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Early Phonological Awareness as a Predictor of Reading Fluency: An MRI Study

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Abstract

Learning to read is a critical building block in the acquisition of reading fluency. Previous studies indicate phonological awareness as the main skill used to acquire reading fluency. Previous studies have also found correlations with cortical thickness in certain regions of the brain associated with phonological awareness as well as higher reading fluency scores. This was a longitudinal study where about 100 children with little to no school experience came in at time 1 for behavioral tests and an MRI. They then came back one year later at time 2 for another set of behavioral tests and again a year later for time 3. Only 19 subjects had completely processed structural data so only these 19 were used in this particular study. The main aim of this study was to take the behavioral test scores from time 1 and run a simultaneous multiple regression analysis to determine the best predictor of reading fluency at time 3. These tests included non-word decoding, word reading, and phonological processing, and IQ measured by WASI and WPPSI. In addition, a whole brain correlation was run using the time 1 MRI and the reading fluency score for time 3 to determine areas of the brain correlated with better readers. Results show that IQ measured at time 1 was the most significant predictor of reading fluency at time 3, while the structural analysis shows that cortical thickness and surface area in several reading-related brain regions measured at time 1 are related to reading fluency skill at time 3.

1. Introduction

The ability to read is a critical skill in the early life of every child. When children are learning to read, they are combining both cognitive and linguistic skills, including fluency, accuracy and phonological awareness (Houston, M.S*., et. al.,* 2013). Phonological awareness is described as one's ability to process and manipulate individual phonemes (Kibby, M. Y., *et. al*., 2014). These skills are used in orthographic decoding, which is the process of translating print into its equivalent auditory representation (Frye, E. R., *et. al*., 2010). A longitudinal study done by B. R. Foorman, *et. al*. (2015), found that reading comprehension in third and fourth grades was mediated by their phonological awareness as well as letter knowledge when they were in first and second grade. In addition to phonological awareness, general intelligence, (or g), seems to predict the strength of an individual's reading skills as well (Benson, *et. al.,* 2010). However, the IQ test used in these studies were using is an overall measure of intelligence, which includes verbal IQ as opposed to just individual IQ subtests (Benson *et al*., 2010). This is important because verbal IQ tests measures language skill as well.

Besides behavioral measures, functional neural activation during reading in several regions of the brain has also been associated with reading skill. Pugh *et. al*. (2001), have identified two main reading-related systems. These are the ventral and dorsal systems. The ventral circuit is composed of the lateral extrastriate areas and a left inferior occipito-temporal area (Pugh K. R., *et. al*., 2001). The extrastriate cortex is a region in the occipital cortex, located near the primary visual cortex. The dorsal reading system includes the angular gyrus and supramarginal gyrus in the inferior parietal lobe, as well as Wernicke's area (Pugh *et. al*., 2001). The ventral circuit is important for word reading. Activation of this area increases with age and is associated with reading skills (Pugh *et. al.,* 2001). Vogel A. C. *et. al.* (2014), also proposed that the function of the ventral system is word-form recognition. In contrast, the dorsal region is used in pseudoword reading and activation is increased during phonological analysis of words. The hypothesized function of this region is for rule based analysis function (Pugh *et. al.,* 2001). Using information about typical development in these circuits used in reading, MRI studies can be used to determine whether these regions are typically or atypically developing in young children. Two major structural measures of the brain in neurological studies are cortical thickness and surface area. Cortical thickness and surface area are measures of gray matter structure. Studies which measure structural brain development have shown that gray matter proliferates through early childhood, when learning to read, and decreases in thickness as adolescence begins (Porter J. N., *et. al.,* 2011). From the moment we are born, pruning in our brain begins and continues into adolescence. Pruning is a process where damaged or degraded neurons are removed from the brain. The pruning process supports the findings of Porter *et. al*. (2011), because through childhood and adolescence the brain continues the pruning process, decreasing the cortical thickness. An additional finding by Karama *et. al.* (2009)*,* is an increase cortical thickness associated with a better IQ.

The inferior frontal gyrus has been shown to be involved in phonetic processing. Using fMRI, N. Golestani (2012) found less activation in the left inferior frontal gyrus in 'faster' readers as opposed to the 'slower' readers, which is consistent with the fact that phonetic processing is less effortful in faster readers than the slower readers. Though the activation in the inferior frontal gyrus decreases the better reader a child is, the gray matter has been shown to thicken in the left inferior frontal cortex with improving phonological processing scores (Lu L. H., *et. al*., 2007). In addition, the supramarginal gyrus is thought to be involved in the subsegmental aspects of speech, as well as translating between acoustic and motor representations (Frye, *et. al*., 2010). Another major area of the brain associated with reading skill is the fusiform gyrus. Prior research has shown that an increase in gray matter density in the right fusiform gyrus is associated with better reading scores (Hoeft, M., *et. al.,* 2007).

Despite having great educational opportunity and adequate intellectual ability, about 3-15% of children fail to acquire competent reading skills, (Cornelissen, P., P. Hansen, 1998). Years of research have determined that phonological processing issues are correlated with the reading skills of dyslexic individuals (Cornelissen, 1998). The difference between children who have typical reading skills and those that fail to acquire them is traced back to brain differences. These brain differences in individuals with dyslexia are established in early cortical development (Frye *et. al.,* 2010). Frye *et. al.* (2010), have claimed that the difference between dyslexic and typical brains is related to cortical folding. Consistent with this hypothesis was the findings of Pugh *et. al.* (2010), that there is a decrease in gray matter volume and surface area in the inferior frontal gyrus of only dyslexic readers. Cross-sectional studies of impaired readers done by Houston *et. al.* (2014), have found reduced gray matter volume in the fusiform gyrus and the supramarginal gyrus in the right hemispher. Interestingly, functional MRI studies have shown that dyslexic individuals rely on the left inferior frontal gyrus and the right superior temporal regions while they are practicing phonological decoding skills, (Lu, L. H., 2006). In addition, after children are characterized as having dyslexia and then put through remediation, they have shown gains in their right-hemisphere reading pathway, whereas typical readers are left-hemisphere dominant (Hoeft M., *et. al.,* 2010). These findings suggest that poor readers may use right hemisphere homologues of left-hemisphere reading-associated regions in order to compensate for their weak left hemisphere development. One barrier to effective treatment of dyslexia is that it is typically not detected until after the best window for remediation has passed, which is know as the 'dyslexia paradox,' (Ozernov-Palchik O., N. Gaab 2016).

The main aim of this study was to examine the relationship between performance on specific behavior tests of phonological awareness tests given to the subjects at time one when they entered the study and their reading fluency scores at time three. Studies using structural imaging in addition to behavior tests, indicate that neuroimaging data is just as predictive of reading disability as behavioral tests (Hoeft, F., *et. al.,* 2007). Thus, in addition to looking at behavioral tests to predict reading fluency scores, the MRI scans of the subjects at time one were analyzed with the reading fluency scores at time 3 to identify neural predictors of reading skill. Reading fluency was chosen because it is important when connecting word recognition and comprehension. I hypothesized early phonological awareness would be the main predictor of later reading fluency and the greater cortical thickness and surface area in the inferior frontal gyrus, supramarginal gyrus and fusiform gyrus is at time one, would be associated with higher reading scores at time 3. Structural imaging has the potential to be used to detect reading disabilities at a young age. Though a more expensive method than behavioral tests, neuroimaging provides unique predictive information. Further, the combination of behavioral tests with neuroimaging data has been observed to predict how much just one year of education can influence these fundamental reading skills in young children (Hoeft, F., *et. al.,* 2007).

2. Methods

Subjects

19 subjects between the ages of 5.58 and 6.75 years at time 1 (mean= 6.16 years, SD=0.34; 5 males and 14 females) were recruited for a study of behavioral tests with regards to reading skills, as well as an MRI study. These subjects came back 1 year later at time 2 and again another year later for time 3. The ages at time 3 of these subjects ranged from 7 to 9.08 years, with an average age of 8.15 years at time 3. All of these subjects showed right hand dominance based on the Edinburgh Handedness Inventory (Oldfield R.C., 1971). All of the subjects appeared to be typically developing and any subject with an IQ of less than 80 was omitted from the study. Their IQ was tested using the Weschler Abbreviated Scale of Intelligence (WASI) (Weschler, D., 2011) or the Weschler Preschool and Primary Scale of Intelligence (WPPSI) (Weschler, D., 2002) depending on the age of the subject at time 1.

Behavioral Measures

The subjects were put through a number of behavioral tests to test for phonological awareness skills as well as reading skills. These skills varied from time 1 to time 3 based on the age of the subjects, as their reading level should have progressed by time 3. With regards to this study, the behavioral measures focused on were the Woodcock Johnson Word Attack subtest (Schrank, F. A., et. al., 2014), the Woodcock Johnson Letter Word Identification subtest (Schrank, F. A., et. al., 2014), and the composite score of the

Comprehensive Test of Phonological Processing (CTOPP) (Wagner, R. K., et. al., 2013) at time 1, as well as their IQ scores measured using WASI or WPPSI. The Woodcock Johnson Word Attack is a subtest of reading decoding and phonetic coding in which nonsense words are visually presented to the subject to read aloud, which all follow the rules of the English language. For example, the word "tiff" may be given to the child to read aloud. The Woodcock Johnson Letter Word Identification is a subtest of sight-word reading in which the subject is tested orally on reading skills. They are visually presented a series of real words that gradually get more difficult and single-word reading is assessed. The composite CTOPP score is made up of the CTOPP Elision and CTOPP Blending subtests. For the CTOPP Elision subtest, the subject is given a word, and then told to leave out a phoneme and say it again. For example, "Stay 'stop,'" (pause) "Now say 'stop' without the /s/ sound." The subject should respond "Top." For the CTOPP Blending subtest, the child has to put sounds together to form a word. For example, one would say to the subject, "What word do these sounds make: '/B/-/oi/?'" The subject should respond with, "Boy." The scaled scores of these tests were combined to calculate composite scores norm-based to an average of 100, with a standard deviation of 15, just as with IQ. The IQ scores were composite, which included block design, vocabulary, matrix reasoning and similarities. The vocabulary test included 3 picture items and 28 verbal items. In the verbal portion, they would have to define words. 5 of the subjects were administered the WPPSI, while 14 were administered the WASI based upon their age at time 1. The behavioral measure of interest at time 3 was the Woodcock Johnson Reading Fluency test (Schrank, F. A., et. al., 2014). This subtest is a measure of how quickly a subject can read simple sentences. It is a timed test, typically three minutes, and they read simple sentences and then must indicate if they are true or false. This score was also standardized with the normed average set at 100 and a standard deviation of 15.

MRI Scanning and Processing

The T1-weighted anatomical scans were collected on a Siemens 3T Trio MR scanner at Yale University Medical Center in New Haven, Connecticut. The acquisition parameter voxel size was 1.3x1.3x4.0mm, the field of view was 256 mm, the TR was 15 ms, the TE was 6.86 ms and the flip angle was 25 degrees with interleaved slice acquisition. The measures of surface area and cortical thickness were obtained using the program *FreeSurfer.* FreeSurfer is a software using to analyze neuroimaging data, available at this link http://surfer.nmr.mgh.harvard.edu/ for downloading. It uses the reconstructed surface model to analyze an array of anatomical features and is highly specialized in its representation of cortical surfaces and thickness, while also measuring the volume of subcortical structures (Dale, A.M., et. al., 1999). The typical processing stream was taken here. The input is T1-weighted MR images with approximately 1mm voxel size (Dale, A.M., et. al., 1999). The skull and dura are then stripped away and subcortical structures are labeled. White matter is segmented following the intensity normalization followed by surface atlas registration, surface extraction, and gyral labeling, (Dale, A.M., et. al., 1999). The processing stream is not always accurate in removing the dura or segmenting white and grey matter accordingly, so visual inspection is required for quality control and manual edits often must be made as well. Errors in the processing stream may occur due to scan acquisition parameters or artifacts such as subject motion during scanning. The common edits made to our subjects included brainmask editing to remove the dura still included in the grey matter segmentation, or adding control points to areas which appear to be white matter, but were not segmented as white matter. White matter segmentation is based on an intensity threshold of 110, however some voxels containing white matter may fall below this threshold and so not all of the white matter is picked up by Freesurfer at default settings. Control points are “manually selected locations in the volume that the user feels is inside the white matter boundary, and subsequently should be normalized to an intensity of 110,” (“Using Control Points to Fix Intensity Normalization”, p. 1). After these manual edits are made, they are run through recon editing and undergo multiple rounds of editing until they appear to be ready for data analysis.

Statistical Approach: Behavioral Analyses

The behavioral measures were analyzed with SPSS Statistics Software using the multiple regression approach. Multiple regression is used for estimating the relationships among specific variables. In this case, the scores from time 1 administration of the Woodcock Johnson Word Attack and Woodcock Johnson Word Identification subtests, as well as the combined CTOPP score and WASI/WPPSI were analyzed to determine which was the best predictor of the Woodcock Johnson Reading Fluency score at time 3. A significance threshold of $p<0.05$ was used.

Statistical Approach: Neuroimaging Analyses

For the MRI analysis, the program QDEC within the Freesurfer software package was used. QDEC stands for Query, Dseign, Estimate, Contrast. It is used for performing intersubject or group averaging and inference on cortical surface and volume data which was previously produced by FreeSurfer, (FreeSurfer Tutorial, p.1). Using the selected subjects, the necessary data is put in, including a design matrix (X), which contains the explanatory variable, a parameter estimate (A), and the contrast vector. The cluster extent threshold was manually set at 50mm based on previously read literature in which the researchers has also set their cluster extent threshold at 50mm, (Golestani, N., 1990). This was used to minimize any noise. The Woodcock Johnson Reading Fluency score at time 3 was used to see if there was a relationship between cortical thickness and surface area measured at time 1 and later outcomes in reading fluency. For surface area, intracranial volume was included as a nuisance variable due to prior evidence showing a significant association between surface area and cortical volume measures (Frye, R. E*., et. al.,* 2010).

3. Results

Behavioral Analyses

Using the Woodcock Johnson Reading Fluency subtest score as the dependent variable and Woodcock Johnson Word Attack, Word Identification, CTOPP composite and WASI/WPPSI as predictor variables, a simultaneous multiple regression analysis was run. IQ as measured by WASI/WPPSI was the only significant predictor or reading fluency (b=0.404, p=0.039). This indicates that for every standard deviation increase of their IQ, they would also have a 0.404 increase in their reading fluency subtest score as well. A p-value of 0.05 is the standard threshold in psychology research, so anything below this is considered to be significant. While the CTOPP composite score had a standardized beta coefficient of 0.349, which was the second highest, the p-value was 0.265, proving to be an insignificant relationship. The standardized beta coefficients for Woodcock Johnson word attack and letter word identification were 0.148 (p=0.686) and 0.129 (p=0.749), respectively. It is important to note the IQ scores were composite scores of all the IQ subtests administered, and thus performance on the verbal subtests may be driving the association with reading fluency due to shared linguistic processing load. Though insignificant, there are correlations between the other independent variables and WJ reading fluency.

Neuroimaging Analysis-Cortical Thickness

The time 1 MRI of the subjects was run for a whole brain correlation of the reading fluency scores of the subjects at time 3. After setting the cluster extent threshold to 50mm, numerous spots on the brain correlated to better reading fluency scores, with either an increase or decrease in cortical thickness or surface area. The aim of this analysis was to determine if gray matter structure in any parts of the brain are significant for reading at this young age. In the right hemisphere of the brain, the superiorfrontal gyrus, parahippocampal gyrus, pericalcarine sulcus, and the cuneus all showed negative correlations, with increased reading fluency scores associated with decreased cortical thickness. The pericalcarine sulcus is located by the lingual gyrus, which is another region of interest. The cuneus is also located in the occipital lobe of the brain, and is bounded by the pericalcarine sulcus on one side. In addition, the superiorfrontal gyrus showed a positive correlation, with increased scores associated with increased cortical thickness. In the left hemisphere of the brain, the supramarginal gyrus also showed a positive correlation.

Neuroimaging Analysis- Surface Area

The other measurement used was surface area. In the right hemisphere of the brain, the medialorbitofrontal gyrus, superiorfrontal gyrus, lateraloccipital gyrus, fusiform gyrus, and lateralorbitofrontal gyrus showed positive correlations, with an increase in reading fluency associated with an increase in surface area. For the left hemisphere of the brain, the superiofrontal gyrus, the parsorbitalis, which is the orbital part of the inferior frontal gyrus, the precentral gyrus, supramarginal gyrus and lingual gyrus also showed positive correlations for surface area and reading scores.

4. Discussion

This studied aimed to find the best predictor of later reading fluency using measures of reading-related behaviors and brain structure obtained at a young age. Although my initial prediction was that phonological awareness and increased surface area and cortical thickness in reading-related brain would be most strongly associated with increased reading fluency, the behavioral results were not consistent with this prediction and the imaging findings were more complicated. Specifically, results from our simultaneous multiple regression analysis revealed IQ as the only significant predictor of reading fluency at time 3. In addition, the structural MRI analysis shows that cortical thickness and surface area in several reading-related brain regions measured at time 1 are related to reading fluency skills at time 3. Imaging data is complicated in the sense that it is not always consistent in terms of greater surface area predicting better reading scores.

At time 1, the subject's IQ scores ranged from 88-127 (M= 109.53, SD=10.10) and at time 3, the reading fluency scores ranged from 92-134 (M= 113.79, SD=13.90). WASI and WPPSI are normed at 100, with one standard deviation set at 15 and the reading fluency scores are normed the same way. The mean of both of these scores with this set of subjects is over 100, almost one standard deviation away, showing this set of subjects used are above average in both IQ and reading fluency scores. Because the hypothesis was that the phonological awareness tests would be the best predictors of later reading fluency, it was a surprise to find our results indicated IQ as the most significant predictor (standardized beta=0.404, p=0.039). As described in the methods section, WASI and WPPSI composite scores include verbal subtests. For example, in the WASI, there is a vocabulary section which requires children to define words of increasing difficulty (Weschler, D., 2011). In addition, the WPPSI, though for younger children, still includes a verbal comprehension section in the full scale IQ. This subtest consists of general knowledge questions and similarity questions between common objects and concepts, (Weschler, D., 2002). These verbal subtests may be driving the association with reading fluency due to shared linguistic processing. In future analyses, we will explore relations between early performance on the individual subtests and later reading fluency.

The structural analysis of MRI at time 1 with reading fluency at time 3 provided partial support for my hypothesis. Positive correlations with both cortical thickness and surface area in the supramarginal gyrus (an area of the brain associated with language perception) associated with increased reading fluency scores has been supported by previous literature, (Frye et. al., 2010). Also supportive of the hypothesis was the increase in surface area of the right fusiform gyrus associated with higher reading fluency scores. The fusiform gyrus is important with regards to word recognition, another vital skill involved in reading. It is located between the lingual and parahippocampal gyrus. The left lingual gyrus was positively correlated with an increase in surface area and higher reading fluency scores.

The lingual gyrus is involved in processing letters. In previous studies, the inferior frontal gyrus was found to have a vital role in phonological processing. There is a positive correlation with increased left gray matter thickness and better reading scores (Lu L. H., et. al., 2007). These previous findings were consistent with the ones found in this study. The parsorbitalis, which is the orbital part of the inferior frontal gyrus, controls motor syllable programs and was positively correlated with increased surface area associated with better reading fluency scores.

One interesting finding was both the positive and negative correlations between right hemisphere cortical thickness and reading fluency scores in the superiorfrontal gyrus. The function of the superiorfrontal gyrus is associated with working memory. Perhaps at a young age, memory plays a role in reading still until a child's phonological awareness and decoding skills are really able to develop. This hypothesis would support the findings of a decrease in cortical thickness associated with better reading fluency scores, as well as the increase in cortical thickness associated with better reading fluency scores. In order to test if this hypothesis were true, it would be interesting to compare the MRI from time 3 with the subjects' reading fluency scores at time 3 to see whether or not their working memory still shows positive correlations, or the cortical thickness decreases.

As discussed in the introduction, two main reading circuits have been proposed; the ventral and dorsal circuits (Pugh *et. al.,* 2001). The ventral region is also named the occipito-temporal region. This region increases in activation with age and predicts reading skill and is considered the word-form area (Pugh *et. al.,* 2001). Results in this study were consistent with the findings of Pugh *et. al.* (2001), as increased surface in the right lateraloccipital gyrus, found in the ventral region, was positively correlated better reading fluency scores.

Limitations and future directions

One limitation of this study was the number of subjects used. Over 100 subjects were used in entirety of this study, however only these 19 have completely processed structural data at this time. It would be important to see if our results remain when data from all the children are analyzed. Moving forward, it would be intriguing to see if combining behavioral and brain measures into a composite model would better predict reading fluency outcomes. This could help with detecting dyslexia in children before they reach school age, and begin remediation during the crucial window of brain development. In addition, it is important to break down the IQ tests into subtests to see what is driving the IQ and relations to reading fluency.

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Table 1

Demographic and Behavioral Measures of Interest

Measure	Full Sample
Sex	
Male	5
Female	14
Age (Years) at T1	
Range	5.58-6.75
Mean	6.16
Age (Years) at T3	
Range	7-9.08
Mean	8.15
WJ Word Attack	
Range	101-138
Mean (SD)	109.53 (11.29)
WJ Word Identification	
Range	94-148
Mean (SD)	121.21 (15.69)
CTOPP Composite	
Range	82-137
Mean (SD)	112.16 (16.26)
WASI/WPPSI IQ	
Range	88-127
Mean (SD)	109.53 (10.10)
WJ Reading Fluency	
Range	92-134
Mean (SD)	113.79 (13.90)

Table 2
The coefficients of the relationship between WJ reading fluency and the 4 independent variables, WJ word attack, WJ word ID, CTOPP composite, and WASI/WPSSI.

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	-16.402	27.871		-.588	.566	-76.179	43.376
	WJ Word Attack	.183	.442	.148	.413	.686	-.766	1.131
	WJ Word ID	.114	.350	.129	.326	.749	-.636	.864
	CTOPP Composite	.298	.257	.349	1.161	.265	-.253	.850
	WASI/WPSSI	.557	.244	.404	2.278	.039	.033	1.081

a. Dependent Variable: WJ Reading Fluency

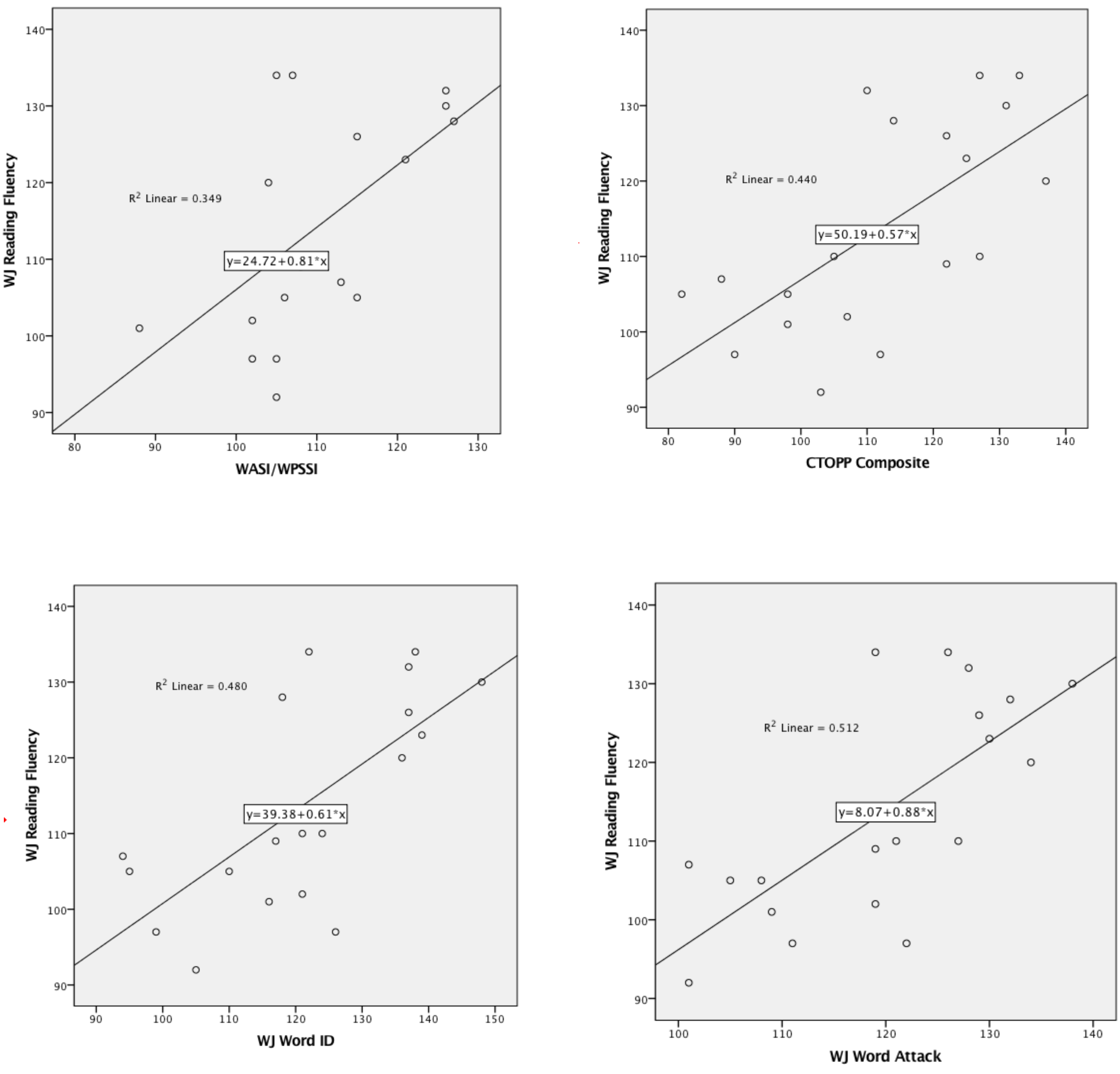

Figure 1: The correlations between reading fluency and WASI/WPSSI (p=0.039), CTOPP composite (p=0.265), WJ Word Attack (p=0.686), and WJ Word ID (p=0.749).

Figure 2: Increase in cortical thickness in the supramarginal gyrus in the left hemisphere associated with better reading fluency scores.

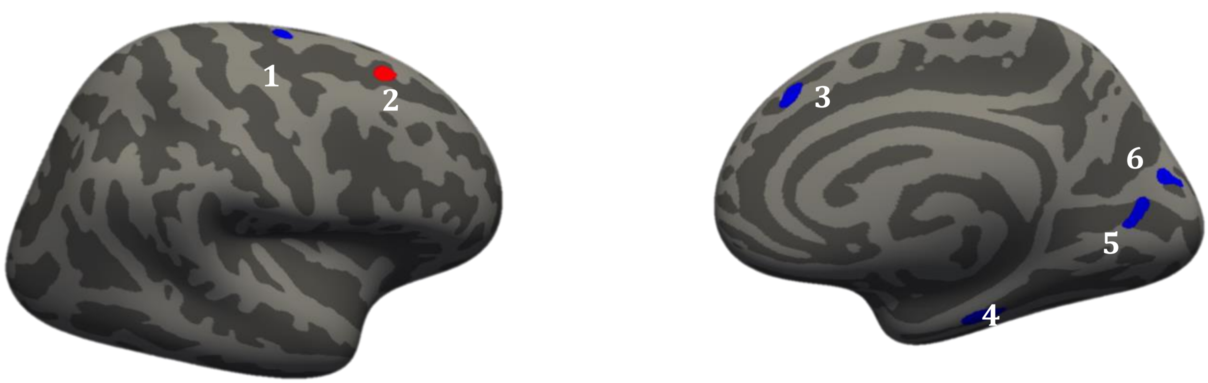

Figure 3: Right hemisphere. Red indicates an increase in cortical thickness associated with increased reading fluency scores while blue indicates a decrease in cortical thickness associated with reading fluency scores. The areas of the brain are as follows: 1, 2, 3: Superiorfrontal gyrus, 4: Parahippocampal gyrus, 5: Pericalcarine sulcus, 6: Cuneus.

Figure 4: Left hemisphere. Red indicates an increase in surface area associated with better reading fluency scores. The areas of the brain are as follows: 1: Lingual gyrus, 2: Superiorfrontal gyrus, 3: Parsorbitalis, 4: Caudalmiddlefrontal gyrus, 5: Precentral gyrus, 6: Supramarginal gyrus.

Figure 5: Right hemisphere. Red indicates an increase in surface area with better reading fluency scores. The brain areas are as follows: 1: Medialorbitofrontal gyrus, 2: Superiorfrontal gyrus, 3:Lateralocciptial gyrus, 4:Fusiform gyrus, 5: Lateralorbitofrontal gyrus.

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