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Master Thesis

Reading by One Isolated Hemisphere

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Abstract

The left hemisphere dominance for nearly all processes associated with reading has been firmly established for both mature and young readers (Vigneau et al., 2006; Lindenberg & Scheef, 2007; Fiebach et al., 2002). Involvement of the RH in reading is traditionally associated with populations exhibiting difficulties with reading (Gazzaniga, 1983; Weekes, Coltheart & Gordon, 1997; Patterson et. al., 1988; Coltheart, 2000), although the most recent work suggests that the right hemisphere may participate in reading in normal adults who reach high proficiency (Ettinger-Veenstra et al., submitted). However, the question remains how the two hemispheres work together during reading and to what extent each isolated hemisphere can support reading and the decoding processes associated with reading (e.g., phonological awareness, phonological memory, rapid naming and vocabulary retrievals). In this study we investigated the latter issueis issue by assessing reading abilities in twenty three children and young adults (age range 6-25 years) who have undergone left or right cerebral hemispherectomy for intractable catastrophic epilepsy. All participants had either complete removal of one hemisphere, i.e. anatomical hemispherectomy, or partial removal and complete disconnection of the affected hemisphere in a modified functional hemispherectomy.

The goal of our study was to assess reading abilities including word recognition and oral comprehension. While reading is an extremely complicated cognitive task including a variety of knowledge areas and metacognitive skills we focused on those components of reading that Chall (1983) called "learning to read" steps (in contrast to "reading to learn" which comes later in life). We investigated whether phonological awareness and memory, rapid naming and vocabulary size predict reading capacity similar to neurologically-intact readers.

About 60% of all the participants had average reading abilities. Similar to our previous results (Smets, 2010), we documented that side of the resection by itself was not a meaningful predictor of reading and its underlying components. Instead, side and etiology (developmental vs. acquired pathology) together was a better predictor of reading capacity.

As with general language outcomes following hemispherectomy (Liegeous et al., 2008a; b) we saw both functional lateralization and equipotentiality of both hemispheres for reading. Participants with pathology acquired after a period of normal development showed a predicted pattern of reading outcomes reflecting progressive language lateralization, i.e. participants with left hemisphere removal had the worst outcomes while those who had the right hemisphere removed uniformly scored within the normal range. In contrast, participants with developmental pathology did not exhibit any clear hemispheric advantage. We had few cases of developmental pathology with a right-sided resection, commanding caution in our conclusions, with 2 out of 3 participants failing to reach average levels. However, in sharp contrast to the acquired group, 6 out of 9 participants with the developmental pathology and left resection were average readers.

Surprisingly, there was no straightforward correlation between reading components and reading capacity in this population. Phonological processing and rapid naming presented significant difficulty for almost all participants including those with average reading skills. As a group, only in participants with the remaining *right* hemisphere phonological awareness, phonological memory and vocabulary predicted reading capacity. No such correlations were found for individuals with the remaining left hemisphere. Furthermore, rapid naming did not correlate with reading in any group.

These results present an opportunity to extend our knowledge of how reading is acquired and question the role of traditional reading components. In the future, these findings could be potentially applied to reading instruction in both clinical and normal populations and suggest there is no one-way-fit-all method as we are discovering there are more ways to read than we currently know of.

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1. Introduction

1.1. Hemispherectomy

The term *hemispherectomy* is applied to surgeries in which all or large amounts of cortical tissue in one cerebral hemisphere are removed. The most favorable surgical procedure for hemispheric removal has been debated. Cases of serious, potentially fatal late neurologic deterioration after complete *anatomic* hemispherectomy were reported. This led to modifications of the procedure. One alternative to the anatomical hemispherectomy is the *functional* hemispherectomy with resection of central cortex and transection of all interhemispheric connections and all white matter tracts in the remaining frontal, parietal, occipital, and temporal regions. This procedure leaves most of the hemisphere vascularized and anatomically intact but functionally disconnected from the rest of the brain (Wyllie, 1998).

Candidates for hemispherectomy are individuals who have medically intractable seizures arising from lesions in a single hemisphere (Carson et al. 1996). The epileptic seizures can be caused by a variety of etiologies, the most common of which include infarcts, Sturge-Weber syndrome, Rasmussen's encephalitis, hemimegalencephaly and cortical dysplasia. Children with severe epilepsy often have physical disability and their cognitive and adaptive development are usually severely compromised (Pulsifer et al. 2004). These problems associated with intractable epilepsy can be a serious impediment to independent living in adulthood and, generally, have adverse effects on the quality of life.

As reported in studies of relatively large groups of children after hemispherectomy, the procedure has favourable outcomes with regard to seizure freedom. Intelligence, language, visual-motor, and adaptive/developmental skills for most children are generally no worse than before surgery (see Pulsifer et al. 2004; Devlin et al. 2003).

1.2. Hemispheric involvement in reading

Although the human brain works as an integrated whole, each of the cerebral hemispheres is believed to have an advantage for processing certain types of information (Waldie & Mosley, 2000). Hemispheric involvement in the processing of orthographic information has been widely studied, with neuroimaging studies repeatedly demonstrating left hemisphere superiority; at the same time, some studies suggest that right hemisphere is also involved in reading, mainly in impaired populations.

1.2.1. Left Hemisphere involvement

Lindenberg and Scheef (2007) carried out an fMRI study to identify the cortical areas engaged in the processing of auditory and visual language tasks in healthy adult subjects. In the visual task twenty healthy subjects were presented with three reading conditions and a fixation. The reading conditions consisted of (1) a continuous text, (2) a text of pseudo-words (pronounceable letter strings), and (3) a text of non-words (consonant strings). All three conditions yielded widespread activation clusters in the left hemisphere, in particular in the inferior frontal gyrus (Brodman's areas 44, 45 and 47). The continuous text condition was contrasted with the pseudo- and non-word conditions, activations were detected in a fronto-temporal system with a global maximum in the left temporal cortex.

Fiebach et al. (2002) studied the different roles that occipito-temporal and left inferior frontal brain areas play during visual word processing in a lexical decision task. Participants were presented with a sequence of high- and low frequency words and with the same number of phonologically legal pseudowords that were derived from the word stimuli by randomly exchanging one or two letters. The participants' task was to judge whether or not each stimulus was a legal German word. Contrasting words with pseudowords, bilateral occipito-temporal brain areas and left posterior middle temporal gyrus were identified as contributing to the successful mapping of orthographic script onto visual word form representations. Low-frequency words and pseudowords caused greater activations than high-frequency words in the superior pars opercularis (BA 44) of the left inferior frontal gyrus, in the anterior insula, and in the thalamus and caudate nucleus. Since processing of these stimuli during lexical decision is known to rely on phonological information, it was concluded that these brain regions are involved in grapheme-to-phoneme conversion.

Vigneau et al. (2006) performed a large-scale meta-analysis to define the composition of various language processing networks in the left hemisphere. Phonological processing results were largely based on the studies using reading tasks (e.g. reading letters, reading pseudo-words, discriminating whether a word ended with the same sound). The meta-analysis revealed that activations during these phonological processing tasks were located in the posterior part of the frontal lobe distributed along the precentral gyrus in the left hemisphere.

Another meta-analysis of literature on cerebral structures underlying word reading (Jobard et al., 2003) used an automated analysis method based on the inventory of activation peaks issued from word or pseudoword reading contrasts of 35 published neuroimaging studies. No cluster of activations was recruited more by word than pseudoword reading, implying that the first steps of word access may be common to word and word-like stimuli and would take place within a left occipitotemporal region. Next, the results also indicated the existence of brain regions predominantly involved in graphophonological conversion, namely left lateralized brain structures such as superior temporal areas, supramarginal gyrus, and the opercular part of the inferior frontal gyrus.

1.2.2. Right Hemisphere involvement

In the classical literature, the right cerebral hemisphere was considered “word blind” (Dejerine, 1892 mentioned in Coslett & Monsul, 1994; Geschwind, 1965). Some investigators, however, have argued that the right hemisphere has a certain capacity to read. For example, clinical studies on reading abilities of patients with deep dyslexia and global alexia (Coltheart, 1980, 1983 mentioned in Waldie & Mosley, 2000; Gazzaniga, 1983; Weekes, Coltheart & Gordon, 1997; Patterson et. al., 1988; Coltheart, 2000) show that in these populations, the right hemisphere plays a crucial role in reading.

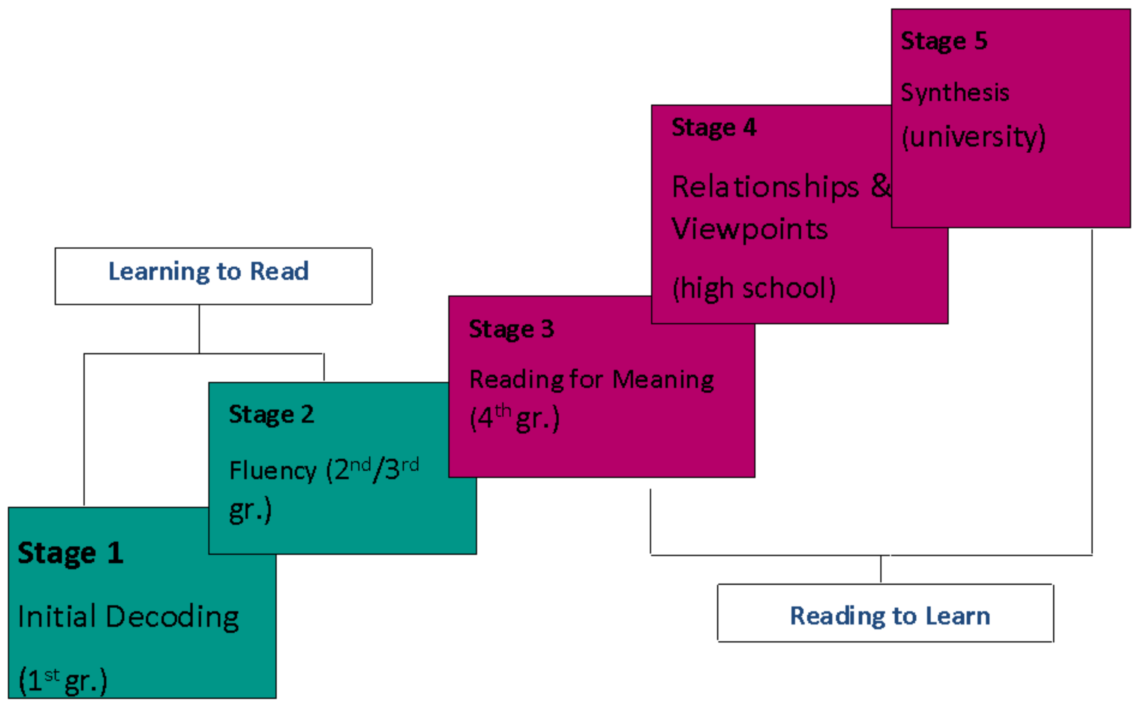
Interestingly, a recent fMRI study of eighteen healthy subjects (Van Ettinger-Veenstra, submitted) suggests that the right hemisphere may participate in reading in neurologically-intact adults who reach high proficiency The study showed that performance on reading and high-level language tests correlated positively with increased right-hemispheric activation in the inferior frontal gyrus (specifically Brodmann area 47), the dorsolateral prefrontal cortex, and the medial temporal gyrus (Brodmann area 21). Moreover, a negative correlation between performance and left hemispheric dorsolateral prefrontal cortex activation was found.

1.3. Reading and its Critical Components

One of the most important abilities which determine quality of life and is frequently affected by developmental or acquired deficits is reading (Dejerine, 1891, 1892; Hinshelwood, 1902; Beauvois and Derouesne, 1979; Damasio and Damasio, 1983; Kawamura et al., 1987; Coslett and Saffran, 1989; Anderson et al., 1990; Taylor Sarno, 1998 in Roux et al. 2004). In today's “information explosion” living without accurate reading skills is almost impossible to imagine (McLaughlin, 2006). The ability to read is an acquired process and is considered a complex skill (Roux et al., 2004; Smith Gabig, 2009).

We based our study on a model proposed by Chall (1983) (Figure 1.). We focused on the first two stages which the author describes as “learning to read” in contrast to “reading to learn” because many of our participants are still struggling readers. None of the participants reads for leisure, and we were interested in investigating whether difficulties with reading components would explain weaknesses and strengths in this population.

Figure 1. Stages of reading development.



Most recent literature on reading suggests phonological awareness and decoding, phonological memory, and rapid naming predict reading capacity.

Phonological processing refers to the use of phonological information, especially the sound structure of the oral language, in processing written information (Wagner, Torgeson & Rashotte, 1999). A considerable body of research indicates that reading is strongly associated with phonological capacities, and that weaknesses in such capacities are linked to reading disability (e.g., Lonigan, Schatschneider, & Westberg, 2008; Scarborough, 2005; De Jong & Van Der Leij, 1999; Hansen & Bowey, 1994;Mann & Liberman, 1984; Ramus, et al., 2003).

Phonological awareness (PA) refers to the ability to recognize and manipulate the rhymes and phonemes in words (Maddox, 2008). A number of studies demonstrate that phonological awareness is a reliable predictor of the reading capacity. Scarborough (1988) conducted a meta-analysis of phonological and other cognitive and language measures from 61 research samples to see predictors of future reading scores for kindergarten children. . Although the highest correlations with reading were usually obtained for predictor measures that require knowledge of print itself (letter identification and familiarity with print), phonological awareness strongly predicts reading outcomes as well. Joseph et al (2003) explored the relationships among cognitive processing, phonological processing and basic reading skill performance in a sample of 62 primary grade children with reading problems. The study showed that among the measures administered, the strongest relationship was found between phonological awareness and basic reading performance.

Phonological Memory (PM) measures short-term retention of verbally presented information (Wagner, Torgeson & Rashotte, 1999) and is considered a good predictor for reading. As a short term workspace, PM provides for the retention of a phonological representation while its meaning is retrieved from the lexicon. Moreover, phonological memory also supports learning of new words by facilitating their transfer to semantic memory (Gathercole et al., 1999). In a survey of longitudinal studies, Lonigan, Schatschneider and Westberg (2008) found the correlation between phonological memory, measured in preschool children, and later reading comprehension to be .51.

Rapid naming (RN) measures retrieval of phonological information from long-term memory (Wagner, Torgeson & Rashotte, 1999). RN tasks are widely used in predicting reading outcomes in children who are in the process of mastering reading skills or to diagnose difficulties in reading development from childhood up to adulthood. Existing research supports this relationship. Swanson et al (2003) in their meta-analysis of 35 studies which yielded 49 samples showed that RN tasks have predictive value for reading performance. Powell et al (2007) investigated whether RN tasks are associated with reading deficits in a large sample of school-children. The sample consisted of some children with a double deficit profile (deficits in RN and PA), some with a single PA deficit, and some with a single RN deficit. Both single RN and single PA deficits were associated with modest deficits in reading as assessed by a single word reading task. However, the double deficit profile was associated with the most severe reading problems.

Vocabulary has been also shown to correlate with reading (Aarnoutse & Leeuwe, 1998). The size of *vocabulary* is an important factor for reading fluency because expansion of easily recognizable written patterns is critical for the development of automatic reading in children learning to read (Smith Gabig, 2010).

Aarnoutse & Leeuwe (1998) conducted a longitudinal study on several factors influencing fluent reading. One of the main questions of their study was the relationship between vocabulary size and reading comprehension. A sample of 363 primary school children was followed for five years. Administration of vocabulary and reading comprehension tests demonstrated that vocabulary is a good predictor for reading comprehension.

To see participants' decoding abilities, we tested their performance on *nonwords*. Some researchers and clinicians think that nonword stimuli offer a purer measure of phonological decoding skills that are less affected by an individual's vocabulary knowledge *(*Wagner, Torgeson & Rashotte, 1999*).*

1.4. Current Study

The research on reading abilities and the potential of each isolated hemisphere in children who have undergone cerebral hemispherectomy is limited to one case study (Patterson, 1989). The working hypotheses for this study were based on the previous literature discussing hemispheric involvement in reading as well as on our own observation that not only the side of resection but also clinical variables leading to it are to be accounted for in predicting language outcomes following hemispherectomy (Curtiss, deBode & Mathern, 2001; Smets, 2010). Our working hypotheses were:

- Hypothesis 1: Children with the right-sided resection will always outperform participants with the left-sided resection.

- Hypothesis 2: Similar to neurologically-intact participants Vocabulary, Phonological Awareness, Memory and Rapid Naming will predict reading capacity in individuals post-Hemispherectomy.

2. Methods

The data were collected at the University of South Carolina, (USA, NIH R 21, PI Stella de Bode). This study was approved by the Offices for Human Subjects Protection at the University of South Carolina and University of California Los Angeles.

2.1. Participants

All participants who entered rehabilitation at the University of South Carolina between 2005 and 2007 and were monolingual speakers of English participated in the study. Of the total of twenty three participants, nine had undergone right hemispherectomy (i.e. with a remaining left hemisphere) of which two were diagnosed with an prenatal infarct (PI), six with Rasmussen's encephalitis (RE) and one with Sturge-Weber syndrome (S-W). Fourteen participants had undergone left hemispherectomy (i.e. with a remaining right hemisphere) of which eight had been diagnosed with PI, four with RE, one with S-W and one with cortical dysplasia (CD).

- Participants' age at the time of testing ranged from 6 to 25 years with a mean of 14 (± SD 5).
- Participants' age at surgery ranged from 1 to 15 years with a mean of 7 (± SD 4).
- Age at seizure onset ranged from 0;1 to 12 years with a mean of 4 (S.D. 3;5).

Information about seizure control was available in nineteen participants. For fifteen of these nineteen patients surgery had brought complete relief from seizures, ten of which were no longer taking any medication. Seizures were persistent to some degree for four participants despite still taking medication. An overview of patient information is given in Table 1:

Table: 1. Overview of patient information.

Subject no.	Side of resection	Etiology	Age at testing	Age at seizure onset	Age at surgery	Seizures present	Medication
1	Left	PI	13	5	8	no	no
2	Left	PI	14	4	10	no	no
3	Left	PI	21	birth	10	no	no
4	Left	PI	14	4	6	no	no
5	Left	PI	6	birth	1	no	no
6	Left	RE	14	2	4	yes	yes
7	Left	PI	10	3	4	yes	yes
8	Left	RE	17	11	12	no	no
9	Left	S-W	10	birth	1	no	no
10	Left	PI	20	7	11	no	no
11	Left	RE	9	1	2	yes	yes
12	Left	PI	11	5	10	no	yes
13*	Left	RE	13	2	3	-	-
14*	Left	CD	12	birth	3	-	-
15*	Right	PI	12	7	7	no	yes
16	Right	RE	22	10	12	no	yes
17	Right	PI	18	2	15	no	yes
18	Right	RE	6	4	4	no	yes
19	Right	RE	25	2	4	no	no
20	Right	S-W	10	3	7	no	no
21	Right	RE	16	12	15	yes	yes
22*	Right	RE	11	1	8	-	-
23*	Right	RE	16	2	3	-	-

* Participants who have not completed all the test batteries.

Eighteen participants were tested on all tests and subtests.

2.2. Tests

Three standardized tests were administered:

- The Comprehensive Test of Phonological Processing, CTOPP (Wagner et al., 1999);
- Peabody Picture Vocabulary Test third edition, PPVT III (Dunn & Dunn, 1997);
- The reading subtest from the Kaufman Test of Educational Achievement K-TEA II brief, (Kaufman & Kaufman, 2005).

For detailed information see Appendix 1.

3. Results

Twenty three children participated in the study. Eighteen of them completed all test batteries: CTOPP (PA, PM, RN), K-TEA II Brief (Reading), PPVT (Vocabulary) with the remaining five completing some of the tasks but not all. Table 2 below shows performance of individual participants on these tests.

Table: 2. Individual performance on all test batteries.

Subject no.	**Side of resection**	**Etiology**	**Performance on all test batteries**				
			PA STD 100; SD 10	**PM** STD 100; SD 10	**RN** STD 100; SD 10	**Reading** STD 100; SD 15	**Vocabulary** STD 100; SD 15
1	Left	PI	88	76	88	94	94
2	Left	PI	79	70	109	73	70
3	Left	PI	82	94	70	85	94
4	Left	PI	112	100	94	96	99
5	Left	PI	79	73	82	59	72
6	Left	RE	79	82	64	77	93
7	Left	PI	91	88	112	84	76
8	Left	RE	58	61	49	42	74
9	Left	S-W	79	94	94	93	101
10	Left	PI	80	80	80	100	103
11	Left	RE	61	67	58	46	74
12	Left	PI	85	109	79	103	80
13	Left	RE	58	67	--	--	--
14	Left	CD	82	82	88	--	--
15	Right	PI	100	100	--	90	80
16	Right	RE	82	79	73	100	100
17	Right	PI	76	85	79	81	90
18	Right	RE	100	100	76	106	90
19	Right	RE	112	103	91	100	92
20	Right	S-W	79	76	64	71	81
21	Right	RE	76	76	70	98	102
22	Right	RE	76	64	--	--	--
23	Right	RE	82	79	--	--	--

For analyzing the results we divided the participants of the study by the side of removal and etiology. We classified etiologies into developmental pathology (PI, S-W and CD) and acquired pathology (RE) as discussed by Curtiss, de Bode and Mathern (2001). The division resulted in four groups:

- *LH*, the left hemispherectomy group (i.e. participants with the isolated right hemisphere) was further classified according to underlying pathology as developmental, **LH Dev**, and acquired, **LH Acq.**

- *RH***,** the right hemispherectomy group (i.e. participants with the isolated left hemisphere) was further classified according to underlying pathology as developmental, **RH Dev**, and acquired, **RH Acq**.

3.1. Reading, K-TEA II Brief

Nineteen participants completed K-TEA. Table 3 below shows the number and etiologies of the subjects who performed average and below average on the reading test:

Table: 3. K-TEA: The Number of average and below average readers by side of resection and etiology.

K-TEA II Brief		**Average readers**, STD 100; SD 15	**Below average** STD < 85
Left Hemispherectomy	Developmental	6	3
	Acquired	0	3
Right Hemispherectomy	Developmental	1	2
	Acquired	4	0
Total		**11**	**8**

- The mean score for 11 participants who scored within an average range were 97 ± SD 6. The mean scores for 8 readers who scored below average were 67 ± SD 16.
- The RH Acquired and Developmental group mean reading scores were 101 ± SD 3 and 81 ± SD 10 respectively. All subjects with RH acquired damage were average readers. In the developmental group 2/3 participants were poor readers with 1 participant performing average.

- The LH Acquired and Developmental group mean reading scores were 55 ± SD 19 & 87 ± SD 14 respectively. All participants with the acquired damage, n=3, performed significantly below average. Only 3/9 participants with early developmental pathology did not score within the average range.

3.2. Phonological Processing, CTOPP

Phonological Processing was assessed using three composite subtests of CTOPP: Phonological Awareness (PA), Phonological Memory (PM), and Rapid Naming (RN).

3.2.1. Phonological Awareness (PA)

Twenty three participants completed this part of CTOPP. PA results are the combination of Elision and Blending Words subtest scores. The results are shown in Table 4.

Table: 4. Number of participants with average and below average PA skills by side of resection and etiology.

Phonological Awareness, PA		**Average** STD 100 ± SD 10	**Below average** STD < 90
Left Hemispherectomy	Developmental	2	8
	Acquired	0	4
Right Hemispherectomy	Developmental	1	2
	Acquired	2	4
Total		**5**	**18**

- The mean PA scores for 5 participants who scored within an average range were 103 ± SD 9. The mean scores for 18 participants who scored below average were 77 ± SD 9.

- The RH Acquired and Developmental group mean PA scores were 88 ± SD 15 and 85 ± SD 13 respectively. Only 2 out of 6 acquired pathology participants were average on PA. In the developmental group 2 out of 3 were had poor results on PA.
- The LH Acquired and Developmental group mean PA scores were 64 ± SD 10 and 86 ± SD 10 respectively. In the acquired damage group 2 out of 6 children managed to reach average. In the developmental group the majority, 8 out of 10 failed to reach average.

3.2.2. Phonological Memory (PM)

Twenty three participants completed this part of CTOPP. PM results are the combination of Memory for Digits and Blending Nonwords subtest scores. The results are shown in Table 5.

Table 5. Number of participants with average and below average PM skills by side of resection and etiology.

Phonological Memory, PM		**Average** STD 100; SD 10	**Below average** STD < 90
Left Hemispherectomy	Developmental	4	6
	Acquired	0	4
Right Hemispherectomy	Developmental	1	2
	Acquired	2	4
Total		**7**	**16**

- The mean PM scores for 7 participants who scored within an average range were 100 ± SD 5. The mean scores for 16 participants who scored below average were 75 ± SD 8.
- The RH Acquired and Developmental group mean PM scores were 84 ± SD15 and 87 ± SD 12 respectively. In the acquired pathology group 2 out of 6 children

showed average results. In the developmental damage group 2 out of 6 reached average level.

- The LH Acquired and Developmental group mean PM scores were 69 ± SD 9 and 87 ± SD 13 respectively. None of the 4 acquired damage participants managed to achieve average results on PM. IN the developmental group 4 out of 10 scored average.

3.2.3. Rapid Naming (RN)

Nineteen participants completed this part of CTOPP. RN results are the combination of Rapid Letter and Rapid Digit Naming (Rapid Objects and Rapid Color Naming for 2 participants younger than 6 years) subtest scores. The results are shown in Table 6.

Table: 6. Number of participants with average and below average RN skills by side of resection and etiology.

Rapid Naming, RN		**Average** STD 100 ± SD 10	**Below average** STD < 90
Left Hemispherectomy	Developmental	4	6
	Acquired	0	3
Right Hemispherectomy	Developmental	0	2
	Acquired	1	3
Total		**5**	**14**

- The mean score for 5 participants who scored within an average range were 100± SD 10. The mean scores for 14 participants who scored below average were 73 ± SD 11.
- The RH Acquired and Developmental group mean reading scores were 78 ± SD 9 & 72 ± SD 11 respectively. One out of 4 acquired damage participants was average on RN while both children in the developmental group failed to reach average.

- The LH Acquired and Developmental group mean reading scores were 57 ± 8 & 90 ± SD 13 respectively. None of the 3 acquired pathology participants reached average. In the developmental group 6 out of 10 scored below average.

3.3. PPVT: Vocabulary

Nineteen participants completed vocabulary testing. The results are shown in Table 7.

Table: 7. Number of participants with average and below average vocabulary size by side of resection and etiology

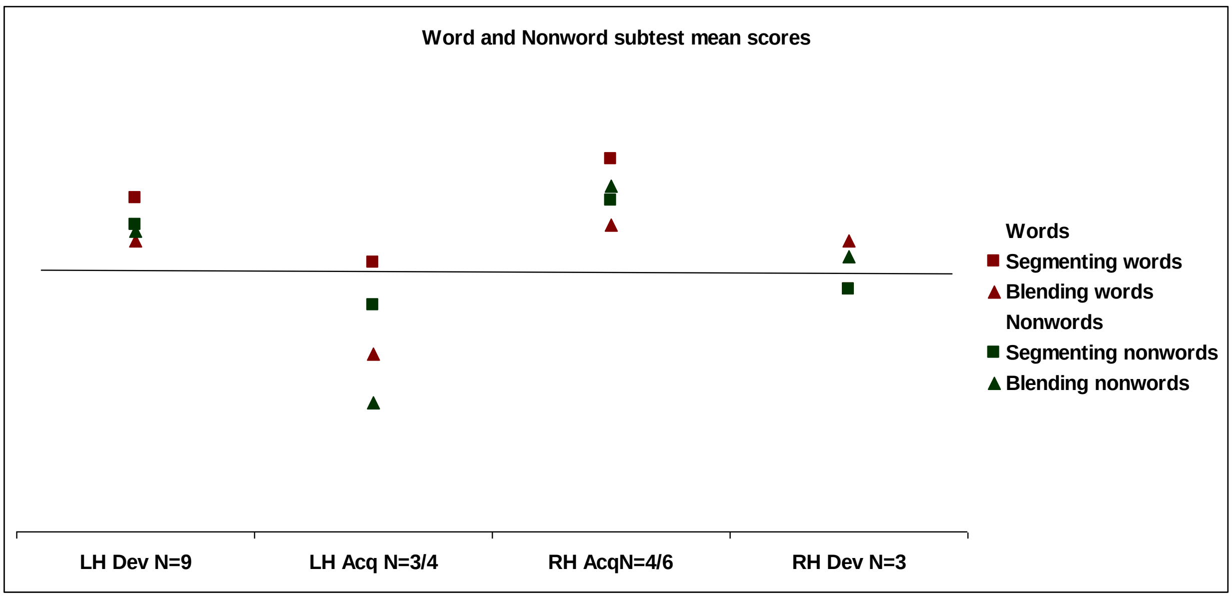
Vocabulary		**Average** STD 100 ± SD 15	**Below average** STD < 85
Left Hemispherectomy	Developmental	5	4
	Acquired	1	2
Right Hemispherectomy	Developmental	1	2
	Acquired	4	0
Total		**11**	**8**

- The mean scores for 11 participants who scored within an average range were 96 ± SD 5. The mean scores for 8 participants who scored below average were 76 ± SD 4.
- The RH Acquired and Developmental group mean reading scores were 96 ± SD 6 and 84 ± SD 5.5 respectively. All 4 children in the acquired damage group had average scores. In the developmental group 1 out of 3 reached average.
- The LH Acquired and Developmental group mean reading scores were 80 ± SD 11 and 88 ± SD 13 respectively. In the acquired pathology group 1 child out of 3 showed average results and in the developmental group 5 out of 9 did so.

3.4. CTOPP: Performance on words and nonwords

We compared participants' performance on their ability to manipulate both words and nonwords (CTOPP subtests: Segmenting Words, Blending Words, Segmenting Nonwords, Blending Nonwords). Twenty two individuals completed all word and nonword tests. The results are shown in Figure 2.

Figure 2. Performance on word and nonword subtests of CTOPP by side of resection and etiology (Mean 10 ± SD 2).



3.5. Correlations between Reading scores and PA, PM, RN and Vocabulary

We examined the participants' vocabulary knowledge (PPVT) and phonological processing (PA, PM and RN) correlations with reading performance.

Table: 8. Correlations: Reading and its components (Spearman's two-tailed)

Reading Scores			
Tests	**Entire Group**	**Right Hemispherectomy**	**Left Hemispherectomy**
PA	***r*=.650, *p*=.003**	*r*=.569, *p*=.183	***r*=.747, *p*=.005**
PM	***r*=.718, *p*=.001**	*r*=.495, *p*=.258	***r*=.788, *p*=.002**
Vocabulary	***r*=.613, *p*=.005**	*r*=.47, *p*=.284	***r*=.747, *p*=.005**
Rapid Naming	*r*=.285, *p*=.252	*r*=.288, *p*=.513	*r*=.428, *p*=.189

4. Discussion

The aim of the current study was to investigate to what extent each isolated hemisphere can support reading and its components phonological awareness, phonological memory, rapid naming and vocabulary.

4.1. Reading Capacity

About 60% (n =11, left hemispherectomy n=6, right hemispherectomy n=5) of all the participants in our group had average reading abilities (mean score 97 ± SD 6). Participants who did not reach average levels (n=8, left hemispherectomy n=6) scored on average 2 SD below mean (67 ± SD 16).

Similar to previous studies reporting left hemisphere dominance for reading we found that 5/7 (71%) of all participants with an isolated left hemisphere were average readers. In contrast, only 6/12 (50%) of the participants with the isolated right hemisphere reached average levels. Although at first glance this confirms Hypothesis 1, a more careful look into our results indicated that in a subgroup of developmental pathology the left hemisphere superiority for reading was not found. Therefore, we conducted further investigation by dividing participants based on the *side of removal x etiology* interaction to indicate the distinction between children who at the moment of insult were prelingual and those children who have already started developing language normally (Curtiss, de Bode & Mathern, 2001).

Acquired pathology. As expected, the removal of the left hemisphere following a period of normal development has devastating consequences on reading skills (Table 3). All three participants (100%) scored on average 3 SD below norm (55 ± SD 19). These scores were by far the lowest in our sample. In contrast, those participants who lost their right hemisphere later in life (n=4, 100%) are *all* average readers (101 ± SD 3). These results suggest that a period of normal development in this group allowed for a predictable pattern of language skills' lateralization with the right hemisphere when finding itself in isolation struggling to assume functions it has never supported before. On the other hand, the isolated left hemisphere supports reading successfully with its right counterpart removed.

Developmental pathology. In contrast to participants with late insult/surgery, the group with developmental early-life pathologies demonstrates full potential of each hemisphere since this group has never developed any language skills in their deceased hemisphere due to both the profound lesion extent and prenatal timing of insult. Demonstrating the right hemisphere's abilities 6 participants (66%) became average readers (95 ± SD 6) with the remaining 3 participants reading within 1 SD below norm (72 ± SD 13).

We had only 3 participants with the isolated left hemisphere in this group. Surprisingly, 2 individuals (67%) did not reach average levels falling within 1 SD from norm (76 ± 7) with only one child successfully reaching norms for her age.

Although on a group level our results support Hypothesis 1, examining the developmental pathology groups we conclude that the isolated right hemisphere has the potential to fully develop and support reading yet this potential is not always realized, withone of every 3 children in the LH Dev group failing to reach normal reading levels. At the same time the isolated left hemisphere, although expected to fully support reading, showed inconsistent results with only 1 out of 3 children in the LH Acq group reaching normal reading. This, however, may be an artifact of our small sample in this group and requires further investigation.

4.2. Phonological processing – PA, PM and RN

PA. Only 5 participants out of 23 (22%) reached normed average (103 ± SD 9) (left hemispherectomy n=2). Eighteen participants (left hemispherectomy n=12) who did not reach average levels scored on average 2 SD below mean (77 ± SD 9). Although the isolated left hemisphere supported phonological awareness somewhat better than the isolated right hemisphere – 33% (3/9) versus 14% (2/14) – the below average scores in the majority of the children with an isolated left hemisphere is surprising in view of the established left hemisphere dominance for all phonological processes.

Acquired Pathology. Similar to the results of our reading test all 4 participants (100%) with late left-sided insult/surgery (isolated right hemisphere) scored the lowest (64 ± SD 10) on PA. However, in contrast to reading scores where 100% of the participants with the isolated left hemisphere due to late insult scored average, the PA scores were more heterogeneous with only 2 out of 6 children scoring average (33%).

Developmental Pathology. Since 67% of all participants with the isolated right hemisphere due to early damage scored average on reading tests we expected similar numbers would be found on their PA scores. To our surprise only 20% (2/10) scored average with the remaining children scoring mean 82 ± SD 3. The results for the isolated left hemisphere were identical to those in reading, showing a surprising profile with 2 out of 3 children not reaching average levels.

The results of PA testing suggest that reading and PA scores are similar in only 2 etiology x side groups. Namely, on both tests the isolated right hemisphere when faced with a necessity to support reading following normal development predictably performs poorly (3-4 SD below norms).

The group with the isolated left hemisphere due to early insult also has similar results in both reading and PA tests with only 1 individual scoring normal and 2 participants scoring below norms.

The remaining two *etiology x side* groups, RH Acq and LH Dev, have significantly fewer participants scoring average on PA when compared to their reading scores. Even though all individuals with the isolated left hemisphere following late insult scored average on reading, only 2 out of 6 participants scored average on PA. It suggests that in some subjects with the isolated left hemisphere reading is average without full mastery of phonological skills. However, it is worth noting that participants scoring average on PA are those who did not read at the time of insult (2 years). The rest of our subjects had grade-appropriate reading skills when they contracted acquired pathology. It is not clear why their PA scores are below average since they should have been fully established in the left hemisphere prior to insult.

The group with the isolated right hemisphere due to early insult shows the same trend in having 20% of children scoring average on PA compared to 67% on reading.

PM. Similar to PA, overallresults on PM were poor. Only 7 (30%) (left hemispherectomy n=4) out of 23 reached average levels (100 ± SD 5). The 16 participants who failed to reach average level scored on average 2 SD below mean. The isolated left hemisphere supported phonological memory slightly better than the isolated right hemisphere, 33% (3/9) versus 28% (4/14) and in this way is similar to the performance on phonological awareness. However, the failure of the isolated left hemisphere to consistently support normal phonological memory is again an unexpected outcome from the perspective of established left hemisphere dominance for all phonological processes.

Acquired Pathology. Similar to the results of the reading and PA tests all 4 participants (100%) with the isolated right hemisphere performed poorer than any other group (69 ± SD 9) on PM. On the other hand, in contrast to reading scores where 100% of the participants with the isolated left hemisphere due to late insult scored average, in parallel to PA results only 2 out of 6 children in this subgroup reached average results on PM (33%).

Developmental Pathology. As with PA performance, we expected that participants with the isolated right hemisphere due to early damage would score well on PM since 67% of all participants in this subgroup scored average on the reading test. Surprisingly, only 40% (4/10) obtained average scores. It should be note though that we had more average performers on PM than on PA (40% vs 20%). The results for the isolated left hemisphere were identical to those on PA and reading, 1 average performance out of 3. Similar to the tests discussed above, the left hemisphere alone showed surprising results with 2 out of 3 children not reaching average levels.

Like in the case of PA, only 2 etiology x side groups showed similar results on PM to reading. Specifically, on all three tests the isolated right hemisphere fails to perform well (3-4 SD below norms) when required to support reading following normal development. This suggests that when insult/surgery occurs later in life the right hemisphere fails to acquire skills to subserve reading.

The other group with similar results to reading and PA, with only 1 child scoring normal and 2 below norms was the RH Dev group.

Again similar to PA, the remaining two *etiology x side* groups, RH Acq and LH Dev, have considerably fewer participants reaching average levels when compared to their reading scores. For participants with the isolated left hemisphere following late insult – all of whom scored average on reading – performance was less impressive on PM, only 2 out of 6 participants scoring average. This pattern of results suggests that some subjects with the isolated left hemisphere are average readers without full mastery of phonological skills. This below average results on phonological tests is surprising since the left hemisphere should have developed phonological skills before the insult had occurred.

Similar to PA, the group with the isolated right hemisphere due to early insult shows the same trend having 40% of children scoring average on PM in contrast to 67% on reading.

RN. Only 5 participants out of 23 (26%) reached normed average (100 ± SD 10) (left hemispherectomy n=4). The 14 participants (left hemispherectomy n=9) who scored below average scored on average 3 SD (73 ± SD 11) below the mean. Contrary to other phonological processing measures (PA, PM) and reading, the isolated left hemisphere participants scored worse than the participants with the isolated right hemisphere, 17% (1/6) versus 31% (4/13). This is an unexpected outcome because first, RN is widely considered a good predictor for reading capacity which is not the case in our sample (the left hemisphere ourperfomed its right counterpart in reading) and second, it contradicts the established left hemisphere dominance for all phonological processes.

Acquired Pathology. Similar to the results of our reading, PA and PM tests all 3 participants (100%) with late left-sided insult/surgery and isolated right hemisphere scored below average (57 ± SD 8) on RN. However, in contrast to reading scores where 100% of the participants with the isolated left hemisphere due to late insult scored average, on RN only 25% (1/4) of children scored average.

Developmental Pathology. Again, since 67% of all participants with the isolated right hemisphere due to early insult/surgery scored average on reading tests we expected similar numbers would be found on their RN scores. In contrast, 40% (4/10) children in this subgroup reached average. The results for the isolated left hemisphere were similarly poor to reading and other phonological tests but in this case we had only 2 participants, both failing to reach the normed average.

The results on RN show that reading and RN scores as well as those of PA and PM are similar in only 2 etiology x side groups, i.e. all these tests are poorly performed in these two groups (LH Acq and RH Dev). More specifically, the isolated right hemisphere when faced with a necessity to support reading following normal development predictably performs poorly (3-4 SD below norms); however, why the isolated hemisphere of early insult/surgery cannot cope with either reading or phonological processing tests is not clear.

Similarly to the rest of the phonological processing tests, on RN the remaining two *etiology x side* groups (RH Acq and LH Dev) have significantly fewer participants scoring average when compared to their reading scores. Even though all individuals with the isolated left hemisphere following late insult scored average on reading, only 1 out of 4 participants scored average on RN. As already shown by PA and PM results, in some subjects with the isolated left hemisphere reading is average without fully developed phonological skills. Next, it is unclear why the isolated right hemisphere outperformed its left counterpart since all phonological processing tasks are traditionally considered to be subserved by the left hemisphere.

4.3. Receptive vocabulary (PPVT)

Quite similarly to reading, about 60% (n=11, left hemispherectomy n=6) of all the participants in our group had average vocabulary (mean score 96 ± SD 5). Participants who did not reach average levels (n=8, left hemispherectomy n=6) scored on average 2 SD below mean (67 ± SD 4). The isolated left hemisphere showed advantage over the isolated right hemisphere on the vocabulary test, 71% (5/7) versus 50% (6/6) which is in line with the outcomes of the reading test.

Acquired Pathology. Similar to the results of our reading test participants with late left-sided insult/surgery and isolated right hemisphere scored below average on vocabulary (80 ± SD 10). However, in contrast to reading scores where 100% of the participants with the isolated right hemisphere due to late insult scored below average, on the vocabulary test only1 child out of 3 reached average (33%). The isolated left hemisphere showed exactly the same results to reading withall 4 children (100%) scoring average.

Developmental Pathology. The isolated right hemisphere showed somewhat similar results to those on reading. While 67% of the participants in this group had average scores on reading, 55% (5/9) reached average on vocabulary. The isolated right hemisphere had identical results to reading, 1 out of 3 children (33%) scored average.

The outcomes of vocabulary testing suggest that the trend of performance is quite similar to reading results in all four groups. On both tests the isolated left hemisphere copes with reading better than its right counterpart. The isolated right hemisphere, however, shows full potential to support both vocabulary and reading when the insult/surgery takes place early in development.

In line with previous findings (Liegouis 2008a), our results of vocabulary testing suggest that vocabulary may be the relatively spared language function following hemispherectomy.

4.4. Correlations between Reading scores and PA, PM, RN and Vocabulary

PA. Scores were significantly correlated with reading results for all participants taken together (*r*=.650, *p*=.003, n=18) and the left hemispherectomy group (*r*=.747, *p*=.005; n=12); however, for the right hemispherectomy group separately, the correlation was not statistically significant (*r*=.569, *p*=.183, n=7).

PM. Likewise, reading and PM scores were significantly correlated in all the children (*r*=.718, *p*=.001) and the left hemispherectomy group (*r*=.788, *p*=.002). For the participants with the isolated left hemisphere, however, the scores were not correlated (*r*=.495, *p*=.258,) These outcomes of the correlation analysis suggest that PA and PM are not reliable predictors for reading when the isolated left hemisphere has to support reading. At same time, this finding cannot lead to a definitive conclusion due to a small sample size (N=7) which is problematic for the statistical power of an analysis.

RN. Scores on RN were not significantly correlated with reading score, neither in each side of resection group separately (LH *r*=.428, *p*=.189, n=12; RH *r*=.288, *p*=.513, n=7), nor in all participants take together (*r*=.285, *p*=.252, n=19). Contrary to previous studies showing that RN is a good predictor of reading capacity, in our population, this measure of phonological processing did not prove to predict reading capacity.

Vocabulary. Correlation with reading turned out to be significant for all participants together (r=.613, p=.005, n=19) and only the left hemispherectomy group (r=.747, p=.005. n=9) while the correlation was non-significant for the right hemispherectomy group (r=.470, p=.284, n=7). Again, taking into consideration the small sample size, the finding that vocabulary size is not a reliable predictor for right hemispherectomy participants cannot be conclusive.

These results suggest there is no straightforward correlation between reading components and reading capacity in this population. As a group, only in participants with the remaining *right* hemisphere phonological awareness, phonological memory and vocabulary size predicted reading capacity. No significant correlations were found for individuals with the remaining left hemisphere. Furthermore, rapid naming did not correlate with reading in any group. This pattern of results questions the role of traditional reading components in hemispherectomy populations.

4.5. Performance on words and nonwords

In contrast to poor results on PA, PM and RN, performance on word and nonword tests was relatively good. Seventy two % of the participants (n=22, left hemispherectomy n=13) scored average on word tests (11 ± SD 3) and 74% (n=21, left hemispherectomy n=13) had similarly good results on nonword tests.

Words. Surprisingly, the results on word decoding tests did not show hemispheric differences while the difference was obvious on all other tests in our study; both hemispheres had almost equal proportion of average and below average performers: 67% (n=6/9) of participants with the remaining left hemisphere reached average level (11 ± SD 3) and 69% (n=9/13) of isolated right hemisphere participants had similarly good results (10 ± SD 3). Children from the left hemispherectomy group who did not reach average level scored on average 3 SD below the mean and right hemispherectomy children scored 2 SD below the mean.

Acquired pathology. In accordance with the other tests in our study, the left hemisphere after late insult/surgery showed better scores than its right counterpart on word decoding tests, 66% (n=4/6) of children with isolated hemisphere reached average (11 ± SD 2) versus 25% (n=1/4) of right hemisphere participants did so (10).

These results suggest that looking at the capacities of each hemisphere without taking into account the etiology does not give a full picture of those capacities. While there was no hemispheric difference in performance on left hemispherectomy and right hemispherectomy when all etiologies were combined, we see an obvious left hemisphere advantage looking at acquired etiologies separately.

Developmental pathology. Contrary to PA and PM results, the isolated left hemisphere had fewer average results than the isolated right hemisphere, 66% (n=2/3) (9 ± SD 2) versus 77% (n=7/9) (10 ± SD 2). Although inconsistent with PA and PM results, this trend of performance, i.e. the right hemisphere in case of early/insult successfully acquiring skills for phonological decoding, is similar to our reading tests outcomes.

These results show once more that only side of removal is not enough to assess the capacities of each isolated hemisphere. While there was no meaningful difference in performance between left and right hemispherectomy groups for all etiologies combined, when we looked at side of removal x etiology subgroups the different capacities of each hemisphere was obvious. Namely, the right hemisphere has difficulty to support phonological decoding skills after late insult/surgery while the left hemisphere has difficulty when damage occurs early in the development.

Nonwords. Similarly to performance on PA and PM, on nonword decoding tests participants with the isolated left hemisphere outperformed children with isolated right hemisphere, 85% (n=7/8) (10 ± SD 3) versus 69% (n=9/13) (10 ± SD 2) . At the same time, in sharp contrast to PA and PM poor results, a majority of the children scored average on nonwords, as the percentages show. Children who had below average results scored on average 2-3 SD below the mean.

Acquired pathology. Like all other tests in our study, the left hemisphere after late insult/surgery showed better scores than the isolated right on nonword decoding tests, 83% (n=5/6) of children with isolated hemisphere reached average (11 ± SD 3) versus 25% (n=1/4) of right hemisphere participants (9.5).

These results once more show that in our population, the isolated right hemisphere with late insult/surgery following a period of normal development cannot fully support phonological decoding skills.

Developmental pathology. In contrast to the poor results on PA and PM by the isolated right hemisphere participants, 89% (n=8/9) of the participants from the same subgroup showed average results for nonwords (10 ± SD 2). In the isolated left hemisphere subgroup we had only two participants on nonword tests, one scoring average (9) and the other below average (7).

These results on nonword decoding tests by the isolated right hemisphere are surprising taking into account the poor performance by the same side of removal x etiology group on PA, PM and RN. It is unclear why the same participants on the one hand, failed to reach average scores on these phonological processing tests and on the other hand a great majority of them scored average on nonword tasks.

These results contradict previous findings that impaired populations perform poorly on nonwords and worse than word decoding tasks. This discrepancy can be explained by the fact that on nonword tests our participants had to blend or segment nonwords, while in previous studies that report poor results on nonwords, the tasks required participants to read nonwords.

5. Conclusion

To conclude, the isolated left hemisphere generally has better capacities to support reading and its components (phonological processing and vocabulary) than the isolated right hemisphere. However, our results showed that the right hemisphere has a potential to subserve reading, phonological processing and vocabulary to acquire the necessary skills if the damage occurs early in development. However, if the right hemisphere is required to adopt skills that are not naturally associated with it later in the development, consequences are devastating.

Contrary to neurologically-intact cases where vocabulary, phonological awareness, phonological memory and rapid naming predict reading fluency, in our participants this correlation was not always straightforward. Measures of phonological processing and rapid naming presented significant difficulty for almost all participants including those with average reading skills. We conclude that traditionally accepted predictors of reading capacity do not hold for post-hemispherectomy individuals in our study.

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Appendix 1:

Figure: 3. Mean scores on RD & RL and RO & RC.

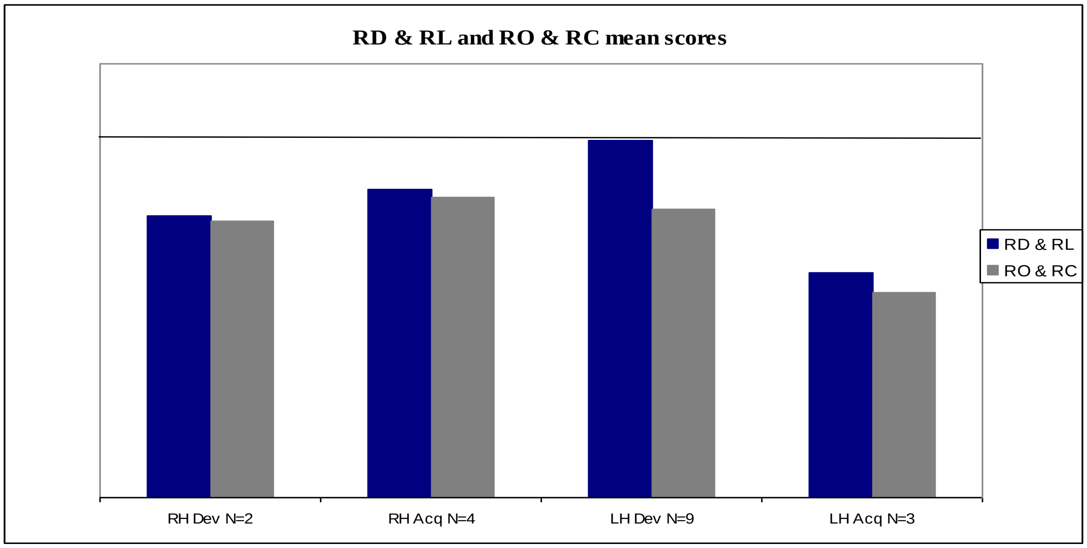

Table: 9. COPP composite test group means.

Test	LH Dev (N=9)	RH Dev (N=3)	LH Acq (N=4)	RH Acq (N=6)
Phonological awareness	86	85	64	88
Phonological memory	87	81	69	83
Rapid naming	90	72	57	78

Table: 10. RH group (N=7) z-scores for K-TEA Reading subtest, Word Recognition and Comprehension.

# & Etiology	Word Recognition	Comprehension
16 Acq	DND	
18 Acq	0.4	–
21 Acq	0.2	0.2
19 Acq	0.5	-0.45
17 DEV	-1.9	-0.65
20 DEV	-2.2	-1.8
15 DEV	0.13	-1.4

Table: 11. LH group (N=12) z-scores for K-TEA Reading subtest, Word Recognition and Comprehension

# & Etiology	Word Recognition	Comprehension
1 DEV	-1.15	0.2
3 DEV	-2.03	-1.4
12 DEV	0.4	0.2
9 DEV	-0.4	-0.4
10 DEV	0.5	-0.2
4 DEV	0.02	2.6
2 DEV	-1.7	-1.6
5 DEV	-1.27	–
7 DEV	-0.75	-1.16
8 Acq	-3	-4
11 Acq	-2.6	n/a
6 Acq	-1.15	-1.6

Appendix 2:

Behavioural measured used

CTOPP

CTOPP (Wagner et al., 1999) was used to assess participants' phonological skills. CTOPP has two versions: one normed for individuals from five to six years old and the second for seven through twenty four years old. The subtests of five and six year old version of the CTOPP include Elision (EL), Rapid Color Naming (RC), Blending Words (BW), Sound Matching (SM), Rapid Object Naming (RO), Memory for Digits (MD) Non-word Repetition (NR) and Blending Nonwords (BN). The subtests of seven through twenty four year old version includes the subtest from the younger version with the addition of Rapid Letter naming (RL), Rapid Digit Naming (RD), Phoneme Reversal (PR), Segmenting Words (SW) and Segmenting Nonwords (SN) while SM is not included in this version. EL requires the individual to repeat a verbally presented stimulus word while omitting a sound. For example, *Say ball. Now say ball without saying /b/*. RC, RO, RD and RL are timed tasks on which the individual is expected to rapidly identify several rows of colors, objects, letters or digits from pages in a stimulus booklet in the respective subtests. A score is derived based on the total time it takes an individual to complete a page. On SM the examinee is asked to identify the correct picture from an array of three that shares the same onset or ending sound as a stimulus picture. For example, *Which word starts with the same sound as bear? Pig, bat, or rabbit?* MD is a measure of an individual's ability to repeat increasingly longer lists of numbers in the exact order as presented on an audiotape. NR requires that an examinee to repeat nonwords, varying in length from 3 to 15 sounds. On BW and BN subtests the examinee listens to a series of audiocassette-recorded separate sounds and then is asked to put the separate sounds together to make either word or nonword. On PR the individual listens to a series of audiocassette-recorded nonwords, is instructed to repeat the nonword, then to say the same nonword backwards to form a real word. SW requires the examinee to repeat a word, then to say it one sound at a time while on SN the individual is required to perform the same task but using nonwords. Average for standard scores for each subtest is 10 with S.D. of 2. Some of the subtests are combined to form composite scores. The subtests are combined to represent three conceptualizations of phonological processing:

Phonological Awareness (PA), Phonological Memory (PM) and Rapid Naming (RN) (average 100, S.D. 10). PA is comprised of EL and BWin older age version, and SM in the younger age version. PM includes MD and NR. The RN is made up of Rapid Object Naming and Rapid Color Naming for the five and six year old version and of RL and RD for the older age version. In addition, there are two alternative composites of the older age version: Alternative Phonological Awareness (APA) comprised of BN and SN and Alternative Rapid Naming (ARN) made up of RC and RO.

PPVT

Lexical comprehension was measured using PPVT III (Dunn & Dunn, 1997). It is composed of seventeen sets of lexical items that have to be matched to the corresponding pictures. These sets are of increasing difficulty ranging from a child's typical first words to words of low frequency even among adult. PPVT III is normed for adults as well as children: the normative range is from 2 years 6 months through to 90 years 11 months. Examples of one set of each word are given below:

x. increasing difficulty: *bus, drum, empty, astronaut, delivering, oval, horrified, flamingo, bouquet, inflated, hazardous, pedestrian, syringe, poultry, quintet, coniferous, terpsichorean.*

K-TEA II brief

We report results from only the reading section of K-TEA II brief form (Kaufman & Kaufman, 2005). The reading score is based on performance on two parts: Recognition and Comprehension. There are 37 items in the Recognition part which require reading and pronouncing irregular words that do not strictly follow phonetic rules, ensuring that word recognition, or reading vocabulary, is measured more so than decoding ability. Most of the 46 Comprehension items require reading a passage and giving oral answers to literal or inferential questions. Some items require response to commands given in printed statements, for example: *Turn your head* (Kaufman et al., 2009). The brief form of the test is normed for 4-6 through 90 +.