are visible. By multiplying each length measurement by the slice thickness, an area measurement of the complete folded cortical surface area in mm$^2$ can be obtained (Steinmetz, 1989). This measurement technique does not control for the possible differences in gyrification between hemispheres, but prior research has shown that the gyrification index is consistent across hemispheres (Zilles et al., 1988).

Borders of the PT were defined based on guidelines suggested by Shapleske and colleagues (1999) in their comprehensive review of the PT. The anterior border of the PT was defined as Heschl’s sulcus, or the sulcus immediately behind the first Heschl’s transverse gyrus. This definition included any additional Heschl’s gyri into the measurement of the PT. In cases where Heschl’s gyrus did not extend laterally to the surface of the temporal lobe, an imaginary line was drawn to complete the anterior border. The use of computer software that allowed measurement lines to remain in place as different slices were shown aided in this process. The posterior border of the PT was defined as the transition from the horizontal ramus of the sylvian fissure (SF) into a posterior ascending ramus (PAR) and/or posterior descending ramus (PDR). All cortex buried in the PDR was included in the PT, in keeping with Steinmetz and colleagues. The lateral border was defined as the superolateral margin of the superior temporal gyrus, while the medial border was defined as the point at which the anterior and posterior borders met. The PP was defined in accordance with Jäncke et al. (1993), whose definition of borders has been
Figure 3: The borders of the PT and PP as defined by and adapted from Preis et al., 1998. The figure shows three noncontiguous slices moving medially to laterally (A to C). The outlined arrows denote the anterior and posterior borders of the PT, while the black arrow denotes the posterior border of the PP.
used in further studies of the PP (Heiervang et al., 2000; Heiervang, February, 1998; Preis et al., 1999). The PP was defined as the floor of the PAR of the SF. In one case, a PAR was absent from the brain and the PP could not be measured. The borders of the PT and PP are presented in Figure 3. The supertentorial area on the midsagittal slice was measured as an estimate of total brain size.

All measurements were done by the first author (J.L.S.) who was blind to group membership. Inter-rater reliability was achieved by first measuring PT and PP length collaboratively with an experienced investigator (G.W.H.) who provided guidance as to boundaries and measurement. Each investigator then measured 10 scans (20 hemispheres) independently and an inter-rater reliability coefficient was determined. Inter-rater reliability was excellent, with correlations as follows: PT (r = .987, p < 0.01), PP (r = .976, p < 0.01), and total planum length (PT + PP) (r = .985, p < 0.01).

Interhemispheric and intrahemispheric asymmetry coefficients were determined for the PT, PP, and total planum length, in accordance with Steinmetz et al. (1990). The coefficient \((\frac{R-L}{(R+L)(0.5)})\) was used to determine interhemispheric asymmetry, with negative scores indicating leftward asymmetry and positive scores indicating rightward asymmetry. Intrahemispheric asymmetry quotients were derived for the left and right hemispheres as \((\frac{PT-PP}{(PT + PP)(0.5)})\).

**Analyses**

Statistical analyses for this study were conducted for each hypothesis (see Table 3). The first hypothesis was that, regardless of diagnostic group, PT asymmetry will be positively correlated with right-handedness, male gender, verbal intelligence, and phonological processing.
Correlations were conducted to test these hypotheses, with the exception of gender, for which a
directional t-test was conducted. The second hypothesis was that rightward PP asymmetry will
be significantly correlated with right-handedness, male gender, verbal intelligence, and
phonological awareness. As with the first hypothesis, correlations were conducted to test these
hypotheses, with the exception of gender, for which a directional t-test was conducted.

To investigate the third hypothesis, that leftward PT asymmetry, phonological processing
skills, and rapid naming skills will predict reading fluency, a multiple regression analyses was
performed which included both genders. Analyses were then performed separately for boys and
girls to assess for gender differences in the models, as gender is potentially a confounding
variable in studies of PT morphology.

The fourth hypothesis is that children identified as having dyslexia will show less
leftward asymmetry of the PT than children who do not meet criteria for dyslexia. Analysis of
Covariance was used to test this hypothesis, with handedness, verbal intelligence, and
supertentorial area used as covariates. The fifth hypothesis is that children identified as having
dyslexia will show less rightward asymmetry of the PT than children who do not meet criteria for
dyslexia. As with the fourth hypothesis, Analysis of Covariance was used to test this hypothesis,
with handedness, verbal intelligence, and supertentorial area used as covariates. The sixth
hypothesis is that children with dyslexia will show differences in intrahemispheric asymmetry
when compared to children who did not meet criteria for dyslexia. Again, Analysis of
Covariance was used, with handedness, verbal intelligence, and supertentorial area used as
covariates. As the fourth and fifth hypotheses were directional, significance level was determined
at the one-tailed level, while the two-tailed level of significance was used for the sixth
hypothesis, which was non-directional.
CHAPTER IV
RESULTS

The three primary goals of this research were to 1) determine the relationships between PT/PP morphology, neuropsychological test performance, and demographic variables (hypotheses one, two, and three), 2) to investigate the unique contribution of PT morphology to reading achievement (hypothesis four), and 3) to determine whether children with dyslexia show different patterns of PT and PP asymmetry when compared to clinic-referred controls (hypotheses five and six). This chapter outlines the major findings of this study as they relate to each hypothesis and specifies the extent to which data analyses supported each hypothesis. Descriptive statistics for the sample, the results of the analyses investigating each hypothesis, and analyses conducted to explore questions raised by the results of the originally proposed analyses are presented below.

Statistical analyses were conducted in eight stages. In the first stage, descriptive statistics and frequency data on variables of interest were calculated for the total sample and the sample divided by the presence of absence of dyslexia.

Descriptive Statistics

In the total sample of 55 children, there were 34 males and 21 females. Twenty-six children met the described criteria for dyslexia diagnosis, while 29 children did not meet those criteria and were used as clinical control subjects. Of children with a diagnosis of dyslexia, 18 were male and 8 were female, while there were 16 males and 13 females in the clinical control subjects. Thirty-six children in this sample did not meet criteria for ADHD, while nine were diagnosed with ADHD-Primarily Inattentive Subtype, one was diagnosed with ADHD-Hyperactive Impulsive Subtype, and nine were diagnosed with ADHD-Combined Subtype. Of
children with a diagnosis of dyslexia, 16 did not meet criteria for ADHD, while four were
diagnosed with ADHD-Primarily Inattentive Subtype, none were diagnosed with ADHD-
Hyperactive Impulsive Subtype, and six were diagnosed with ADHD-Combined Subtype. Of the
clinical control subjects, there were 20 subjects that did not meet criteria for ADHD, while five
were diagnosed with ADHD-Primarily Inattentive Subtype, one was diagnosed with ADHD-
Hyperactive Impulsive Subtype, and three were diagnosed with ADHD-Combined Subtype.

Group means and standard deviations for age, laterality quotient, phonological
processing, rapid naming, FSIQ, VIQ, PIQ, reading fluency, and mathematics achievement are
presented in Table 4. While no statistical analyses were conducted comparing children with
dyslexia to children who did not meet criteria for dyslexia, group means on age, FSIQ, PIQ, and
VIQ appear to be close. Table 5 contains means and standard deviations for neuroanatomical
variables, including the left and right PT, the left and right PP, the left and right total plana,
supertentorial area, PT ratio, PP ratio, and total ratio. As means and standard deviations were
calculated on the entire sample as well as categorized by the presence or absence of dyslexia
diagnosis, these descriptive statistics are presented in both manners.

It should be noted that the ratio variables measure asymmetry of the PT, PP and total
plana, with negative values indicating leftward asymmetry and positive values indicating
rightward asymmetry. Positive values on intrahemispheric asymmetry ratios indicate that the PT
is larger than the PP. In the total sample, leftward asymmetry was found for the PT, PP, and total
plana ratio.

The frequencies of laterality quotients for the total sample are depicted in Figure 4. Two
members of the sample did not complete the Edinburgh Handedness Inventory and, therefore,
laterality quotient data were not available for those subjects. As mentioned previously, laterality
### Table 4: Demographic and Psychometric Variables in Dyslexics, Non-Dyslexics, and the Total Sample

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total Sample (N = 55)</th>
<th>Dyslexics (N = 26)</th>
<th>Non-Dyslexics (N = 29)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Age (in months)</td>
<td>126.04</td>
<td>17.26</td>
<td>129.65</td>
</tr>
<tr>
<td>Laterality Quotient</td>
<td>87.74</td>
<td>23.77</td>
<td>90.77</td>
</tr>
<tr>
<td>WASI FSIQ</td>
<td>102.45</td>
<td>12.66</td>
<td>102.65</td>
</tr>
<tr>
<td>WASI PIQ</td>
<td>104.25</td>
<td>15.74</td>
<td>105.85</td>
</tr>
<tr>
<td>WASI VIQ</td>
<td>100.11</td>
<td>12.35</td>
<td>99.19</td>
</tr>
<tr>
<td>GORT-3 Passage</td>
<td>83.52</td>
<td>16.30</td>
<td>70.19</td>
</tr>
<tr>
<td>CTOPP Phoneme Reversal and Elision</td>
<td>89.34</td>
<td>11.61</td>
<td>85.00</td>
</tr>
<tr>
<td>Alt. Rapid Naming</td>
<td>87.38</td>
<td>16.93</td>
<td>80.59</td>
</tr>
<tr>
<td>WRAT Mathematics</td>
<td>91.44</td>
<td>15.95</td>
<td>94.69</td>
</tr>
<tr>
<td>Neuroanatomical Variables</td>
<td>Total Sample (N = 55)</td>
<td>Dyslexics (N = 26)</td>
<td>Non-Dyslexics (N = 29)</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------------------</td>
<td>--------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
</tr>
<tr>
<td>Left PT Area (in mm$^2$)</td>
<td>811.68</td>
<td>167.98</td>
<td>815.12</td>
</tr>
<tr>
<td>Right PT Area (in mm$^2$)</td>
<td>761.53</td>
<td>187.47</td>
<td>811.99</td>
</tr>
<tr>
<td>Left PP Area (in mm$^2$)</td>
<td>399.83</td>
<td>130.74</td>
<td>402.98</td>
</tr>
<tr>
<td>Right PP Area (in mm$^2$)</td>
<td>360.22</td>
<td>87.62</td>
<td>360.37</td>
</tr>
<tr>
<td>Left Total Area (in mm$^2$)</td>
<td>1211.51</td>
<td>230.12</td>
<td>1218.10</td>
</tr>
<tr>
<td>Right Total Area (in mm$^2$)</td>
<td>1121.75</td>
<td>203.53</td>
<td>1172.36</td>
</tr>
<tr>
<td>Supertentorial Area (in mm$^2$)</td>
<td>10392.95</td>
<td>846.12</td>
<td>10480.31</td>
</tr>
<tr>
<td>PT Ratio</td>
<td>-0.0752</td>
<td>0.23755</td>
<td>-0.0094</td>
</tr>
<tr>
<td>PP Ratio</td>
<td>-0.0707</td>
<td>0.43469</td>
<td>-0.0678</td>
</tr>
<tr>
<td>Total Ratio</td>
<td>-0.0758</td>
<td>0.21909</td>
<td>-0.0359</td>
</tr>
<tr>
<td>Left Intrahemispheric Ratio</td>
<td>.6862</td>
<td>.32824</td>
<td>.6992</td>
</tr>
<tr>
<td>Right Intrahemispheric Ratio</td>
<td>.6895</td>
<td>.33340</td>
<td>.7667</td>
</tr>
</tbody>
</table>
Figure 4: Laterality quotient in the sample used for this study (N = 53)
quotient is a continuous measure of handedness, with a laterality quotient of zero indicating complete left-handedness and a laterality quotient of 100 indicating complete right-handedness. Based on an observation of Figure 4, it appears that laterality quotient in this sample is distributed in a similar manner to the normal population distribution of handedness, which shows a large peak in right-handedness. A small peak in left-handedness, typically observed in the normal population, was not found in this sample. A non-directional t-test indicated that laterality quotient does not differ significantly depending on the presence or absence of dyslexia diagnosis ($t (51) = -.810, p = .422$).

**Correlational Analyses**

In the second stage of data analysis, Pearson correlations were calculated on selected variables as a test of the first and second hypotheses. The first hypothesis posited that leftward PT asymmetry would be positively correlated with phonological processing, verbal intelligence, and right-handedness in the total sample, regardless of diagnostic group. Similarly, the second hypothesis posited that rightward PP asymmetry would be positively correlated with phonological processing, verbal intelligence, and right-handedness in the total sample, also regardless of diagnostic group. Total plana ratio, which is ratio of the left and right combined plana (PT and PP), was also included in this correlation matrix. A summary of the results of these correlations is presented in Table 6. Results indicated that PT ratio and PP ratio are significantly positively correlated with total plana ratio, as would be expected due to the fact that PT ratio and PP ratio make up the total plana ratio. PT ratio was correlated with laterality quotient but not verbal intelligence or phonological processing. PP ratio was not correlated with laterality quotient, verbal intelligence, or phonological processing. Verbal intelligence and phonological processing were also positively correlated in this sample.
Independent Samples t-test

The first hypothesis also asserted that leftward PT asymmetry would be systematically larger in males than in females, while the second hypothesis also posited that rightward PP asymmetry would be systematically larger in males than in females. In the third stage of data analysis, directional t-tests were conducted to explore these hypotheses. In addition, total plana ratio was included in this analysis, but as this analysis was exploratory a non-directional t-test was used. None of these analyses yielded statistically significant results. Table 7 summarizes these results.

Regression Analyses

In the fourth stage of data analysis, a multiple regression analysis was conducted to explore the third hypothesis. The model tested used PT ratio, rapid naming skills, and phonological processing skills to predict reading achievement in the total sample. The model was significant overall, with 46.5% of the variance in reading achievement explained by these three independent variables. PT ratio did not contribute significantly to the model (sig = .691), while phonological processing (sig = .000) and rapid naming skills (sig = .019) did contribute significantly to reading achievement. Results are presented in Table 8.

Previous research has suggested that gender may influence the asymmetry of the PT. In order to assess for gender differences that may be present in the multiple regression model described above, a new multiple regression model was created that included all the previously included variables plus gender and the cross-products of gender and phonological processing, rapid naming, and PT ratio. Including gender and the cross-products in the model did not significantly change the model R squared. Neither the cross-products nor gender contributed significantly to the model, indicating that gender differences in the coefficients are not
Table 6: Pearson correlations between PT ratio, PP ratio, total plana ratio, phonological processing, verbal intelligence, and handedness

<table>
<thead>
<tr>
<th></th>
<th>PT Ratio&lt;sup&gt;a&lt;/sup&gt;</th>
<th>PP Ratio&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Total Plana Ratio&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Phonological Processing</th>
<th>WASI VIQ</th>
<th>Laterality Quotient&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT Ratio</td>
<td>1</td>
<td>.134</td>
<td>.805**</td>
<td>-.077</td>
<td>.088</td>
<td>-.270*</td>
</tr>
<tr>
<td>PP Ratio</td>
<td>1</td>
<td>1</td>
<td>.681**</td>
<td>.038</td>
<td>.027</td>
<td>-.080</td>
</tr>
<tr>
<td>Total Ratio</td>
<td>1</td>
<td>-0.037</td>
<td>.079</td>
<td>-0.250</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phonological</td>
<td>1</td>
<td></td>
<td>.362**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Processing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.171</td>
</tr>
<tr>
<td>WASI VIQ</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>.204</td>
<td></td>
</tr>
<tr>
<td>Laterality Quotient</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

<sup>a</sup>PT ratio is a measure of the asymmetry of the PT, which is leftward in this sample.
<sup>b</sup>PP ratio is a measure of the asymmetry of the PP, which is leftward in this sample.
<sup>c</sup>Total plana ratio is a measure of the asymmetry of the combined PT and PP, which is leftward in this sample.
<sup>d</sup>Laterality Quotient is an indicator of handedness, with higher numbers indicating right-handedness.
Table 7: Results of an independent samples t-test assessing gender differences in PT ratio, PP ratio, and total ratio

<table>
<thead>
<tr>
<th>Gender</th>
<th>Mean</th>
<th>SD</th>
<th>t</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT Ratio</td>
<td>Male (N = 34)</td>
<td>-.0845</td>
<td>.22151</td>
<td>-.368</td>
</tr>
<tr>
<td></td>
<td>Female (N = 21)</td>
<td>-.0600</td>
<td>.26647</td>
<td></td>
</tr>
<tr>
<td>PP Ratio</td>
<td>Male (N = 34)</td>
<td>-.1122</td>
<td>.50420</td>
<td>-.900</td>
</tr>
<tr>
<td></td>
<td>Female (N = 21)</td>
<td>.0034</td>
<td>.248818</td>
<td></td>
</tr>
<tr>
<td>Total Ratio</td>
<td>Male (N = 34)</td>
<td>-.0991</td>
<td>.23316</td>
<td>-1.003</td>
</tr>
<tr>
<td></td>
<td>Female (N = 21)</td>
<td>-.0381</td>
<td>.19363</td>
<td></td>
</tr>
</tbody>
</table>
Table 8: Multiple regression model using PT ratio, phonological processing, and rapid naming to predict reading fluency.

<table>
<thead>
<tr>
<th></th>
<th>R Square</th>
<th>F</th>
<th>Sig</th>
<th>Unstandardized Beta Coefficients</th>
<th>Standardized Beta Coefficients</th>
<th>t</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>.465</td>
<td>13.349</td>
<td>.000***</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Constant)</td>
<td></td>
<td></td>
<td></td>
<td>-6.600</td>
<td>--</td>
<td>-0.884</td>
<td>.381</td>
</tr>
<tr>
<td>PT Ratio</td>
<td></td>
<td></td>
<td></td>
<td>-1.632</td>
<td>-0.044</td>
<td>-0.400</td>
<td>.691</td>
</tr>
<tr>
<td>Phonological Processing</td>
<td></td>
<td></td>
<td></td>
<td>.690</td>
<td>.553</td>
<td>4.928</td>
<td>.000***</td>
</tr>
<tr>
<td>Rapid Naming</td>
<td></td>
<td></td>
<td></td>
<td>.332</td>
<td>.272</td>
<td>2.432</td>
<td>.019*</td>
</tr>
</tbody>
</table>

* p < .05, *** p < .001
statistically significant. In addition, the sample was divided by gender and the regression analysis was run again for each gender for descriptive purposes. Overall, results of the assessment testing for gender differences suggest that there is not enough evidence to infer that regression weights for males are different from regression weights for females.

**Analysis of Covariance**

The fifth stage of data analysis used Analysis of Covariance to test hypotheses four, five, and six. As previous research has shown that handedness, verbal intelligence, and an estimate of total brain size are correlated with the PT, these variables were included as covariates in all three analyses. Although previous correlations did not support a significant relationship between verbal intelligence and PT, PP, and total plana ratio in this sample, it was decided that, because the literature suggests a relationship between those variables, it would be prudent to continue to use verbal intelligence as a covariate. Directional hypotheses used one-tailed analyses, while non-directional hypotheses used two-tailed analyses. Neuroanatomical variables were used as the dependent variables.

Hypothesis four stated that children classified as having dyslexia would show less leftward asymmetry of the PT than children who did not meet criteria for dyslexia. Table 9 summarizes the results of the analysis of covariance testing hypothesis four. The relationship between PT ratio and diagnostic group was significant, as was the relationship between laterality quotient and PT ratio. The relationships between verbal intelligence and PT ratio and supertentorial area and PT ratio were not significant. The R squared suggests that 21.4% of the variance in dyslexia diagnosis can be explained by PT ratio, laterality quotient, supertentorial area, and verbal intelligence. Examination of the means of left and right PT area as well as PT ratio across diagnostic groups reveals that PT symmetry was found in children with dyslexia.
while leftward asymmetry of the PT was found in children who did not meet criteria for dyslexia (see Table 5). The PT symmetry found in children with dyslexia is due to a larger right PT ($t (53) = -1.938, p < .05$).

Hypothesis five stated that children identified as having dyslexia would show less rightward asymmetry of the PP than children who did not meet criteria for dyslexia. No variables showed a significant relationship with PP asymmetry. Results are summarized in Table 10.

In addition to examining the PT and PP ratios separately, the total plana interhemispheric asymmetry was also examined. Laterality quotient and supertentorial area were significantly related to total plana ratio. Although the relationship between diagnostic group and total plana ratio was not significant, it approached significance. Table 11 presents these results.

Hypothesis six stated that children with dyslexia would show differences in intrahemispheric asymmetry when compared to children who did not meet criteria for dyslexia. Neither left nor right intrahemispheric asymmetry was associated with diagnostic group or with any covariates. The overall R squared for both analyses was close to zero and not significant. Results of the analysis of covariance for left intrahemispheric asymmetry are summarized in Table 12, while results for right intrahemispheric asymmetry are summarized in Table 13.

The estimated marginal means and standard error of PT ratio, PP ratio, and total ratio divided by diagnostic group are presented in Table 14. The estimated marginal means are generated during analysis of covariance and give an estimate of what the ratio means might be if verbal intelligence, laterality quotient, and supertentorial area were the same in each group. It is important to note that negative numbers indicate leftward asymmetry and positive numbers indicate rightward asymmetry. The estimated marginal means for PT ratio show that children with dyslexia have symmetrical PTs while individuals without dyslexia show leftward
Table 9: Results from the Analysis of Covariance examining the relationship between PT ratio and dyslexia diagnosis covarying by verbal intelligence, laterality quotient, and an estimate of total brain size. Dependent variable: PT ratio.

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Degrees of Freedom</th>
<th>F</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dyslexia Diagnosis</td>
<td>1</td>
<td>5.485</td>
<td>.012*</td>
</tr>
<tr>
<td>Verbal Intelligence</td>
<td>1</td>
<td>2.194</td>
<td>.073</td>
</tr>
<tr>
<td>Laterality Quotient</td>
<td>1</td>
<td>7.358</td>
<td>.005**</td>
</tr>
<tr>
<td>Supertentorial Area</td>
<td>1</td>
<td>2.466</td>
<td>.062</td>
</tr>
</tbody>
</table>

R Squared = .214
* p < .05, ** p < .01 (1-tailed)
Table 10: Results from the Analysis of Covariance examining the relationship between PP ratio and dyslexia diagnosis covarying by verbal intelligence, laterality quotient, and an estimate of total brain size. Dependent variable: PP ratio.

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Degrees of Freedom</th>
<th>F</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dyslexia Diagnosis</td>
<td>1</td>
<td>.206</td>
<td>.326</td>
</tr>
<tr>
<td>Covariates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Verbal Intelligence</td>
<td>1</td>
<td>.224</td>
<td>.319</td>
</tr>
<tr>
<td>Laterality Quotient</td>
<td>1</td>
<td>.632</td>
<td>.216</td>
</tr>
<tr>
<td>Supertentorial Area</td>
<td>1</td>
<td>2.731</td>
<td>.053</td>
</tr>
</tbody>
</table>

R Squared = .063
(Sig values are 1-tailed)
Table 11: Results from the Analysis of Covariance examining the relationship between total plana ratio and dyslexia diagnosis covarying by verbal intelligence, laterality quotient, and an estimate of total brain size. Dependent variable: total plana ratio.

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Degrees of Freedom</th>
<th>F</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dyslexia Diagnosis</td>
<td>1</td>
<td>3.013</td>
</tr>
<tr>
<td>Covariates</td>
<td>Verbal Intelligence</td>
<td>1</td>
<td>1.757</td>
</tr>
<tr>
<td></td>
<td>Laterality Quotient</td>
<td>1</td>
<td>6.134</td>
</tr>
<tr>
<td></td>
<td>Supertentorial Area</td>
<td>1</td>
<td>4.883</td>
</tr>
</tbody>
</table>

R Squared = .200
* p < .05 (2-tailed)
Table 12: Results from the Analysis of Covariance examining the relationship between left intrahemispheric asymmetry and dyslexia diagnosis covarying by verbal intelligence, laterality quotient, and an estimate of total brain size. Dependent variable: left intrahemispheric ratio.

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Degrees of Freedom</th>
<th>F</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dyslexia Diagnosis</td>
<td>1</td>
<td>.403</td>
</tr>
<tr>
<td>Covariates</td>
<td>Verbal Intelligence</td>
<td>1</td>
<td>.387</td>
</tr>
<tr>
<td></td>
<td>Laterality Quotient</td>
<td>1</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>Supertentorial Area</td>
<td>1</td>
<td>.264</td>
</tr>
</tbody>
</table>

R Squared = .019
Table 13: Results from the Analysis of Covariance examining the relationship between right intrahemispheric asymmetry and dyslexia diagnosis covarying by verbal intelligence, laterality quotient, and an estimate of total brain size. Dependent variable: right intrahemispheric ratio.

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Degrees of Freedom</th>
<th>F</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dyslexia Diagnosis</td>
<td>1</td>
<td>2.389</td>
</tr>
<tr>
<td>Covariates</td>
<td>Verbal Intelligence</td>
<td>1</td>
<td>.693</td>
</tr>
<tr>
<td></td>
<td>Laterality Quotient</td>
<td>1</td>
<td>.227</td>
</tr>
<tr>
<td></td>
<td>Supertentorial Area</td>
<td>1</td>
<td>.307</td>
</tr>
</tbody>
</table>

R Squared = .066
Table 14: Estimated marginal means for PT Ratio, PP ratio, and total ratio based on dyslexia diagnosis in the total sample.

<table>
<thead>
<tr>
<th></th>
<th>PT Ratio</th>
<th>PP Ratio</th>
<th>Total Plana Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard Error</td>
<td>Mean</td>
</tr>
<tr>
<td>Dyslexics (N = 26)</td>
<td>.008</td>
<td>.041</td>
<td>-.051</td>
</tr>
<tr>
<td>Non-Dyslexics (N = 29)</td>
<td>-.128</td>
<td>.040</td>
<td>-.107</td>
</tr>
</tbody>
</table>
Table 15: Estimated marginal means for left and right intrahemispheric asymmetry based on dyslexia diagnosis.

<table>
<thead>
<tr>
<th></th>
<th>Left Intrahemispheric Ratio</th>
<th>Right Intrahemispheric Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard Error</td>
</tr>
<tr>
<td>Dyslexics (N = 26)</td>
<td>.704</td>
<td>.067</td>
</tr>
<tr>
<td>Non-Dyslexics (N = 29)</td>
<td>.644</td>
<td>.065</td>
</tr>
</tbody>
</table>
asymmetry. An examination of the left and right PT area in Table 5 shows that this difference is due to a larger right PT in individuals with dyslexia. An independent t-test reveals that this difference is statistically significant (t (53) = -1.938, p < .05). The estimated marginal means for PP ratio indicate leftward asymmetry of the PP, which is slightly reduced in children with dyslexia, but not at a statistically significant level. The total plana showed leftward asymmetry in both groups, which was reduced in children with dyslexia, again not at a statistically significant level.

Estimated marginal means for left and right intrahemispheric asymmetry are presented in Table 15. Positive numbers indicate greater PT area and smaller PP area, as was found in both the left and right hemispheres.

**Post-Hoc Analyses**

**Discriminant Validity**

In order to assess the discriminant validity of the association of PT and PP ratio and dyslexia diagnosis, PT and PP ratio were correlated with a variable with which they were expected to have no relationship: mathematics achievement. A learning disability in mathematics was not chosen due to the paucity of subjects who would meet the criteria. A two-tailed Pearson correlation was run on the study sample (N = 55). Results revealed that neither the correlation between PT ratio and mathematics achievement (r = .127, sig = .355) or the correlation between PP ratio and mathematics achievement (r = .074, sig = .590) were significant. This assessment of discriminant validity was the sixth stage of data analysis.

**Descriptive Analysis of Children With and Without Readable Scans**

Eighteen children were eliminated from the study due to the absence of an MRI scan or because their scans were too blurry to read due to excess movement in the scanner. Two of these
children were eliminated from the study due to age restrictions, leaving 16 children who would have been included in the study if readable scans had been available. As the two most common reasons for the absence of a readable scan were hyperactivity and excessive anxiety regarding being scanned, this group may differ from the rest of the sample in ways that may have impacted study results. In the seventh stage of data analysis, children with readable scans were compared to children without readable scans to assess for bias within the sample.

First, children with and without readable scans were compared on the frequencies of dyslexia diagnosis and on gender. Of children with readable scans, 34 were male (62%) and 21 female (38%), while children without readable scans were composed of 11 males (69%) and 5 females (31%). Of children with readable scans, 26 (47%) met criteria for dyslexia diagnosis while 29 (53%) did not. Ten (62%) children without readable scans met criteria for dyslexia and 6 (38%) did not. Thus, the groups showed approximately the same percentages of males and females and a slightly higher percentage of individuals with dyslexia in the group with no readable scans.

Next, a series of independent t-tests was performed, comparing the 16 children without readable scans to the 55 children with readable scans who comprised the study sample on dyslexia diagnosis, ADHD diagnosis, age, gender, reading achievement, rapid naming skills, phonological processing skills, verbal intelligence, and mathematics achievement. Significance level was two-tailed as these analyses were exploratory.

Significant differences were found in laterality quotient (p < .01) and ADHD diagnosis (p < .01). The group without readable scans was significantly more left-handed than the sample group used in this study. In addition, they had more diagnoses of ADHD than the group with readable scans. Of particular interest is the fact that 8 of 16 children without readable scans were
Table 16: Frequency data on ADHD diagnosis and the presence or absence of MRI scans.

<table>
<thead>
<tr>
<th>Scan (N = 55)</th>
<th>Count</th>
<th>No ADHD</th>
<th>ADHD-PI</th>
<th>ADHD-CT</th>
<th>ADHD-HI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% within sample with scans</td>
<td>65.5%</td>
<td>16.4%</td>
<td>16.4%</td>
<td>1.8%</td>
<td></td>
</tr>
<tr>
<td>% within ADHD diagnosis</td>
<td>92.3%</td>
<td>64.3%</td>
<td>52.9%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scan (N = 16)</th>
<th>Count</th>
<th>No ADHD</th>
<th>ADHD-PI</th>
<th>ADHD-CT</th>
<th>ADHD-HI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% within sample without scans</td>
<td>18.8%</td>
<td>31.3%</td>
<td>50.0%</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>% within ADHD diagnosis</td>
<td>7.7%</td>
<td>35.7%</td>
<td>47.1%</td>
<td>0%</td>
<td></td>
</tr>
</tbody>
</table>
diagnosed with ADHD-Combined Type (47.1% of the sample with ADHD-CT) while 9 of the 55 children who had readable scans were diagnosed with ADHD-CT (52.9% of the sample with ADHD-CT). This indicates that roughly half of the children in the total sample diagnosed with ADHD-CT did not have readable scans. Frequency data on ADHD diagnosis and the presence or absence of readable scans is presented in Table 16.

Removal of Children with ADHD from the Sample

In the eighth stage of data analysis, all analyses were run again excluding children with ADHD to ensure that ADHD was not confounding the results of the study. The exclusion of children with ADHD left 36 children, 20 of whom met criteria for dyslexia while 16 did not. There were 26 males and 10 females in this new sample.

Results for hypotheses one and two remained the same, with the exception that PT ratio was no longer significantly correlated with laterality quotient, although the significance level approached significance (p = .051). As with the total sample, PT ratio and PP ratio were significantly correlated with total ratio, and phonological processing was significantly correlated with verbal intelligence. There were also no gender differences in PT ratio, PP ratio, or total plana ratio.

Hypothesis three was again tested using a multiple regression model using PT ratio, rapid naming skills, and phonological processing skills to predict reading achievement in the sample excluding children with ADHD. Again, the model was significant overall, with 38.9% of the variance in reading achievement explained by these three variables (see Table 17). As with the total sample, PT ratio did not contribute significantly to the model in the subsample of children without ADHD, while phonological processing and rapid naming skills did contribute significantly to reading achievement.
Unstandardized beta weights were examined in the regression models using the total sample and the sample excluding children with ADHD for cross-sample comparison. A difference was observed in the unstandardized regression weights for PT ratio (-1.632 in the total sample, -12.664 in the sample excluding children with ADHD). While statistical significance was not detected in the differences in regression weights associated with PT asymmetry in the total sample versus the subsample without ADHD, the actual sample differences were considerable. To investigate this further, the regression model was run on the subsample with ADHD so the children with and without ADHD could be compared directly. Results of this multiple regression analysis are presented in Table 18, and indicate that PT ratio, phonological processing, and rapid naming all contribute significantly to reading achievement in children with ADHD. As PT ratio was not found to predict reading achievement in the samples that included children without ADHD, these results suggest that the relative role of PT asymmetry in predicting reading achievement is different in children with ADHD. These findings are not generalizable, however, as the sample size of children with ADHD in this analysis is quite small (N = 19). These results suggest the need for further study.

Hypotheses four, five, and six were tested using Analysis of Covariance on the sample excluding children with ADHD. Neuroanatomical ratios served as dependent measures, diagnostic group as the independent variable, and handedness, verbal intelligence, and an estimate of total brain size as covariates. As with the total sample, PT ratio was significantly related to laterality quotient and to diagnostic group, while PP ratio did not significantly relate to any variable. Total plana ratio was again significantly related to laterality quotient and an estimate of total brain size, and, in this sample, diagnostic group. A comparison of the estimated marginal means for PT ratio, PP ratio, and total plana ratio of the two samples reveals that PP
ratio, which showed leftward asymmetry in children with dyslexia in the total sample, shows
rightward asymmetry in children with dyslexia in the sample excluding children with ADHD.
These results are summarized in Table 19. It is important to note that, since estimated marginal
means are theoretical means that assume that covariate means are the same in each group, they
cannot be compared to findings in other studies.
Table 17: Multiple regression model using PT ratio, phonological processing, and rapid naming to predict reading fluency in the subsample without ADHD (N = 36).

<table>
<thead>
<tr>
<th></th>
<th>R Square</th>
<th>F</th>
<th>Sig</th>
<th>Unstandardized Beta Coefficients</th>
<th>Standardized Beta Coefficients</th>
<th>t</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>.389</td>
<td>6.366</td>
<td>.002**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Constant)</td>
<td></td>
<td></td>
<td></td>
<td>-5.558</td>
<td>--</td>
<td>-.263</td>
<td>.794</td>
</tr>
<tr>
<td>PT Ratio</td>
<td></td>
<td></td>
<td></td>
<td>-10.136</td>
<td>-.151</td>
<td>-1.056</td>
<td>.299</td>
</tr>
<tr>
<td>Phonological</td>
<td></td>
<td></td>
<td></td>
<td>.708</td>
<td>.488</td>
<td>3.366</td>
<td>.002**</td>
</tr>
<tr>
<td>Processing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rapid Naming</td>
<td></td>
<td></td>
<td></td>
<td>.293</td>
<td>.282</td>
<td>1.947</td>
<td>.061</td>
</tr>
</tbody>
</table>

** p < .01
Table 18: Multiple regression model using PT ratio, phonological processing, and rapid naming to predict reading fluency in the subsample with ADHD (N = 19).

<table>
<thead>
<tr>
<th></th>
<th>R Square</th>
<th>F</th>
<th>Sig</th>
<th>Unstandardized Beta Coefficients</th>
<th>Standardized Beta Coefficients</th>
<th>t</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>.802</td>
<td>14.840</td>
<td>.000***</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Constant)</td>
<td>-25.566</td>
<td>--</td>
<td>-1.486</td>
<td>.165</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PT Ratio</td>
<td>21.673</td>
<td>.342</td>
<td>2.279</td>
<td>.044*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phonological Processing</td>
<td>.774</td>
<td>.630</td>
<td>4.005</td>
<td>.002**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rapid Naming</td>
<td>.477</td>
<td>.542</td>
<td>3.579</td>
<td>.004**</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* p < .05, ** p < .01, *** p < .001
Table 19: Estimated marginal means for PT Ratio, PP ratio, and total ratio based on dyslexia diagnosis in sample excluding children with ADHD.

<table>
<thead>
<tr>
<th></th>
<th>PT Ratio</th>
<th></th>
<th>PP Ratio</th>
<th></th>
<th>Total Plana Ratio</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard Error</td>
<td>Mean</td>
<td>Standard Error</td>
<td>Mean</td>
<td>Standard Error</td>
</tr>
<tr>
<td>Dyslexics (N = 21)</td>
<td>.003</td>
<td>.055</td>
<td>.026</td>
<td>.092</td>
<td>-.004</td>
<td>.051</td>
</tr>
<tr>
<td>Non-Dyslexics (N = 16)</td>
<td>-.194</td>
<td>.048</td>
<td>-.067</td>
<td>.106</td>
<td>-.149</td>
<td>.044</td>
</tr>
</tbody>
</table>
CHAPTER V
DISCUSSION

As detailed in previous chapters, the purpose of this study was to explore the relationship between PT and PP morphology, reading ability, and dyslexia diagnosis in children. Results of this study will be discussed in reference to the six hypotheses detailed in chapter three.

Summary of Results and Implications

PT and PP Morphology and Ratios

Consistent with results of previous studies, leftward asymmetry of the PT was found in the total sample. In addition, leftward asymmetry of the PP was found in the total sample. The latter finding is not consistent with previous literature on the PP, which suggests that rightward asymmetry is the norm (Jäncke et al., 1994). This discrepancy might be due to the fact that relatively few studies have been published on the PP, and the lack of consistency in defining borders to define the PP in these studies. The use of a clinical sample referred specifically for reading problems may also have affected the results in this study with regards to the asymmetry of the PP, as atypical asymmetry of the PP has been found in children with dyslexia (Heiervang et al., 2000). Total plana ratio, which is a ratio of asymmetry for the combined PT and PP, also showed leftward asymmetry. Intrahemispheric ratios for both the right and left plana indicate that PT area is greater than the PP area in both hemispheres in the total sample. Laterality quotient was normally distributed and did not differ across diagnostic groups.

The Relationship between PT, PP, and Total Plana Ratio, Neuropsychological Test Performance, and Demographic Variables

In the current study, leftward PT asymmetry was significantly correlated with right-handedness, but not with verbal intelligence or phonological processing. In addition, PP and total
plana ratio were not significantly correlated with right-handedness, verbal intelligence, or phonological processing. As is typically reported in the literature, phonological processing and verbal intelligence were significantly correlated. While previous research had shown that PP asymmetry is a good predictor of handedness (Foundas et al., 2002), this study found no correlation between the two variables. Considering the fact that the current study found leftward asymmetry of the PP, which is at odds with previous findings, it is not surprising that the relationship between handedness and PP asymmetry was not corroborated by this study. It is possible that sufficient power was not present in this study to find relationships between the neuroanatomical variables and verbal intelligence and phonological processing. Another possibility is that previous findings linking verbal intelligence and phonological processing to atypical PT asymmetry used samples in which the children with dyslexia had lower IQs than the control subjects. The lack of a relationship between PT ratio and phonological processing may also be explained by the fact that many children in our sample had received reading interventions that were phonologically-oriented. Some of the children who had received intervention had improved phonological processing skills, which in some had led to improvements in reading, while some were able to read accurately but not fluently. Future studies should attempt to control for reading interventions, particularly as many children are receiving phonologically-oriented interventions at young ages, sometimes before diagnoses are made.

Gender differences in neuroanatomical ratios were not found in the current study. However, it is important to continue to assess for gender differences when studying the PT due to previous findings showing differences in interhemispheric asymmetry of the PT in males and females (Honeycutt et al., 2000). Furthermore, when using non-ratio neuroanatomical variables,
it is important to control for the effect of total brain size, as males typically have larger brains than females, even as children (Schultz et al., 1994).

**The Relationship between PT Ratio, Phonological Processing, Rapid Naming, and Reading Achievement**

Results from this study suggest that PT asymmetry does not predict reading achievement, while phonological processing and rapid naming skills do predict reading achievement. These results are consistent across males and females. There has not been another study that has attempted to use PT asymmetry to predict reading achievement in a regression model, likely due to sample size limitations (e.g. (Hynd et al., 1990; Leonard et al., 1993; Robichon, Levrier, Farnarier, & Habib, 2000b; Rumsey et al., 1997b; Schultz et al., 1994; Semrud-Clikeman et al., 1991). Consistent with the double-deficit hypothesis (Wolf & Bower, 1999), phonological processing and rapid naming skills are good predictors of reading achievement.

**PT, PP, and Total Plana Ratio in Children With and Without Dyslexia**

Results of this study suggest that children with dyslexia differ from a clinical control sample with regards to asymmetry of the PT. No differences were found between groups on PP or total plana ratio, although the total plana ratio approached statistical significance. Relatively small sample size may have decreased statistical power in this instance, affecting the results. It is important to note that potentially confounding variables, including an estimate of total brain size, verbal intelligence, and laterality quotient, were used as covariates in this analyses. Controlling for these variables is a significant strength of this study.

This study supports the findings of Hynd et al. (1990), Larsen et al. (1990), Hugdahl et al. (1998), and Heiervang et al (2000), who found atypical asymmetry of the PT at statistically significant levels in children with dyslexia using structural MRI. This study also corroborates
postmortem studies of adults with dyslexia in which symmetrical PT were found (Galaburda & Kemper, 1979; Galaburda et al., 1985; Humphreys et al., 1990). Specifically, this study found symmetry of the PT in children with dyslexia while controlling for handedness, verbal intelligence, and total brain size. This symmetry was due to a larger right PT in the brains of children with dyslexia. This result is consistent with the postmortem studies of Galaburda and colleagues (Galaburda et al., 1987; Humphreys et al., 1990), who have suggested that the right PT is larger in individuals with dyslexia due to insufficient pruning during corticogenesis. Galaburda and colleagues have theorized that excess cortex in the PT on the right side of the brain may interfere with language processing in the PT on the left side of the brain, putting individuals at risk for developmental dyslexia (Galaburda, 1993). In fact, one study has found that larger right PTs are associated with weaker linguistic skills (Foster et al., 2002). Findings from this study lend further support to Galaburda’s theory.

Readable Scan Bias

Results of descriptive analyses between children with readable scans and children without readable scans suggest that there are significant differences between the two groups. Children without readable scans were significantly more left-handed and had a higher percentage of diagnoses of ADHD-PI and ADHD-CT than children with readable scans. Nearly half of all children in the sample who were diagnosed with ADHD-CT did not have readable scans, and ten children with dyslexia were eliminated from the study because they did not have readable scans. This suggests that some of the most severely impaired subjects in our sample, those with comorbid diagnoses of dyslexia and ADHD, severe hyperactivity and/or inattention, anxiety, and/or left-handedness, self-selected out of this study due their inability to remain still in a confined space for the 25 minute time period needed to complete the MRI scan.
This bias may have impacted this study in many ways. First, it could have lessened Berkson’s bias, which states that a clinical sample is more impaired than a non-clinical sample due to self-referral to a clinical setting (Berkson, 1946). In this case, some of the most severely impaired children may have eliminated themselves from this study sample, lessening that bias. Second, the elimination of children without readable scans reduced the power of the results of this study because of the reduced number of subjects. Third, the generalizability of the results of this study may have been affected by this bias as this sample does not perfectly represent a clinical sample referred for reading problems; rather, the sample represents the 78% of a clinical sample referred for reading problems who were not eliminated due to low IQ, cut score diagnostic group, or age restrictions and were able to successfully participate in an MRI scan.

In order to avoid the elimination of subjects due to poor or absent scans in future studies, it is suggested that other researchers consider taking precautions to make certain that children are given every opportunity to participate in the MRI scan. In the present study, every effort was made to ensure that children did not experience anxiety in the MRI scanner during data collection for this study. Parents and clinicians talked with the children about the scanner beforehand in a calm, relaxed manner, and often went into the scanner room with the child for some or the entire MRI scan if a child was anxious. Fewer precautions, however, were taken to reduce the effects of hyperactivity in the scanner which may have led to unreadable scans. Children who typically take stimulant medication did not take the medication on the day of the assessment so the clinician could accurately assess for the presence of ADHD. In retrospect, it may have been beneficial to ask the parents of these children to administer the stimulant medication to the children after testing and before being scanned. Furthermore, in future studies
it may be beneficial to scan children on a separate day, as the stress of assessment may increase hyperactivity in these children.

**Removal of Children with ADHD from the Sample**

When children with ADHD were removed from the study sample, the results for most hypotheses remained the same. The exceptions are the third and sixth hypotheses. The results for the third hypothesis, which tested a multiple regression model that used PT asymmetry, phonological processing, and rapid naming to predict reading achievement, were the same in the sample without ADHD as they were in the total sample. When children with ADHD were used to test this model, however, PT asymmetry, phonological processing, and rapid naming were all found to predict reading achievement at a statistically significant level. This differed from the total sample and sample excluding children with ADHD in that these models did not find that PT asymmetry predicted reading achievement. Different results were also found for hypothesis six, which tested the relationship between total plana ratio and dyslexia diagnosis using analysis of covariance. This relationship had neared statistical significance in the total study sample, but reached statistically significant levels when children with ADHD were removed from the study despite the reduced sample size. Although it is possible to conclude that ADHD may have played a confounding role in the examination of the relationship between total plana asymmetry and dyslexia diagnosis, this is not believed to be a valid conclusion that can be reached from the data. Rather, caution in interpreting this finding is necessary due to the lower sample size used in this statistic and the number of data analyses that were run in this study. Further study is necessary to investigate the relationship between ADHD, PT asymmetry, reading achievement, and dyslexia diagnosis.
Contributions to the Literature

The current study contributes to the literature on the relationship between plana morphology, reading ability, and dyslexia diagnosis in several ways. Compared to the sample sizes ranging from 9 per group to 25 per group found in the literature on plana morphology and dyslexia diagnosis, the sample sizes of 26 and 29 per group is larger than those typically found in the literature. Samples sizes tend to be relatively small in this literature due to the time and expense of full neuropsychological evaluations, MRI scans, and measurement of brain areas. Although the sample size is larger in this study in comparison to other studies in this literature, increased sample size in further studies may serve to increase the potential to adequately test these hypotheses.

Another area in which this study contributes to the literature is the use of widely accepted methodologies in the measurement of the PT and PP, and the calculation of the neuroanatomical ratios that derive from those measurements. The use of borders of the PT has not been consistent in the literature, but recent reviews of the literature on the PT have suggested the use of specific borders so that a standard for PT measurements is emerging in the literature (Barta et al., 1995; Beaton, 1997; Shapleske et al., 1999). These suggested borders were followed in this study. These reviews of PT measurement procedures also suggested that MRI scans should have gapless slices with 1.5mm slice thickness or smaller. The MRI scans used in this study met this criterion. In addition, the use of the Steinmetz methodology (Steinmetz et al., 1989) in the measurement of the PT and the calculation of plana ratios is a strength of the current study. This method is popular in the literature currently being published on the PT. While criticized by some, this methodology is a great improvement over length measurements as it is a measure of area that takes cortical folding into account.
The use of reading fluency as the outcome measure in the multiple regression analysis and as a part of the diagnostic criteria for dyslexia diagnosis is both a contribution to the literature and a limitation of this study as it limits its ability to generalize to other studies. Reading fluency has not been used extensively in this literature as a means of diagnosing dyslexia, although some studies have employed it due to its increased sensitivity in detecting reading problems (Rumsey et al., 1997a). However, due to the number of children in this study who had received extensive phonologically-based intervention, the use of the most sensitive measure to reading problems was deemed necessary and appropriate.

Limitations of the Study

One limitation of this study is its reliance on a clinical sample. Berkson’s bias states that clinical samples are more likely to show comorbidity and severity of a disorder due to the process of self-referral to the study. Parents with more severely impaired children or children whose behavior was more externalizing were more likely to bring their children in for the assessment, which required that both parents miss work and that they pull their child or children out of school. This also biased the sample to include children of parents who are more assertive in seeking services for their children. Furthermore, both biological parents were required to participate in the assessment unless the child was African-American, which often eliminated divorced families who were not African-American.

An important limitation of this study is the fact that head tilt in the scanner was not corrected for, and therefore measurements taken of the PT and PP are taken on brains that have not been aligned. While it is plausible that head tilt is random over subjects and does not impact measurements, there remains the possibility of systematic bias in the measurements. Head tilt was not corrected for due to the limitations of the particular software program used for brain
measurements. This is the same software program used by Steinmetz and colleagues, whose published studies measuring the PT and PP employed the methodology outlined in Steinmetz et al. (1989), which does not correct for head tilt and was used in the present study (Heiervang et al., 2000; Hugdahl et al., 2003; Hugdahl et al., 1998).

Another limitation of this study is the number of analyses conducted. Considering the number of statistical analyses conducted in this study, there is a possibility of Type I error. A Bonferroni correction was deemed to be inappropriate for this study due to the sample size and the type of statistical analyses run, but caution should be used in interpreting results that are not consistent with previous research until confirmatory studies have been conducted.

Conclusions and Future Directions

This study demonstrates that there is a relationship between PT asymmetry and dyslexia diagnosis that exists even when controlling for handedness, verbal intelligence, and total brain size. The question remains as to exactly how the PT affects neural processing in a way as to put an individual at risk for dyslexia. This study does not support a relationship between PT asymmetry and phonological processing, considered by many researchers to be the core deficit in dyslexia. This may be due to the amount of intervention the children in this sample have received, particularly phonologically-oriented reading interventions. Previous research has shown that PT function is involved in language-related tasks other than phonological decoding (Shapleske et al., 1999) and other studies have found a relationship between the PT and receptive and expressive language (Morgan, 1996). It is possible, therefore, that a relationship exists between PT morphology and other types of language skills, such as receptive language, expressive language, and confrontational naming. As many children with severe and specific language impairments have difficulty with reading, it may be the relationship between PT
asymmetry and language impairments that explains the association between PT asymmetry and
dyslexia diagnosis. Some research has suggested that larger right PTs are associated with weaker
linguistic skills (Foster et al., 2002), while other studies have posited that plana morphology is
associated with global language skills (Morgan, 1996). Further research is needed to target this
question specifically by employing detailed language assessments as part of the diagnostic
process.

An additional area for future study is the PP. Few studies have been conducted on this
structure to date, and fewer have related this structure to dyslexia. Although this study does not
support the conclusion that PP morphology may be related to dyslexia, other studies have found
reduced rightward asymmetry of the PP in children with dyslexia. In addition, while other studies
have found rightward asymmetry of the PP in normal subjects, this study found leftward
asymmetry of the PP in both diagnostic groups. Further research is needed to define what PP
morphology in a normal sample as well as the morphological changes that may occur in a sample
with dyslexia and/or a clinical sample. Finally, research linking the PP with a non-diagnostic
variable that may suggest a function for the area, such as handedness, language skills, or visual-
spatial abilities, as have been suggested in the literature, is warranted.

Another important area for future study is to relate structural MRI research on the PT
with functional MRI research. As mentioned previously, researchers have found underactivation
of the left temporo-parietal region, which corresponds roughly to the left PT, and overactivation
in the right temporo-parietal region, which corresponds roughly to the right PT, in children with
dyslexia during reading tasks in functional MRI studies (Pugh, Mencl, Jenner, Lee et al., 2001;
Shaywitz et al., 2002). Based on findings from structural MRI studies that the right PT is larger
in children with dyslexia, it is possible that the overactivation of the right temporo-parietal area
and corresponding underactivation of the left temporo-parietal area found in children with
dyslexia in functional MRI studies is due to the interference of a larger right PT in the processing
of language in these children. This mechanism would be consistent with the theory of
interference of the right PT in language processing as postulated by Galaburda (1993). This
larger right PT may be interfering with language processing in the left PT, causing
underactivation of that region in children with dyslexia. Linking these two areas of research
would help elucidate the function of the PT as well as the role this structure may play in
developmental dyslexia in children.
References


