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Relationship of Temporal Lobe Volumes to Neuropsychological Test Performance in Healthy Children

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Abstract

Ecological validity of neuropsychological assessment includes the ability of tests to predict real-world functioning and/or covary with brain structures. Studies have examined the relationship between adaptive skills and test performance, with less focus on the association between regional brain volumes and neurobehavioral function in healthy children. The present study examined the relationship between temporal lobe gray matter volumes and performance on two neuropsychological tests hypothesized to measure temporal lobe functioning (Visual Perception-VP; Peabody Picture Vocabulary Test, Third Edition-PPVT-III) in 48 healthy children ages 5-18 years. After controlling for age and gender, left and right temporal and left occipital volumes were significant predictors of VP. Left and right frontal and temporal volumes were significant predictors of PPVT-III. Temporal volume emerged as the strongest lobar correlate with both tests. These results provide convergent and discriminant validity supporting VP as a measure of the "what" system; but suggest the PPVT-III as a complex measure of receptive vocabulary, potentially involving executive function demands.

Keywords

Neuropsychological Tests; Visual Perception; Receptive Language; MRI; Brain Volumes; Temporal Lobe; Normal Development; PPVT

INTRODUCTION

Ecological validity of pediatric neuropsychological assessment is considered the ability of laboratory tests to predict real world functioning and/or to correlate with underlying brain structures. Although a few studies have examined the relationship between "real life" skills and intelligence (Kahn, 1992), attention (Price, Joschko, & Kerns, 2003), and executive

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functions (Isquith, Gioia, & Espy, 2004), there has been less focus on the relationship between these daily life skills and neuropsychological measurement of skills considered to be dependent on temporal lobe integrity (e.g., visual perception or receptive language skills).

Functional neuroimaging studies and research involving patients with known lesions or specific disorders have contributed to our understanding of temporal lobe functioning. Studies involving patients with lesions of the left temporal lobe (e.g., middle temporal gyrus, superior temporal gyrus, superior temporal sulcus, angular gyrus) have documented language comprehension deficits (Boatman, Lesser, & Gordon, 1995; Dronkers, Wilkins, Van Valin, Redfern, & Jaeger, 2004). Research with specific clinical populations (e.g., autism and dyslexia) has also documented temporal lobe abnormalities. Specifically in autism, a disorder characterized by primary deficits in language and social interaction, abnormalities in the function of the superior aspect of the temporal lobes have been identified (Abell et al., 1999; Boddaert et al., 2004; Meresse et al., 2005; Ohnishi et al., 2000; Zilbovicius et al., 2000). In healthy individuals a leftward asymmetry of the temporal lobe has been documented (Geschwind & Levitsky, 1968); whereas, in developmental dyslexia the volume of the temporal lobes has been shown to be symmetrical (Rumsey et al., 1986). Recent studies have not consistently found symmetrical temporal lobe volumes in dyslexic individuals, but have documented exaggerated asymmetries for those with dyslexia. Specifically, smaller left temporal lobe volumes, particularly in the planum temporale, and decreased overall temporal lobe volumes have been found when compared to control participants (e.g., Eliez et al., 2000; Hugdahl et al., 2003; Leonard et al., 1993; Vinckenbosch, Robichon, & Eliez, 2005). Similarly, neuroanatomical findings from Livingstone and colleagues indicate that poor readers have smaller lateral (LGN) and medial (MGN) geniculate nuclei (Galaburda & Livingstone, 1993; Livingstone, Rosen, Drislane, & Galaburda, 1991). In additional studies of language functioning in dyslexia, Tallal and colleagues have found difficulties in auditory and somatosensory processing of linguistic and nonlinguistic speech sounds (Tallal & Piercy, 1973; Tallal, 1980; Tallal & Stark, 1982; Tallal, Stark, & Mellits, 1985; Tallal & Katz, 1989). These findings were later supported by Binder and colleagues (1994), who utilized functional magnetic resonance imaging (fMRI) of language functioning in healthy adults, and found that the superior temporal lobes are involved in decoding the acoustic signals of speech. Thus the left temporal lobe appears to be specialized for language processing, and is therefore crucial in a variety of school-related abilities including development of reading skills (Molfese & Molfese, 1986).

Functioning of the right temporal lobe is less well researched and its function is also not as clearly defined. Early studies have documented deficits in visual form discrimination following right temporal lobectomy (Meier & French, 1965) and right hemisphere missile wounds (Newcombe, 1969). The right superior temporal cortex is thought to process the ‘what’ in visual perception tasks (Ungerleider & Haxby, 1994). According to Goodale and Milner (1992, 2008), there are two streams of visual processing: the dorsal “action” stream, projecting from early visual areas and the superior colliculus (via the pulvinar) to the posterior parietal cortex; and, the ventral “perception” stream, projecting from the retina to the lateral geniculate nucleus (pars dorsalis) in the thalamus, to primary visual cortex, and then to regions in the occipito-temporal cortex. The ventral stream is described to provide the detailed representations of the world that are required for cognitive processes including recognition, identification, and planning. There is increasing yet inconsistent evidence supporting a relationship between visual perception and other brain regions, particularly in the parietal lobe (Himmelbach & Karnath, 2005). Much of this evidence comes from early reports of patients with spatial neglect, which is a lack of awareness of space and object parts in the hemi-space contralateral to the brain lesion. From these early studies it has been believed that spatial neglect is associated with lesions of the right inferior parietal lobe and the temporal, parietal, and occipital lobe juncture (Heilman & Valenstein, 1972). In a study by Karnath, Ferber, and Himmelbach (2001), only patients with spatial neglect without visual-field defects were included, as it was felt that previous research may have been confounded by inclusion of those with visual-field impairments. Computed tomography (CT) or MRI scans revealed the lesions of these patients were predominantly in the superior temporal gyrus. As Karnath (2001) elucidated, the rostral portion of the superior temporal sulcus and superior temporal gyrus are located at the transition between the ventral "what/perception" and dorsal "where/action" streams of visual processing, which may account for mixed findings of temporal and parietal lobe involvement in object perception. Goodale and Milner (1992, 2008) also note that the dorsal and ventral streams both process information about the structure and spatial location of objects. They further state that although this information is mediated by different pathways, the two systems are intimately connected with the response of one stream often contingent upon the complex mechanisms of the other stream.

Although previous pediatric neuroimaging research examining brain development in healthy children has been cross-sectional (Caviness, Kenney, Richelme, Rademacher, & Filipek, 1996; Courchesne et al., 2000; Giedd et al., 1996; Jernigan, Trauner, Hesselink, & Tallal, 1991; Pfefferbaum et al., 1994; Reiss, Abrams, Singer, Ross, & Denckla, 1996), Giedd and colleagues (1999) published longitudinal data in which linear increases in white matter volume with age were observed, whereas age-related changes in gray matter were nonlinear and regionally specific. Particularly, frontal lobe gray matter volumes increased during pre-adolescence, peaked around 12 years of age for boys (11 years of age for girls), and declined during post-adolescence resulting in an overall net decrease across the age span (i.e., 4 to 20 years). Results were similar for parietal lobe volumes and differed only in that the slope of the curve was steeper and volumes peaked one year earlier for each gender. In contrast, temporal lobe volumes peaked around 16 years of age for both boys and girls with a mild decline thereafter. Occipital lobe gray matter followed a linear increase over the age range with no evidence of decline or plateau. Total cerebral gray matter volume was approximately 10% larger in boys and peaked slightly earlier in girls, but the shapes of the curves were similar for both genders.

While studying patients with known brain lesions has led to advances in the study of brain-behavior relationships, fewer studies have documented an association between regional brain volumes and neurobehavioral function in healthy children. Recently, Shaw and colleagues (2006) investigated the relationship between intellectual functioning and cortical development. They found a negative correlation between IQ and cortical thickness in young children, suggesting that timing and trajectory of changes in gray matter volume are associated with efficiency of cognitive functioning. That is, in young children, higher IQ was associated with thinner cortex, particularly in the frontal and temporal lobe regions; however, this relationship reversed in late childhood, with positive correlations observed between cortical thickness and IQ. Interestingly, children with superior IQ had thinner superior prefrontal cortex at an early age, with a rapid increase in cortical thickness peaking at age 13, and attenuating into late adolescence.

In healthy individuals, studies have documented a modest relationship between total brain volume and intellectual functioning (Reiss et al., 1996; Schoenemann, Budinger, Sarich, & Wang 2000; Willerman, Schultz, Rutledge, & Bigler, 1991). In contrast, research examining correlations between *specific* neuropsychological tests and regional brain volumes in healthy individuals are limited (Egan et al., 1994). Studies involving individuals with temporal lobe damage have implicated the temporal lobes in auditory sensation and perception; selective attention for auditory and visual stimuli; visual perception; organization and categorization of verbal material; language comprehension; long-term memory; personality and affective behavior; and, sexual behavior (Kolb & Wishaw, 1990). Volumetric MRI studies with temporal lobe epilepsy patients have been successful in documenting a correlation between hippocampal volume and verbal memory performance (e.g., Pegna et al., 2002; Reminger et al., 2004) and amygdalar volumes have been correlated with visuospatial memory (e.g., Pegna et al., 2002).

The purpose of the present study was to determine whether regional temporal lobe volumes would predict performance on two neuropsychological tests hypothesized to measure temporal lobe functioning in a sample of healthy children. Specifically, we hypothesized that, after consideration of age, gender, and total cranial volume, right temporal lobe gray matter volume would be the best predictor of performance on a test of visual object perception and left temporal lobe gray matter volume would be the best predictor of performance on a test of receptive vocabulary.

MATERIALS AND METHODS

Participants

Forty-eight typically developing children ages 5-18 years (24 boys) were recruited from the Baltimore, MD area by advertisement. Each participant and parent signed a consent form that met the institutional review board standards of the Johns Hopkins Medical Institutions. Participants were initially screened over the telephone and excluded if there was a history of neurological disorder, mental retardation, or learning disability. Parents of those children meeting this eligibility criterion participated in a structured diagnostic interview using the Diagnostic Interview for Children and Adolescents - Fourth Edition (DICA-IV; Reich, Welner, & Herjanic, 1997), which is based on the Diagnostic and Statistical Manual of Mental Disorders - Fourth Edition (DSM-IV; American Psychiatric Association, 1994). Children meeting DSM-IV criteria for a psychiatric disorder were subsequently excluded. Socioeconomic status of each participant was estimated by a widely used four-factor index (i.e., gender, marital status, education, and occupation; Hollingshead, 1975). All study participants received MRI scans and completed a neuropsychological assessment that included measures of attention, memory, language, visual, and motor skills. A test of receptive vocabulary and a visual perception test were analyzed for the current study. Taking into consideration the larger neuropsychological test battery, these two tests were selected as the purest and most widely-accepted measures of temporal lobe functioning (further description of the measures is provided below).

Magnetic Resonance Image Acquisition and Processing

High-resolution three-dimensional MRI images of each participant's brain were acquired with a GE-Signa 1.5 Tesla LX scanner (General Electric, Milwaukee, WI) using the standard birdcage quadrature head coil. Axial images were obtained with a 3-D volumetric radiofrequency spoiled gradient echo (SPGR) series partitioned into 124, 1.5-mm contiguous slices.

Raw, GE-Signa formatted image data was transferred from the MRI scanner at Johns Hopkins Hospital to Apple Macintosh Power PC workstations at SUNY Upstate Medical Institutions via existing networks. The image data were imported into the program *BrainImage* (Reiss, 2002; http://spnl.stanford.edu/tools/brainimage.htm) for visualization, processing, and quantitation (Subramaniam, Naidu, & Reiss, 1997). The importation process creates a 124-slice image stack composed of spatially registered, 8-bit images that have been processed to minimize signal artifacts related to RF field inhomogeneity. To prepare the stacks for measurement, nonbrain material (i.e., skull, scalp, and vasculature) is removed from these image stacks using a semi-automated edge detection routine that involves region growing as well as stepwise morphologic operations (Subramamiam et al., 1997). These “skull-stripped” images are resliced so that the interpolated slice thickness (z-dimension) is the same as the x and y pixel dimensions thereby converting the image stacks into cubic voxel data sets. The cubic voxel data sets are opened into the multiplanar visualization mode of *BrainImage* so that three orthogonal representations of the data can be viewed simultaneously.

Image Measurement

Isolated brain tissue was subdivided into cerebral lobes, subcortical regions, brainstem, and cerebellar regions using the revised Talairach (Talairach & Tournouz, 1988) stereotaxic grid atlas specific for measurement in pediatric study groups (Andreasen et al., 1993; Kaplan et al., 1997; Kates, Abrams, Kaufmann, Breither, & Reiss, 1997). With this approach, high levels of sensitivity and specificity are achieved for all revised Talairach-based calculations of lobar brain regions (Kates et al., 1999). Each region was then segmented to delineate and measure lobar volumes of gray, white, and ventricular compartments using a constrained fuzzy algorithm that assigns voxels to one or more tissue categories based on intensity values and tissue boundaries (Reiss et al., 1998). The segmentation method used was determined reliable for all gray matter, white matter, and CSF volumes (Reiss et al., 1998).

Neuropsychological Measures

Beery-Buktenica Developmental Test of Visual-Motor Integration (Fifth Edition), Visual Perception Test (Beery & Beery, 2004)—On the Visual Perception test (VP), the first three items are designed for very young children and require identification of their own body parts, picture outlines, and parts of a picture. For the remaining 27 test items, the child is shown one geometric form and is asked to choose the geometric form that is exactly the same from a group of forms within a 3-minute time limit. For example, the child is shown a target stimulus of a Necker cube and is asked to select (by pointing or circling) the exact match of the cube among five choices, four of which may be smaller, missing parts, rotated, etc. Thus, the test is designed as a measure of motor-free visual-perceptual ability and has been shown to differentiate children with deficits in perception from those having problems with motor coordination and integration of perceptual and motor skills (Kulp & Sortor, 2003). Raw score total was analyzed for the present study.

Peabody Picture Vocabulary Test, Third Edition (PPVT-III; Dunn & Dunn, 1997)—The PPVT-III is a screening test of verbal ability and a measure of receptive (i.e., listening) single-word vocabulary attainment for standard English. The child is shown a page with four pictures and the examiner provides the child with a vocabulary word. The child is asked to identify which picture best describes that word either by pointing or verbalizing the number of the picture. Thus, the test requires little to no motor or expressive language output. The child continues the test until 8 of 12 items are missed in an item set. Raw score totals were used for analysis in the present study.

Data Analysis

Intercorrelations for left and right hemisphere volumes of each lobe were examined. Pearson product-moment correlation coefficients for total cranial volume and individual lobar gray matter volume (frontal, parietal, temporal, and occipital lobes) were examined for each hemisphere and to determine the relationship between lobar gray matter volumes and the two neuropsychological test scores.

General linear model was applied to examine the relationship between the neuropsychological test scores and lobar gray matter volumes. Based on findings by Lenroot et al. (2007) of nonlinear, regional, and gender-specific changes in gray matter development, gender was entered as a fixed factor in all regression analyses. Absolute lobar gray matter volumes (i.e., the left or right gray matter volume for each lobe) and *relative* lobar gray matter volumes (i.e., expressed as ratios of left or right frontal, parietal, temporal, or occipital gray matter volumes to total cranial volume) were used in the calculations. Since lobar gray matter volumes were not age-corrected, raw scores for the two neuropsychological tests (i.e., VP and PPVT-III) were also used. To account for the effect of age on the neuropsychological test scores and lobar gray matter volumes (both absolute and relative), residuals for all variables (after regressing on age) were used in the statistical analyses. Homoscedasticity of the data was confirmed by employing the method suggested by Glejser (as described in Zar, 1998). Fisher's r-to-z transformation (Cohen & Cohen, 1983; Preacher, 2002) was used to compare the magnitude of the correlations between left and right temporal lobe gray matter volumes and neuropsychological test scores with the other lobar hemispheric volumes and both test scores.

RESULTS

Relevant demographic characteristics of all 48 participants are summarized in Table 1. The mean age of the study sample was 12.18 years (standard deviation = 3.56). Fifty percent of the sample was male and 81% right-handed, with no mixed-handed participants. The race composition was 54% African American, 37% Caucasian, and 8% biracial.

Lobar Correlations and Intercorrelations

Analysis of the correlation among gray matter lobar volumes *within* the right hemisphere (e.g., right frontal lobe volume correlations with right parietal, temporal, and occipital lobes; See Table 2 values above the diagonal) were statistically significant (all $p < 0.001$). Correlations ranged from $r = 0.65$ to $r = 0.97$. Similarly, correlations among gray matter lobar volumes *within* the left hemisphere (See Table 2 values below the diagonal) were also statistically significant (all $p < 0.001$) and ranged from $r = 0.68$ to $r = 0.94$. When examining correlations between hemispheres within each of the four lobes of the brain, right and left hemisphere volumes were very highly intercorrelated—all $p < 0.001$ and greater than or equal to $r = 0.90$ (see Table 2).

Analysis of the bivariate correlations between age, VP and PPVT-III raw scores, individual (total, left, and right) lobar gray matter volumes, and total cranial volume was performed and are presented in Table 3. Scatterplots depicting the relationship between VP scores and lobar gray matter volumes are shown in Figure 1. Among lobar volumes, temporal lobe volumes demonstrated the strongest correlation with VP scores, accounting for 18% of the total variance in the test scores. Figure 2 shows the relationship between PPVT-III and gray matter volumes for each lobe. Again, temporal lobe volumes had the strongest relationship with PPVT-III scores, accounting for 14% of the total variance in the test scores.

Using Fisher's r-to-z transformation, the correlation between left temporal lobe gray matter volumes and PPVT-III test scores ($r = .377$) was significantly greater than the correlation between left parietal ($p < .05$) and both left ($p < .05$) and right ($p < .01$) occipital volumes and PPVT-III scores. Similarly, the correlation between right temporal lobe gray matter volumes and PPVT-III test scores ($r = .359$) was significantly greater than the correlation between both left and right occipital gray matter volumes ($p_s < .05$) and PPVT-III scores. The magnitude of the correlation between both left and right temporal lobe gray matter volumes and VP test scores was not significantly greater than the correlation between left and right frontal, parietal, and occipital volumes and VP scores. There was a trend toward a significantly larger correlation between right temporal lobe gray matter volumes and VP scores ($r = .416$) compared with right parietal lobe volumes and VP scores ($p = .07$).

Regression Analyses

A series of linear regression analyses were used to examine the relationship between absolute and relative lobar hemispheric volumes and the two neuropsychological tests of interest (i.e., VP and PPVT-III). To account for multiple comparisons, statistical significance was set to *p*

< 0.01. In developing the regression models, all predictor variables were entered simultaneously and gender served as a covariate. Although the correlation between left and right lobar volumes was highly significant, individual hemispheric lobar volumes were used in all regression analyses to determine whether the relationship with both neuropsychological tests showed the expected higher correlation in the hypothesized hemispheric lobe (i.e., right temporal volume for VP and left temporal for PPVT-III). The results of the analyses for each neuropsychological test are summarized in Tables 4 and 5. Absolute *temporal* left and right and *occipital* left gray matter volumes, but not left or right frontal and parietal or right occipital gray matter volumes significantly predicted performance on the VP test. Absolute *frontal* left and right and *temporal* left and right gray matter volumes, but not left or right parietal or occipital gray matter volumes were significant predictors of the PPVT-III scores. None of the relative lobar volumes (corrected for total cranial volume) were significant predictors of either VP or PPVT-III test performance. In addition, none of the analyses detected a significant gender effect in predicting test performance.

DISCUSSION

The present study examined the relationship between lobar gray matter volumes and two neuropsychological tests hypothesized to measure aspects of temporal lobe function (i.e., VP and PPVT-III). After controlling for age and gender, left and right temporal and left occipital lobe volumes, but not left or right frontal and parietal lobe volumes, were significant predictors of VP test scores. In contrast, left and right temporal and frontal lobe volumes were significant predictors of PPVT-III scores. For both tests, however, temporal lobe volumes emerged as the strongest correlate of raw score test performance. Thus, these results provide initial convergent and discriminant validity supporting the VP test as a measure of the temporal lobe “what” ventral perception system in healthy children and also provide evidence for the hypothesis of the PPVT-III as a complex measure of receptive language as there is evidence that it involves aspects of executive functioning.

The study findings are consistent with previous research that has emphasized temporal lobe contributions to visual-perceptual processing—especially object perception *and* to language functioning—especially receptive vocabulary. Research involving brain-behavior correlates of visual object perception is primarily limited to adults. The present findings support the longstanding notion from the adult literature that the visual “what” ventral perception stream is primarily processed through the temporal lobes. More specifically, our findings of bilateral temporal lobe involvement in object perception has been previously shown in several experiments. For example, Kourtzi and Kanwisher (2000) performed a series of experiments, one of which involved fMRI investigation of areas activated by line drawings. Results from this investigation revealed bilateral activation in temporal and occipital regions for identifying object structure. In another experiment, Marsolek (1995) demonstrated that abstract visual form information primarily operates in the left hemisphere, where this information is stored and then later recalled for use in distinguishing different form types. Marsolek and colleagues (1996) also provided evidence for right hemisphere involvement in holistic processing (rather than parts-based) of abstract forms for distinguishing specific details of a form within the same category. Pins, Meyer, Foucher, Humphreys, and Boucart (2004) also noted bilateral temporal lobe activation in an fMRI paradigm involving object matching. The VP task used in the present study is structured such that the participant must distinguish the exact match of a target object among a group of objects that differ only in small detail (e.g., smaller, rotated, missing line, etc.). Thus, performing the VP task involves holistic and parts-based analysis of abstract form type.

Although occipital lobe volume was not hypothesized to be a significant predictor of performance on the VP test, this result was not surprising given the visual presentation of the task. Previous research has supported the finding of primary visual cortex involvement in object perception. For example, in an fMRI study of healthy young adults, Calhoun and colleagues modified the Motor-Free Visual Perception Test - Revised (MVPT-R; a measure of visual perceptual processing involving spatial relationships, visual discrimination, figure-ground, and visual closure) to an event-related fMRI paradigm for localizing changes in blood flow/oxygenation during visual perceptual processing (Calhoun et al., 2001). They recorded activation in a large network including primary visual cortex and visual association areas. In a similar study, Moritz, Johnson, McMillan, Haughton, and Meyerand (2004) investigated the neuroanatomical correlates of the Hooper Visual Organization Test (HVOT) using fMRI. They also found a large activation network including ventral temporal-occipital cortex, posterior visual association areas, and frontal eye fields.

Numerous imaging studies have analyzed the neuroanatomical mechanisms involved in the linguistic processes underlying reading development. For example, Turkeltaub, Gareau, Flowers, Zeffro, and Eden (2003) found increased activation in the left superior temporal sulcus during an implicit word processing task using fMRI in children. Two separate studies using diffusion tensor magnetic resonance imaging (DTI) in healthy children found correlations between the left temporal lobe and word reading ability (Beaulieu et al., 2005; Nagy, Westerberg, & Klingberg, 2004). In a positron emission tomography (PET) study, Büchel, Price, and Friston (1998) investigated modes of language acquisition in blind (i.e., auditory-tactile association) and sighted adults (i.e., auditory-visual association) by presenting strings of words and non-words. They found activation of the left basal posterior temporal lobe area 37 for both groups. Recent imaging studies involving both adults and children with dyslexia have employed PET (McCrory, Mechelli, Frith, & Price, 2005), magnetic resonance spectroscopy (MRS; Rae et al., 1998), volumetric MRI (Vinckenbosch et al., 2005), and magnetoencephalography (MEG; Salmelin, Service, Kiesila, Uutela, & Salonen, 1996; Trauzettel-Klosinski, Durrwachter, Klosinski, & Braun, 2006). Across all these studies, analysis of participants' performance on behavioral measures and imaging findings revealed significant involvement of temporal lobe structures. Although the studies focus on involvement of the left temporal lobe, many also revealed involvement of the right temporal lobe in language comprehension.

Although we did not specifically predict that frontal lobe volumes would be correlated with PPVT-III performance, there is some literature to support these findings. For example, Dronkers and colleagues (2004) utilized voxel-based lesion-symptom mapping to evaluate the relationship between brain lesions and performance on a receptive language comprehension task in adult stroke patients. They found that lesions to temporal and frontal brain regions affected performance on the language task. The authors concluded that this finding likely related to the auditory rehearsal component of the language comprehension task (i.e., patients were read a sentence and then asked to select from a picture array the image most closely related to the meaning of the sentence). As previously discussed, evidence from studies of developmental dyslexia have documented decreased temporal lobe, planum temporale, lateral, and medial geniculate nuclei volumes. LGN and MGN project directly to primary visual and auditory cortex and are thought to be involved in the direction and maintenance of attention, a function that is primarily subserved by the frontal lobes. In addition, Turkletaub and colleagues (2003) found that the processes underlying reading development are associated with increased activity of left temporal and frontal structures and decreased activity of right temporal lobe areas.

Construct validity studies provide evidence of the PPVT-III as a measure of intellectual ability (e.g., Bell, Lassiter, Matthews, & Hutchinson, 2001; Campbell, Bell, & Keith, 2001; D'Amato, Gray, & Dean, 1988); however, several of these studies have also shown that the PPVT inaccurately classifies intellectual functioning (e.g., Childers, Durham, & Wilson, 1994;

Tarnowski & Kelly, 1987). D'Amato, Gray, and Dean (1988) showed in their construct validity study that the PPVT was strongly associated with measures involving verbal abstract reasoning and decision-making skills. The PPVT-III task requires the participant to choose one picture from a field of four that best matches the examiner-provided word. Thus, performance of the task also involves a decision-making component, an aspect of executive functioning, which are skills primarily subserved by the frontal lobes. Results from the above mentioned imaging studies, construct validity studies of the PPVT, the brain's interconnected pathways, and the decision-making component of the task itself might provide support for the present study's finding of frontal and temporal lobe gray matter volumes as predictive of PPVT-III performance. Thus, the current results implicate the PPVT-III as a complex measure of receptive vocabulary with underlying demands for executive functioning skills.

Results of the current study are limited by comparison to large gray matter volumes and warrant follow-up with manual measurement of sub-regions of the temporal lobes. Parcellation of the temporal lobes will permit further investigation of specific structure-function relationships. In addition, the present study utilized a cross-sectional design, limiting the conclusions that can be drawn regarding the impact of brain and skill maturation. Longitudinal studies are needed to investigate factors associated with development. Finally, our finding of nonsignificant correlations between frontal, parietal, and occipital lobar gray matter volumes and both neuropsychological tests raises concern regarding the contribution of total cranial volumes to the finding of left occipital lobe volume as a predictor of VP raw score and both left and right frontal lobe volumes as predictors of PPVT-III. Thus, although the relationship between temporal lobe volume and performance on these neuropsychological tests appears robust, the relative contribution of other lobar volumes to performance on these measures warrants further investigation.

Future research employing a longitudinal design with further parcellation of the temporal lobes is warranted to investigate developmental changes as well as to address the long-standing notion of bigger volume not necessarily associated with better function. For example, recent evidence from Shaw and colleagues (2006) revealed thinner cortical thickness in frontal and temporal regions associated with higher IQ in young children, with increases in cortical thickness peaking in middle childhood and a reverse relationship (i.e., higher cortical thickness associated with higher IQ) observed by adolescence. In addition, a recent DTI study examining white matter integrity in adults diagnosed with William's Syndrome associated higher fractional anisotropy values in the right superior longitudinal fasciculus with deficits in visuospatial construction (Hoeft et al., 2007). Therefore, present findings may not directly apply to clinical populations where there is an aberrant developmental trajectory of the nervous system.

Despite the above-mentioned limitations, the present study is one of the first to demonstrate the relationship between specific brain regions and neuropsychological measures of temporal lobe functioning in, typically developing children using volumetric MRI. These findings support the continued use of volumetric MRI analysis in healthy children for examining the ecological validity of specific neuropsychological tests.

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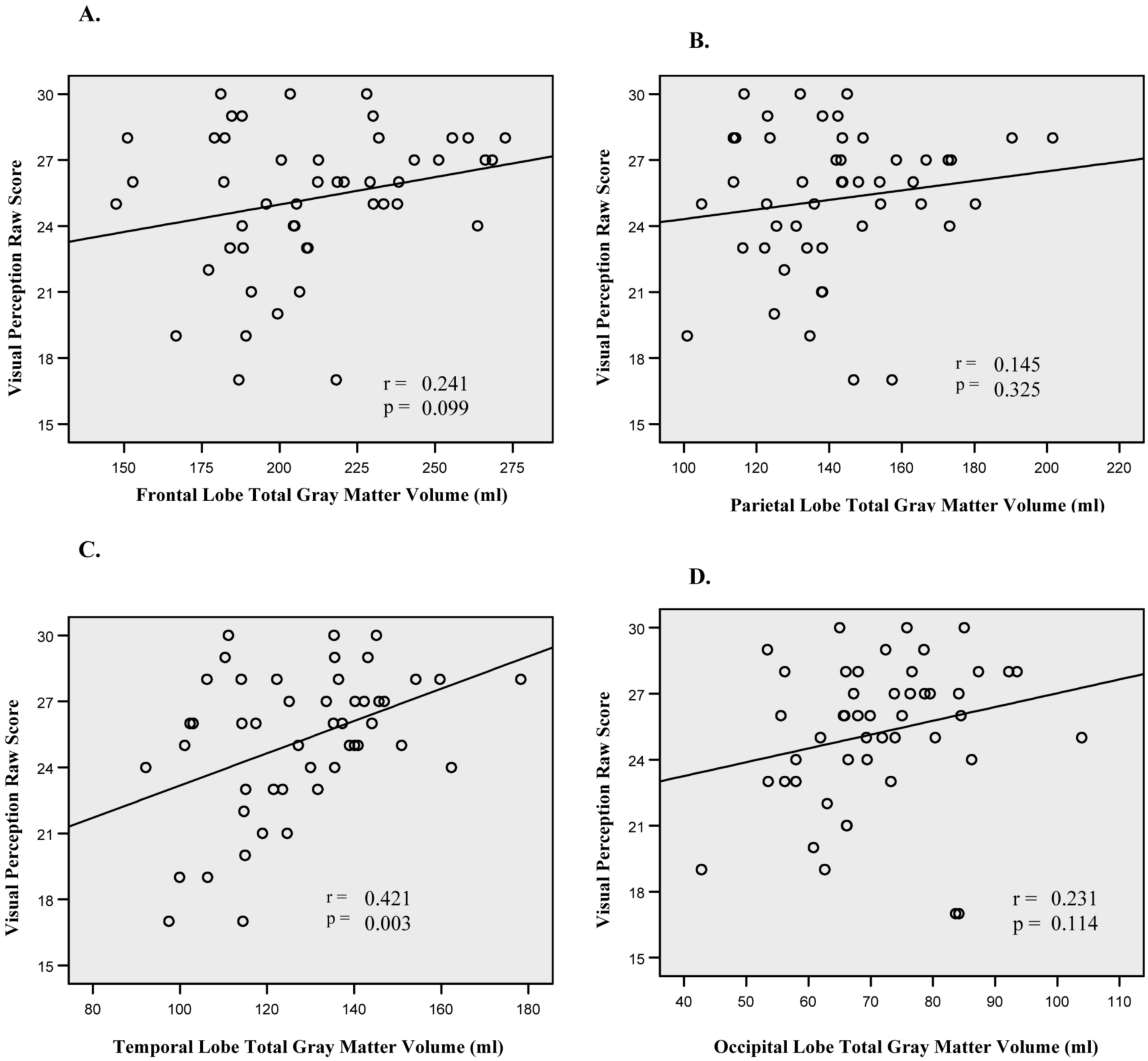

Figure 1. Relationship between VP Raw Scores and Lobar Gray Matter Volumes

Scatterplots depicting the relationship between Visual Perception (VP) raw scores and (A.) frontal, (B) parietal, (C) temporal, and (D) occipital lobe gray matter volumes (ml). Temporal lobe volumes demonstrated the strongest correlation (r = 0.421), accounting for 18% of the variance.

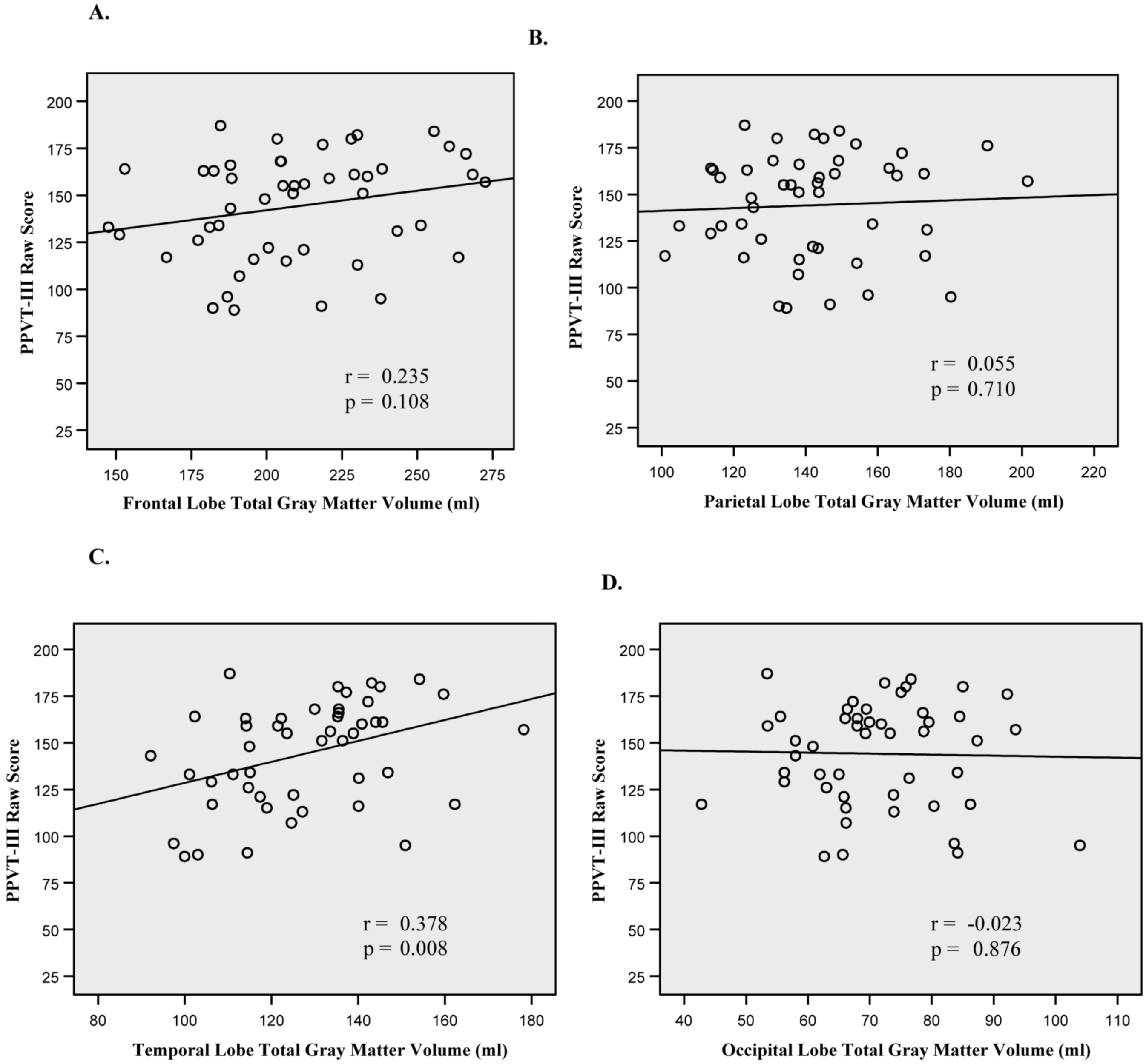

Figure 2. Relationship between PPVT-III Raw Scores and Lobar Gray Matter Volumes

Scatterplots depicting the relationship between PPVT-III raw scores and (A.) frontal, (B) parietal, (C) temporal, and (D) occipital lobe gray matter volumes (ml). Temporal lobe volumes demonstrated the strongest correlation (r = 0.378), accounting for 14% of the variance.

Table 1

Study Sample Characteristics (n = 48)

Variable	**Range**	**Mean**	**SD**
Demographics			
Age (years)	5 - 18	12.18	3.56
SES (Hollingshead Index)*	16 - 66	44.31	11.99
Neuropsychological Test			
PPVT-III Raw Score	89 - 187	144.15	27.88
PPVT-III Standard Score	72 - 150	103.02	16.24
Visual Perception Raw Score	17 - 30	25.23	3.26
Visual Perception Standard Score	59 - 139	97.06	17.17
Volume (ml)			
Total Cranial	860.42 - 1442.17	1105.99	131.35
Frontal Gray Matter	147.52 - 272.54	210.03	31.51
Left Frontal GM	74.30 - 132.84	105.47	15.46
Right Frontal GM	73.22 - 140.99	104.57	16.49
Parietal Gray Matter	100.90 - 201.59	141.87	21.81
Left Parietal GM	50.83 - 100.66	71.06	10.93
Right Parietal GM	50.07 - 100.93	70.82	11.21
Temporal Gray Matter	92.16 - 178.21	127.94	18.74
Left Temporal GM	47.10 - 88.88	64.86	9.39
Right Temporal GM	42.13 - 89.34	63.08	9.83
Occipital Gray Matter	42.82 - 103.92	71.38	12.01
Left Occipital GM	21.33 - 53.56	35.75	6.42
Right Occipital GM	21.49 - 50.37	35.63	5.84

***Notes*: Values are unadjusted mean (SD).**

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[*] n = 47

Table 2

Correlation (Pearson r) of Right and Left Lobar Gray Matter Volumes

	Total Cranial	Frontal	Parietal	Temporal	Occipital
Total Cranial	**.964**	.965	.936	.890	.756
Frontal	*.940*	**.946**	.892	.852	.650
Parietal	*.915*	*.852*	**.943**	.764	.733
Temporal	*.877*	*.773*	*.727*	**.900**	.648
Occipital	*.818*	*.678*	*.802*	*.706*	**.919**

***Note*: Values above the diagonal represent correlations (r) within right hemisphere, whereas values below are correlations within left hemisphere; correlations on the diagonal represent left vs. right hemisphere correlations of the same lobe; *p* < .001 for all values.**

Table 3

Bivariate Correlation Coefficients

Variable (n = 48)	**Age**	**Correlation Coefficients (r)** **Gender**	**VP**	**PPVT-III**
Frontal Lobe Gray Matter Volume	-0.183	0.252	0.241	0.235
Left Frontal GM	-0.226	0.256	0.253	0.207
Right Frontal GM	-0.137	0.241	0.224	0.255
Parietal Lobe Gray Matter Volume	-0.299*	0.240	0.145	0.055
Left Parietal GM	-0.318*	0.236	0.146	0.031
Right Parietal GM	-0.271	0.238	0.140	0.077
Temporal Lobe Gray Matter Volume	0.058	0.230	0.421**	0.378**
Left Temporal GM	0.087	0.258	0.405**	0.377**
Right Temporal GM	0.028	0.192	0.416**	0.359*
Occipital Lobe Gray Matter Volume	-0.416**	0.125	0.231	-0.023
Left Occipital GM	-0.386**	0.177	0.240	0.015
Right Occipital GM	-0.431**	0.063	0.211	-0.064
Total Cranial Volume	-0.053	0.347*	0.384**	0.343*

Note: Values represent Pearson product-moment correlations (r). VP = Visual Perception. PPVT-III = Peabody Picture Vocabulary Test, Third Edition.

** Significant at the .01 level (2-tailed)

* Significant at the .05 level (2-tailed)

Table 4

Regression Analyses of Lobar Gray Matter Volumes and VP[a] Test Performance

Predictor	**R^2**	**F(1,47)**	***p***
Absolute Lobar Volumes (ml)			
Left Frontal Lobe Gray Matter	0.109	5.425	0.024
Right Frontal Lobe Gray Matter	0.072	3.419	0.071
Left Parietal Lobe Gray Matter	0.062	2.853	0.098
Right Parietal Lobe Gray Matter	0.050	2.283	0.138
Left Temporal Lobe Gray Matter	0.161	8.498	0.006
Right Temporal Lobe Gray Matter	0.179	9.673	0.003
Left Occipital Lobe Gray Matter	0.150	8.146	0.006
Right Occipital Lobe Gray Matter	0.138	7.088	0.011
Relative Lobar Volumes (ml)[b]			
Left Frontal Lobe Gray Matter	0.008	0.258	0.614
Right Frontal Lobe Gray Matter	0.024	1.004	0.322
Left Parietal Lobe Gray Matter	0.052	2.385	0.129
Right Parietal Lobe Gray Matter	0.057	2.605	0.114
Left Temporal Lobe Gray Matter	0.016	0.662	0.420
Right Temporal Lobe Gray Matter	0.040	1.789	0.188
Left Occipital Lobe Gray Matter	0.018	0.717	0.402
Right Occipital Lobe Gray Matter	0.004	0.108	0.744

[a] VP = Visual Perception

[b] Corrected for total cranial volume.

Table 5

Regression Analyses of Lobar Gray Matter Volumes and PPVT-III[a] Test Performance

Predictor	**R^2**	**F(1,47)**	***P***
Absolute Lobar Volumes (ml)			
Left Frontal Lobe Gray Matter	0.234	11.142	0.002
Right Frontal Lobe Gray Matter	0.218	9.995	0.003
Left Parietal Lobe Gray Matter	0.127	4.218	0.046
Right Parietal Lobe Gray Matter	0.136	4.725	0.035
Left Temporal Lobe Gray Matter	0.190	8.039	0.007
Right Temporal Lobe Gray Matter	0.217	9.911	0.003
Left Occipital Lobe Gray Matter	0.175	7.081	0.011
Right Occipital Lobe Gray Matter	0.140	5.005	0.030
Relative Lobar Volumes (ml)[b]			
Left Frontal Lobe Gray Matter	0.059	0.702	0.407
Right Frontal Lobe Gray Matter	0.069	1.189	0.281
Left Parietal Lobe Gray Matter	0.060	0.720	0.401
Right Parietal Lobe Gray Matter	0.049	0.215	0.645
Left Temporal Lobe Gray Matter	0.051	0.270	0.606
Right Temporal Lobe Gray Matter	0.076	1.535	0.222
Left Occipital Lobe Gray Matter	0.058	0.619	0.435
Right Occipital Lobe Gray Matter	0.045	0.025	0.874

[a] PPVT-III = Peabody Picture Vocabulary Test, Third Edition

[b] Corrected for total cranial volume.