“In reading, a lonely quiet concert is given to our minds; all our mental faculties will be present in this symphonic exaltation.”

- Stéphane Mallarmé

University of Alberta

Visual and Auditory Phonological Processing During Reading and Listening

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

Department of Psychology

Spring 2013
Edmonton, Alberta

To my best friend and love of my life,
Kevin,
for always believing in me.

Abstract

Reading and listening are two skills used in language processing. Many studies have investigated reading ability but fewer have looked at listening skills and no studies to date have studied the association between the two. This dissertation looks at the relationship between reading skill and listening skill and how this association may be used as a measure of phonological processing efficiency. Reading speed scores were found to be correlated with listening speed scores. The difference between these standardized scores was taken (reading-listening-difference or RLD scores) and compared to other tasks. RLD scores were found to be significantly related to language tasks that access phonological processing but not semantic processing, indicating the RLD effect is phonological. Other confounding factors such as auditory non-linguistic processing, and general cognitive processing were ruled out and not reliably correlated with RLD scores. Implications of this research are discussed, including possible ways to fit this research with current models of reading.

Preface

For most of us, language comprehension is achieved in two ways: visually by reading or auditorily by listening to speech. One generally considers the process of reading to be the act of looking at letters on a page and converting those groups of letters into words that give us meaning. This appears to be a purely visual task and auditory processing does not seem to be a necessary part of the reading process. Generally, we would not think that the ability to *hear* would influence the ability to *read*. However, a large contributing factor to both reading and understanding spoken speech is phonology. Visual phonological processing during reading has typically been considered to be *independent* of auditory phonological processing when listening to speech. Evidence for this is seen in some aphasic individuals who show dissociations between auditory and visual phonological processing abilities. However, there is also evidence to indicate that these processes may be *interdependent*. For example, there are brain areas that functionally overlap for visual and auditory phonological processing. In addition, deaf individuals who do not have access to auditory phonological information are poorer readers on average compared to hearing individuals. To date, many studies have been done on phonological processing, but none have investigated the differences between visual phonological processing that occurs during reading, and auditory phonological processing that occurs during listening. The studies in this dissertation will examine whether these processes are correlated and how this interdependence may influence language processing.

Definition of phonological processing

It is important to be clear about the definition of phonological processing used in this thesis. Phonological processing is an abstract mapping between language representations in different modalities. This mapping can be visual or auditory (or, as this dissertation will argue, a combination of both). Some studies that have investigated phonological processing and reading ability treat phonological processing as one thing: the way we put sounds of letters together to form words (see review by Wagner & Torgesen, 1987). This definition implies that phonological processing is an auditory process. While this is certainly one example of how phonological processing can be used, this is not an accurate psycholinguistic definition. Phonological processing is not only *auditory* linguistic processing because it can occur in the absence of auditory information. For example, American Sign Language (ASL) has a phonology that is used with visual signs. Instead of using phonemes, which are the individual sounds that make up words, ASL phonology uses *cheremes*, which refer to handshape, palm orientation, movement, and location of the signs. This phonological processing is independent of auditory processing or vocal means of production. Phonological processing is not dependent on one specific modality of vision or audition, but rather, is used through either or both modalities depending on the situation.

It is important to note that the research questions in this dissertation do not include whether or not phonological processing is visual or auditory. We already know that phonological processing can use either modality. The research questions of interest here are: Is there a relationship between how phonology is processed visually during reading and auditorily during listening, and does this relate to performance on other language tasks?

In order to address these research questions and other related issues of this topic, this dissertation is divided into seven chapters.

Chapter 1 introduces the topic and covers the ideas that support the notion that phonological processing of auditory and visual language processing are assumed to be interdependent processes. It then goes on to look at the observational counter-evidence that these processes appear to be independent. Chapter 1 also gives some background on phonology and reading disabilities, and ends with discussing the limitations of the previous studies and goals of the present research.

Chapter 2 investigates the relationship between visual and auditory phonological processing to see if faster readers can listen to and comprehend a faster rate of speech as well.

Once the relationship is established, Chapter 3 goes on to examine how the difference between reading speed and listening rate is related to other various language tasks. Specifically, the study looks at effects with early phonological tasks versus a late semantic processing task.

Chapter 4 investigates phonological processing and reading listening difference (RLD) effects in greater depth. Two studies are conducted in this chapter. The first considers RLD effects with regards to the processing of words versus nonwords. The second study looks at irregularity effects and how these results fit into pre-existing models of reading.

The purpose of Chapter 5 is to ensure that the RLD effect found in previous chapters is not due to the confounding variable of being efficient in auditory (non-linguistic) processing in general.

The study in Chapter 6 is done to rule out the possibility that faster readers are also faster listeners simply because they are faster at processing everything, including visual non-linguistic cognitive tasks.

Chapter 7 includes a general discussion of the findings as well as ideas for future research and final conclusions.

Acknowledgements

This work was made possible through the support of my supervisor, Chris Westbury and many undergraduate students who helped with data collection.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

RLD	Reading-Listening Difference
ASL	American Sign Language
HCRD	History of Childhood Reading Difficulties
FM	Frequency Modulation
SLI	Specific Language Impairment
fMRI	Functional Magnetic Resonance Imaging
BA	Brodmann's Area
VWFA	Visual Word Form Area
DRC	Dual Route Cascaded (model)
PDP	Parallel Distributed Processing (model)
SD	Standard Deviation
RT	Reaction Times
ms	milliseconds
ASJ	Auditory Synonym Judgment
ALFAB	Alberta Language Function Assessment Battery
VLD	Visual Lexical Decision
ALD	Auditory Lexical Decision
ACTUATE	Assessing Cases: The University of Alberta Testing Environment
LME	Linear Mixed Effects
MCMC	Monte Carlo Markov Chain
GPC	Grapheme to Phoneme Conversion
CHRD	Childhood Reading Disability
S/M	Shepard and Metzler's
V/K	Vandenberg and Kuse's
WAIS	Wechsler Adult Intelligence Scale
WAIS-R	Wechsler Adult Intelligence Scale – Revised
MAT	Matrix Analogies Test
ERP	Event Related Potentials

Chapter 1

Literature review

The purpose of this first chapter is to review the previous research that has been done that is related to reading and auditory processing associations. There are five main sections. The review will start with the studies that give evidence to suggest that reading and auditory processing are *interdependent*. The next section discusses studies that provide counter-evidence of this, that suggest that these processes are completely *independent* of each other. After that, some background on phonology and reading disabilities will be covered. Finally, the chapter will end with sections on the limitations of previous studies and goals of the present research.

The basic notion: Audition and reading are *interdependent*

The first part of this literature review will cover the many studies that suggest that audition and reading are connected in some way. This includes support from developmental studies, studies on deaf readers, cognitive research, and neurological findings.

Support from developmental studies: Reading ability and auditory skills. The majority of studies that investigate the influences of reading ability have focused on phonological processing with young children learning to read. Only a small number of studies have looked at auditory processing and its effects on reading skill. There are two types of auditory processing to consider when investigating the interactions with reading skill: non-linguistic auditory input and linguistic auditory input. Research has also shown that auditory input interacts with spelling ability, which is related to reading ability.

***Reading and non-linguistic auditory processing*.** Ahissar and colleagues (2000) conducted a study with two groups of adult readers: those who had a history of childhood reading difficulties (HCRD), and a control group that did not have any history of reading difficulties. The aim of the study was to see how auditory processing correlates with reading ability into adulthood, and specifically what kinds of auditory processes are influential. One hundred and two participants were given tests of reading, spelling, cognitive ability, and many psychoacoustic tests such as tone detection, backward detection masking, gap detection, frequency discrimination, intensity discrimination, formant discrimination, frequency discrimination under backward masking, tone-sequence identification, and interval discrimination. Accuracy scores for reading and spelling were highly correlated in both groups, as expected. Reading scores and memory of orally presented words were correlated for the control group of readers, but not for the HCRD group. In looking at the psychoacoustic tests, there was no difference between groups of participants for tone and gap detection, but there were higher correlations with reading performance of the control group than the HCRD group for frequency discrimination and tone-sequence identification tasks. When broken down by reading score, the poorer readers needed larger differences in frequency in order to make discriminations, compared to the better readers. Overall, HCRD participants who were matched on reading scores with control participants did worse on psychoacoustic tasks. This is an intriguing finding in that even though as adults they have overcome their reading difficulties they experienced during childhood, poor auditory acoustic processing still persists for these individuals, which may have been one of the contributing factors to the childhood reading difficulties in the first place. Poor reading may be the result of poor phonological processing, but this study suggests that poor auditory processing could be the primary underlying cause that affects learning phonological skills and, eventually, reading skills.

If auditory processing skills influence phonological skills, which then influence reading skills, it should be possible to predict children's reading ability by seeing how well they do on auditory tasks. A study done by Talcott, Witton, McClean, Hansen, Rees, Green, and Stein (1999) looked at auditory sensitivity problems that might influence phonological processing and, ultimately, reading ability. They had 32 participants with an average age of 9.9 years participate in tests of cognitive skill, reading, spelling, phonological skill and two auditory frequency modulation (FM) tests. For the auditory tests, participants listened to a 1000 Hz tone that had a FM of either 2 Hz (slow modulation) or 240 Hz (fast modulation). Previous research has revealed that listening to these two FMs uses different auditory mechanisms: the 2 Hz FM is detected by the 'wobble' of the tone and is determined by cortical mechanisms, and the 240 Hz FM is detected by the pitch of the tone and uses lower, peripheral auditory mechanisms (Kay, 1982; Kay, 1974; Witton et al., 1998). Talcott et al. found that sensitivity to the 2 Hz FM covaried with phonological processing skills and reading ability. Children's reading skills were strongly predicted by their sensitivity to the 2 Hz FM, but not the 240 Hz FM, of the 1000 Hz tone. These findings imply that detecting a tone with slower frequency changes is important for processing phonological information that influences the reading process.

In addition to changes in frequency, rapid changes in tone also appear to be correlated with reading skill and language abilities of young children. Many studies have shown that children with specific language impairment (SLI) or dyslexia have difficulty with tone discrimination tasks when the inter-stimulus interval between tones is very short (Cowan, 1992; Farmer & Klein, 1995; Hari & Kiesilä, 1996; Stark & Tallal, 1988; Tallal, Miller, & Fitch, 1993). As a result a widely held view is that children with SLI or dyslexia have a deficit in *rapid auditory processing* or *auditory temporal processing* (McArthur & Hogben, 2001; Tallal & Piercy, 1973; Tallal, 1980). Previous studies have found that auditory temporal processing skills and skills in reading decoding are highly correlated (Stark & Tallal, 1979; Stark & Tallal, 1988). Tallal and colleagues (1980; 1997) proposed that children with dyslexia have reading problems that stem from difficulties in processing rapid acoustic information. These difficulties lead to problems in speech perception and create poor phonological representations. These inadequate representations restrict good reading skills from being acquired. Tallal (1980) found that reading impaired children had more difficulty responding to rapidly presented auditory information than children without reading impairment. Correlations between auditory processing, phonological processing, and reading were found: the more difficulty a child had in responding to rapidly presented nonverbal auditory stimuli, the more difficulty he or she had reading and sounding out nonsense words.

Tallal (1997) has proposed a theory based on the extensive research she and her colleagues have done on this topic. Research has shown that children with language impairments chunk larger amounts of auditory information together than children with normal language skills, who process auditory information in smaller pieces with better detail (Merzenich et al., 1996; Tallal et al., 1996). One can imagine that this method works adequately enough for understanding speech because the missing details are 'filled in' during comprehension. For example, though a bad phone connection might prevent every single phoneme of every word from being heard, the meaning of the entire sentence is usually still comprehended without too much difficulty. However, this method does not work well when learning to read. The reader needs to be able to sound out each individual phoneme in order to put all the sounds together to identify the word. Missing phonemes can lead the reader astray or prevent identification of the word all together, resulting in difficulty with acquiring reading skills. Tallal and colleagues speculate that children have poor reading skills as a result of auditory perception impairments that are the direct result of problems with auditory temporal processing. If this is the case, children with reading difficulties should benefit from speech, language, and audiology therapies.

The relationship between poor reading skills, rapid auditory processing problems, and children with language impairments has been demonstrated in the previously mentioned studies. However, not every study that has used a rapid auditory processing task has yielded the same result. Marshall, Snowling, and Bailey (2001) set out to investigate the relationships between rapid auditory processing, phonological ability, and reading skill with normal readers and children with dyslexia. They found that rapid auditory processing tasks (various tone discrimination tasks) did not correlate with reading skill for normal readers, though rapid auditory processing performance was linked with proficiency on phonological tasks. The children with dyslexia showed difficulties with the phoneme deletion task (which requires the child to recognize a word that has a phoneme deleted) and the nonword repetition task, but surprisingly, not on the rapid auditory processing tasks. Contrary to what might be expected based on previous studies (McArthur & Hogben, 2001; Tallal & Piercy, 1973; Tallal, 1980; Tallal et al., 1997), Marshall et al. found that the children who performed poorest on the rapid auditory processing tasks did not have the poorest phonological or reading skills. This study shows that the relationship between auditory processing and phonological processing or reading skill is not yet clear.

In summary, when looking at the literature on children and adults with reading disabilities and how it relates to auditory processing abilities, some, but not all, studies have supported the idea that auditory processing interacts with reading ability. Contradictory evidence has also been demonstrated, indicating that there are still questions to be answered when considering the relationship between auditory processing and reading abilities.

Reading and linguistic auditory processing. In the previous studies mentioned, auditory processing ability of non-linguistic sounds has sometimes, but not always, shown to be influential to phonological processing and reading. Speech perception is a linguistic auditory process that deserves some investigation as well. Much of the previous work that looks at phonological processes and their relations to reading ability have focused on three areas of phonological processing: phonological awareness, recoding in lexical access, and recoding in verbal short-term memory (see for example, Wagner & Torgesen, 1987). McBride-Chang (1996) added a fourth area, speech perception, in an effort to see if linguistic auditory processing made a contribution. Some research has shown that difficulty in distinguishing between auditory consonants was observed in children who were poor readers (Tallal, 1980). Consonant perception difficulties have also been observed in some adult dyslexics (Lieberman, Meskill, Chatillon, & Schupack, 1985; Steffens, Eilers, Gross-Glenn, & Jallad, 1992; Watson & Miller, 1993). Previous studies have shown that speech perception may have a direct relationship with phonological areas such as phonological awareness, verbal memory, and naming (McBride-Chang, 1996). McBride-Chang conducted her study to see if speech perception also has a direct relationship to word reading. In her study, 156 third- and fourth-grade children participated in various tests of reading, IQ, phonological awareness, verbal memory, naming, and speech perception tasks such as phoneme deletion, position analysis, and phoneme counting. Regression analysis was done and a variety of models were tested to see if speech perception had a direct contribution to reading skill, or if it had an indirect influence by contributing through another factor, which then influenced reading. She found that speech perception did not have a direct effect on reading, but instead, contributed to the phonological awareness skills, which then affected reading scores. This study shows additional evidence that auditory factors operating through phonological ability influence reading ability.

The results found by McBride-Chang (1996) also agree with those found in a study by Mody, Studdert-Kennedy, and Brady (1997) on speech perception deficits in poor readers, and whether they are due to temporal auditory processing deficits or phonological deficits. On a rapid phoneme discrimination task, poor readers showed difficulty distinguishing between phonemically similar pairs such as /ba/ - /da/, but not with more distinct pairs such as /ba/ - /sa/. This prompted Mody and colleagues to question if the discrimination problem is due to a temporal auditory processing deficit or if it is the result of a phonological perception deficit. They did an additional experiment with acoustically matched, but perceptually distinct, non-speech control stimuli and found that there were no significant differences between the good readers and poor readers on these stimuli, indicating that the /ba/ - /da/ rapid discrimination problem is likely due to deficits in phonological perception rather than rapid auditory processing. This further supports the idea that auditory processing influences phonological processing which then influences reading ability.

Spelling and auditory processing. Learning to read is traditionally done by looking at the letters in the word, sounding out the letters into phonemes, and blending these sounds together to understand the word as a whole. Learning to spell requires this process to be done in reverse order. The child hears the word, breaks the word down into its different phonemes, and then assigns letters to the phonemes and writes them down. Much of the research to date has focused on the interactions of phonological processing with reading, but some studies have focused on the interactions of phonological processing and spelling ability.

Children need to use phonological and orthographic information during spelling (see Varnhagen, Boechler, & Steffler, 1999). But spelling may also require the use of auditory processes, both linguistic and/or non-linguistic. Kwong (2005) conducted a study that looked at the influences of linguistic and non-linguistic auditory processing on spelling ability. She tested children in grade 2, grade 4, and adults, in spelling and two auditory tasks: a non-linguistic tone discrimination task, and a linguistic phoneme perception task. Her results revealed that linguistic auditory processing scores were correlated with spelling scores for grade 2 children and adults, but non-linguistic auditory processing scores were not correlated with spelling scores for any of the participants. These results are similar to numerous studies that show phonological processing to be important for reading and language processing skills (see Elbro, 1996; Felton & Brown, 1990; Liberman & Shankweiler, 1985; J. K. Torgesen, Wagner, & Rashotte, 1994; Wagner & Torgesen, 1987), but differ from some studies that show non-linguistic auditory processing to be influential to reading and language processing (Cowan, 1992; Farmer & Klein, 1995; Hari & Kiesilä, 1996; Stark & Tallal, 1979; Stark & Tallal, 1988; Tallal et al., 1993). Although, support for Kwong's findings are also shown in a study by Marshall et al. (2001) which revealed no effect of tone discrimination on language tasks for normal and dyslexic participants.

Support from studies of deaf readers: poor readers on average

If auditory input influences the reading process then a lack of auditory linguistic input should hinder the ability to read well. This is the case when we look at deaf readers. Prelingually deaf individuals have an especially difficult time learning to read (Conrad, 1979; Kampfe & Turecheck, 1987; Trybus & Karchmer, 1977; Wood, Wood, Griffiths, & Howarth, 1986). Research has shown that on average, deaf students typically score below the reading ability of hearing students of the same age (Allen, 1986). Studies have also shown that deaf students typically only reach about a fourth grade level of reading achievement (see Center for Assessment and Demographic Studies, 1991; in Allen, 1986; as well as Trybus & Karchmer, 1977) and fail to advance past that level even with training.

Even limited auditory input can improve the reading skills of deaf children. Many deaf children have the opportunity to have cochlear implantation, which restores some hearing. Children with cochlear implants on average have better reading scores than completely deaf children but are still somewhat below the reading scores of hearing children (Geers & Brenner, 2003). One hypothesis is that earlier implantation may result in reading scores that, on average, are closer to the scores of hearing children. Geers (2003) studied 39 children who had a brief period of hearing before deafness occurred, and then received cochlear implants to restore hearing. A measure of *duration of deafness* was taken for each child: the time between when deafness occurred, to the time when the cochlear implants were done. Reading scores were not correlated with duration of deafness, although speech perception, speech production, and other language measures were significantly correlated with this measure. Eighty percent of children who had duration of deafness of less than 1 year scored within the average range of hearing children. Therefore normal speech and language skills can be attained if duration of deafness is short (less than 1 year) during the language acquisition period (Geers, 2004).

Although reading skills were not correlated with duration of deafness, receiving cochlear implants does improve reading skill of deaf readers compared to hearing readers. Geers (2003) studied 181 children between the ages of 8 and 10 who had cochlear implants for 4 to 6 years. Just over half (52%) of these children achieved reading scores within the average range of hearing children their age. It is important to note that many deaf children are put in a grade lower than hearing children of the same age. Therefore it is possible the other 48 % of children that were below the average of age-matched hearing children, were below simply because they were not matched on their level of educational instruction.

Onset of deafness at a later age is associated with better language outcomes after cochlear implantation. Language and reading skills were better for children with cochlear implants who became deaf after birth but before age 3 compared to children with cochlear implants who were deaf from birth. However, there was no difference in the outcomes of speech perception, speech intelligibility, or oral language development between the two groups (Moog & Geers, 2003).

Hearing students have access to sublexical processing by matching orthographic information with phonological information. In contrast, deaf students are limited with regards to phonological processing and therefore a sublexical route may be difficult to follow. Beech and Harris (1997) looked at hearing and deaf readers (with an average age of 7) in order to determine if a sublexical grapheme to phoneme translation route (see for example, Coltheart 1978; 1993; 2001) was used during reading. If a sublexical route is used, we would expect to see more errors for irregularly spelled words than for regularly spelled words (a regularity effect) because sounding out each letter would lead to the incorrect pronunciation, and ultimately, the incorrect reading of the word. The same reasoning applies for homophonic non-word (non-words that sound like real words when pronounced, such as *berd*) effects. Beech and Harris found that hearing readers, but not deaf readers, showed evidence of regularity and homophonic effects. That is, more errors were found for irregular than regular words and homophonic than non-homophonic non-words with hearing readers. Deaf readers did not demonstrate regularity or homophonic effects indicating that reading was based on sight word recognition and not phonological processing.

Support from cognitive studies

Another reason why it might be logical that auditory processing can influence visual processing of language is that the reciprocal relationship has been shown. Visual input can have an effect on auditory processing; that is, what we see can influence what we hear. This is evident in studies of speech perception with blind individuals, where a *lack* of visual input influences perception. It is also robustly demonstrated by the McGurk effect (McGurk & MacDonald, 1976). These studies are reviewed below.

Blind Speech Perception. Deaf children have the obstacle of not having access to the auditory acoustic input used for phonological processing. On the other hand, blind children are not able to access visual information that may help with phonological awareness. Not being able to see how speech is being produced affects phonological processing skills (Perfetti & Sandak, 2000). Some research has found that blind children have a higher number of articulatory problems when learning to speak (see Lezak & Starbuck, 1964; Mills, 1987; Miner, 1963; Stinchfield, 1944). Blind children typically make discrimination errors, such as discriminating between /m/ and /n/ which are quite different visually than when spoken (Wills, 1970). Mills (1983; 1987) compared the spontaneous speech of blind children to sighted children at the same stages of language development between the ages of 1 and 2.5 years. The results showed that blind children were delayed in their mastery of phonology through articulation compared to the sighted children. Mills suggests that this may be due to the absence of lip-reading information for blind individuals. It appears that a lack of visual information (i.e. lip-reading) may affect the auditory processing of phonemes for blind individuals. If poor visual information can influence auditory processing as we see with blind individuals, it seems probable that the reverse effect can occur; that is, poor auditory processing may affect the visual processing of reading.

McGurk Effect. The McGurk effect (McGurk & MacDonald, 1976) also shows how visual input can influence auditory processing. Perceiving speech is considered to be a purely auditory process but research suggests that auditory and visual processing may interact during speech perception. The McGurk effect demonstrates how what we see can influence what we hear. This effect is experienced when an individual sees a video of a person mouthing a sound such as *ga ga ga,* but auditorily a *ba ba ba* sound is played. The result is that the observer perceives *da da da*. If the observer closes his eyes, he will hear the correct *ba ba ba* sound, but when he is influenced by contrasting visual input, it changes what he perceives to hear. This effect is so robust that it still occurs even when the observer is aware of the phenomenon and knows the correct sound that should be heard.

A recent neuroimaging study used functional magnetic resonance imaging (fMRI) and transcranial magnetic stimulation in an effort to find the locus of the McGurk effect (Beauchamp, Nath, & Pasalar, 2010). Behaviorally, the McGurk effect demonstrates an integration of auditory and visual stimuli. Some neurological studies have suggested that the superior temporal sulcus (in BA 22) is implicated during visual and auditory integration of speech and non-speech stimuli (Beauchamp, 2005; Calvert, Campbell, & Brammer, 2000; Miller & D'esposito, 2005; Sekiyama, Kanno, Miura, & Sugita, 2003). Beauchamp and collegues applied transcranial magnetic stimulation to the superior temporal sulcus, rendering the area temporarily inactive, and found that the McGurk effect temporarily disappeared. The neurological architecture of the superior temporal sulcus shows that it consists of "a patchy distribution of neurons that respond to auditory, visual, or auditory-visual stimuli" (Beauchamp, Argall, Bodurka, Duyn, & Martin, 2004; Dahl, Logothetis, & Kayser, 2009; quoted from Beauchamp et al., 2010, p. 2417). This neurological evidence combined with behavioral evidence from the McGurk effect supports the idea that visual and auditory information interact during processing.

Support from neurological studies: Areas of functional overlap

Neurological studies looking at the superior temporal sulcus (Brodmann's area (BA) 22) have indicated an interaction between auditory and visual processing, however this is not the only neurological evidence of auditory-visual processing interactions. Other brain areas have been known to have overlapping functionality for both modalities of language processing. The left midfusiform region (BA 37) is one such area.

Recent neuroimaging studies have resulted in naming the left posterior midfusiform gyrus (BA 37) the *visual word form area* (VWFA) because of its activation while doing visual word processing tasks. However, naming this area the VWFA has been controversial because it also appears to be involved in other functions such as auditory and tactile processing; not just specifically visual word processing (see Demonet, Thierry, & Cardebat, 2005; C. Price & Devlin, 2003). Activation of the left midfusiform area (BA 37) is found during visual word processing tasks (Brunswick, McCrory, Price, Frith, & Frith, 1999; Cohen et al., 2000; Cohen et al., 2002) and auditory word processing tasks such as hearing and repeating words (Price, Winterburn, Giraud, Moore, & Noppeney, 2003), and hearing and making rhyme judgments (Booth, Burman, Meyer, Gitelman, Parrish, & Mesulam, 2002a; Booth, Burman, Meyer, Gitelman, Parrish, & Mesulam, 2002b).

Geschwind (1965) reports early investigations of post-mortem cases of patients with cortical lesions who also had language deficits. These early reports lead to a proposed neurological model in which the process of reading aloud went through areas of visual cortices (BA 17, 18, 19), left angular gyrus (BA 39), left posterior superior temporal cortex (Wernicke's area, BA 22), and left posterior inferior frontal cortex (Broca's area, BA 44/45) (Price et al., 2003). Price and collegues (2003) further tested this neurological model by having participants do auditory repetition and reading aloud tasks in a functional magnetic resonance imaging experiment. They found that "there was common activation for auditory word repetition and reading in the left posterior frontal cortex (Broca's area, BA 44/45) and the left posterior superior temporal cortex (Wernicke's area, BA 22)" (Price et al., 2003, p. 277) as well as activation in the left superior temporal sulcus (BA 22).

Results from these studies indicate that these brain areas are responsible for reading and auditory processing. However, this does not mean that these are the only tasks that activate these brain regions. When looking at neurological results it is important to consider the *one to many* or *many to one* mappings between functions and neurological areas: one brain area may be responsible for not just one, but many different functions and may have many different connections to other brain areas; and one behavioral function may activate not just one, but many different brain areas. This is the problem with labeling specific brain areas in terms of function, such as naming the left posterior midfusiform gyrus (BA 37) the VWFA. The left posterior midfusiform gyrus is not limited only to visual word forms, but is also activated during other tasks that use auditory and tactile stimuli (see Price & Devlin, 2003). Due to this principle and the results seen from previous neurological studies, it is logical that interactions between auditory processing and reading exist and share common brain areas.

Observational counter-evidence: Audition and reading are independent

The first part of this review has focused on pieces of evidence that suggest that processing auditory input may interact with the reading process. Traditionally however, this line of reasoning has not been followed for some of the following reasons. Behavioral evidence shows that individuals who do not have access to auditory input can still read, such as those with pure word deafness or deaf individuals. Theoretical models based on this evidence have not included an auditory input component for visual lexical access. However, these models do include a phonological component that can account for a large amount of experimental evidence.

Evidence from aphasic populations: Pure word deafness

Behaviorally, we find evidence that a lack of auditory linguistic input does not prevent reading from being possible. Pure word deafness is a disorder resulting from brain damage that leaves the individual unable to understand spoken language (speech) even though hearing is still intact. Although individuals with pure word deafness can hear normally but fail to comprehend words spoken to them, they can still read and comprehend language if it is in visual form. This seems to indicate that comprehending auditory speech is not integral to the reading process. Pure word deafness is very rare. The brain areas damaged in individuals with pure word deafness are often extensive and occur in both hemispheres. Cases of individuals with pure word deafness have shown extensive damage to bilateral areas in the temporal lobes, specifically the middle and posterior superior temporal gyrus (BA 22) and connecting white matter pathways with some sparing of Heschl's gyrus and other regions of the planum temporale (BA 41, 42, primary and auditory association cortex) on the left (Bauer & Zawacki, 1997; Geschwind, 1965). It is important to note that pure word deafness always involves lesions to both hemispheres, or at the very least, the connecting pathways between hemispheres. Some cases of individuals with bilateral lesions show that speech perception was still intact after the first lesion, and only became disrupted after the second lesion occurred in the other hemisphere (Poeppel, 2001). Pure word deafness does indicate that one does not need to be able to process auditory linguistic input in order to read. However individuals with pure word deafness can still process non-linguistic auditory input. This supports the idea that visual and auditory phonological processing are separable and distinct. More evidence of this is the fact that deaf individuals who have no access to auditory processing of any kind are still able to read.

Evidence from deaf populations: Reading ability

A real world example that seems to indicate that auditory input may not be absolutely necessary for reading is the fact that the deaf can read. Although it is difficult, deaf individuals are still able to learn to read even though they do not have access to auditory input of any kind, and may not have ever had access to any auditory phonological processing, as in the case of individuals who are congenitally deaf. However, deaf individuals usually do not attain the same level of reading ability as normal readers, even with extensive training (Allen, 1986; Trybus & Karchmer, 1977). Understanding how deaf individuals learn to read, including at what point deafness occurred, can give insight to the reading process and what role, if any, auditory phonological processing plays.

Geers (2003) suggests two models that describe how general reading acquisition can take place. One way is through bottom-up sublexical processing using phonological decoding strategies. Visual text is translated into acoustic units or phonemes. This model relies on grapheme to phoneme conversion skills (see Gough, 1972; Rubenstein, Lewis, & Rubenstein, 1971). This model works well for hearing children but deaf children will need alternative methods for learning phonological information. Deaf readers may use a different model when learning to read. The top-down model bypasses acoustic and phonological information and uses visual representations or semantic cues to memorize associated text. In this way, a letter string is linked with semantic associations and is read by accessing the visual memory of the word's form, and is not influenced by the phonological components associated with the word. This makes it possible for deaf individuals to be able to read words without knowing what the words sound like. However this may not be the most effective way to learn to read. Deaf individuals who are taught to use phonological information are better readers than those who read based on memorizing visual representations (Conrad, 1979; Hanson, 1989; Leybaert, 1993). Although deaf students cannot benefit from traditional phonetic instruction, they do benefit when alternative methods, such as Visual Phonics, are used to provide phonological information during the reading process (Narr, 2008; Trezek & Malmgren, 2005; Trezek & Wang, 2006; Trezek, Wang, Woods, Gampp, & Paul, 2007). Because of this, Wang et al. (2008) stress the importance of phonological skill development in deaf reading education and encourage educators of deaf students to implement instructional tools such as Visual Phonics, Cued Speech, speech reading, and articulatory feedback, in order to facilitate deaf readers.

Evidence by omission: Models of reading have no auditory component

All models of reading have a phonological component. Phonological processing is not simply an *auditory* process but also involves a visual process, especially when reading. Reading words involves a mapping between the visual letters on the page (orthography) and their phonological codes. Phonological codes are used to encode what a word might sound like during output (when we read or speak out loud) and leads to a phonological representation. Models of reading include phonological components but do not differentiate between visual phonological coding and auditory phonological coding which lead to a phonological representation. The reason for this may be that proponents of the models do not believe that any differentiation between auditory and visual phonological processing is used when going from phonological codes to representations needed for reading, or accessing language in general. However, this has not been explicitly tested in order to prove it or rule it out. The next section will explore some prominent models of reading.

Models. Theoretical models of visual lexical access or reading are based on years of experimental psycholinguistic evidence. Models are created and modified to explain the effects seen in psycholinguistic experiments. Some well-known models include Coltheart's (1978; 1993; 1994; 2001) dual route cascaded (DRC) model of lexical access, and the connectionist and computational model of Seidenburg and McClelland (1989); as well as other models of reading proposed by Plaut (1997), Just and Carpenter (1980), and Rayner and Pollatsek (1989). To date, no models of reading include an auditory processing component.

The DRC model (Coltheart, 1978; 1993; 1994; 2001) proposes a lexical route, which goes from the printed word to the lexicon and then to output (speech, if reading aloud), and a non-lexical or sub-lexical route, which uses phoneme to grapheme translation rules to decipher the printed letters (see Figure 1).

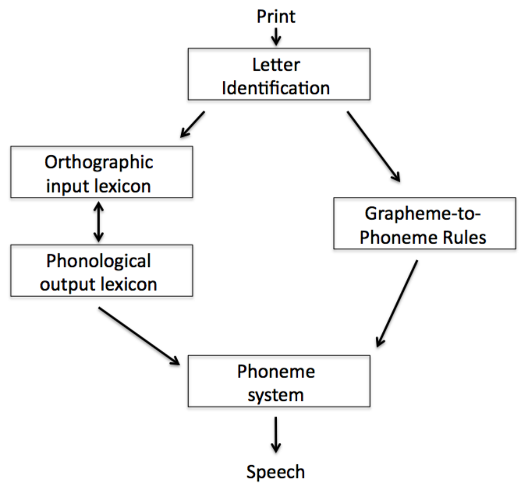

Figure 1 Dual-route cascaded model of visual word recognition and reading aloud (Coltheart & Rastle, 1994).

Parallel distributed processing (PDP) models (Seidenberg & McClelland, 1989) demonstrate a single route that goes from orthographic units to hidden units to phonological units and allows for feedback between components (see Figure 2). It is sometimes referred to as the triangle model.

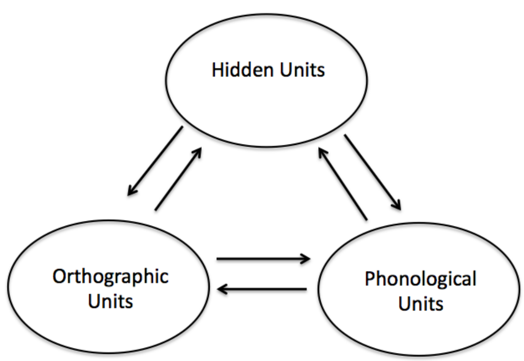

Figure 2 Basic PDP model (based on Seidenberg & McClelland, 1989).

As we can see, there is no auditory component to either of the mentioned theoretical models. This is not surprising because intrinsically there seems to be no logical reason why we would need an auditory component for a non-auditory task such as reading. Also due to this reasoning, psycholinguistic experiments that test for a relationship between auditory processing and reading have not been done. Because models are based on the results of psycholinguistic studies, and these specific studies have not been conducted, there has not been a need to modify the models.

Some background on phonology and reading disabilities

While very little attention has been given to the relationship of auditory phonological processing and reading, a vast amount of literature exists about visual phonological processing and reading ability. Studies mentioned earlier indicate that auditory processing may influence phonological processing and in turn, reading skill. There are many more studies that have just focused on the association of phonological processing and reading ability. In order to fully understand how auditory phonological processing may work together with visual processing to play a role in acquiring reading skill, it is helpful to first understand how phonological processing is correlated with reading ability.

Many studies show that phonological skills are important for reading ability (see Elbro, 1996; Felton & Brown, 1990; Liberman & Shankweiler, 1985; J. K. Torgesen et al., 1994; Wagner & Torgesen, 1987). A large review paper by Wagner and Torgesen (1987) looked at phonological processing in more depth and investigated which aspects (phonological awareness, phonological recoding in lexical access, and phonological recoding in working memory) are related to which aspects of reading (word recognition, word analysis, sentence comprehension). After reviewing many studies they concluded that the ability to process phonological information is a general skill that is necessary in processing tasks that measure phonological awareness, recoding in lexical access and phonetic coding in working memory. This general phonological ability is independent of IQ and seems to be quite stable across age. However, the two specific phonological processing skills of phonological awareness and phonetic coding in working memory, each accounted for unique variance in reading skill. So although, general phonological skills are influential to reading ability, specific phonological skills contribute individually to reading skill.

Phonology in children

Phonological abilities are part of children's cognitive endowment and not just due to knowledge acquisition or learning. Torgesen, Wagner, and Rashotte (1994) conducted a longitudinal study of phonological processing and reading, with 244 children tested at the beginning of kindergarten, then grade 1 and again at grade 2. They used a battery of 22 tests looking at phonological processing, pre-reading and reading skill, and general verbal ability. They used latent variables to stand for the constructs of phonological processing and reading. These latent variables included a number of different tasks to get an average estimate of measurement error and control variability (five phonological variables: analysis, synthesis, memory, isolated naming, serial naming). The correlations for the five phonological variables tested in kindergarten, grade 1, and again in grade 2 were high and remained stable. They found that phonological processing had a positive effect on reading skill, as well as a reciprocal effect: reading skill improved phonological skill. Correlations between latent variables of phonological processing skills and reading skills were significant. Pre-reading skill in kindergarten had a causal effect on subsequent development of phonological skill. These results show that skill level for phonological processing and reading seems to be innate and remains relatively stable over time. Training attempts have been undertaken to help at-risk children improve their phonological processing abilities although these attempts have only been mildly successful (Torgesen, Morgan, & Davis, 1992; Torgesen et al., 1994).

Some studies have shown that phonological processes influence children's ability to recognize words even before full mastery of an alphabet is reached (Ehri & Wilce, 1985; Read, 1986; Reitsma, 1983; Stuart & Coltheart, 1988). Children can use phonetic cues in early word recognition, much more easily than using visual cues (Ehri & Wilce, 1985). For example, when kindergarten children were taught three letter strings to represent a word, the letter string *jrf* was better learned for the word *giraffe* than the letter string *wbc* (Ehri & Wilce, 1985). Laing and Hulme (1999) proposed that children with good phonological awareness would also do well at the word-cue learning task done by Ehri and Wilce. Sixty children who were 5, 6, and 7 years old were given phonological awareness tests, reading ability tests, and the experimental word-cue learning task. Laing and Hulme found that phonetic cues were learned more easily than control cues, even in the group of children who could not yet read. Also, there was a significant correlation between phonological awareness scores and word-cue scores: children who had better phonological awareness skills also did better at the word-cue task. Using a regression analysis, the word-cue learning task was found to be a unique predictor of variance in reading ability.

Phonological processing ability relates to reading skills, but does it only relate to reading skills that use an alphabetic orthography or does it extend to those that use a logographic orthography as well, such as in Chinese? Previous research shows phonological processing is involved in reading and retaining Chinese characters in working memory. Using alphabetic orthographies such as the English alphabet, we see a link between early reading and phonological skill (Wagner & Torgesen, 1987). Hu and Catts (1998) also found a link between early reading of Chinese, using a logographic alphabet, and phonological processing skill. They tested 50 Taiwanese 1st graders exposed to both a Mandarin (logographic) alphabet (Zhuyin fuhao) and an orthographic alphabet (English letters) for 3 months before testing. Regression analysis showed that phonological processing skills contributed to the explained variance in logographic character reading that could not be explained by alphabetic word reading ability. This study found that phonological processing skills are related to children's ability to read Chinese. An alphabetic orthography like English is directly and explicitly paired phonemically but reading Chinese characters is much more indirectly related. Because of this, the traditional view is that phonological skills would not be as important for reading Chinese characters, however this study proves otherwise. These findings also show that the relation between children's early reading ability and phonological skills is not specific to an alphabetic orthography. Using phonological cues to read (even when the orthography is not directly transcribed phonemically) might be a universal process since we see it with different languages using different types of orthographies. “In other words, it is not reading an alphabetic orthography that places demands on children’s phonological processing skills but reading in general” (Hu & Catts, 1998, p. 71).

Phonology in children with reading disabilities

In addition to studies of normal children, studies have been done with children who are at risk for reading disability. Felton and Brown (1990) conducted a study to investigate phonological processing abilities in children at risk of reading disability and to see the relationship to reading tasks. They had 81 children who were assessed to be at risk for reading disability, and tested them on phonological awareness tasks, phonological recoding in lexical access tasks, phonological recoding in working memory tasks, as well as reading tasks. Contrary to many studies including a large review by Wagner and Torgesen (1987), Felton and Brown did not find any significant relationship between phonological awareness, rapid naming, or short-term memory tasks. However, this could be due to the special population of at risk children tested, as these children were at least 1 standard deviation below the group mean or in the bottom 16^{th} percentile in at least three of the administered experimental tests. Therefore, there may not have been enough variance in the sample to get the correlations they were looking for. They did find a correlation between phonological processing and reading tasks but when IQ was accounted for, the correlation was no longer significant.

In contrast to the study by Felton and Brown (1990), many previous studies have shown that children with dyslexia also have difficulty with tasks that use phonological processing (Brady, Shankweiler, & Mann, 1983; Jorm, Share, Maclean, & Matthews, 1984). Other studies show that children with dyslexia report deficits in speech perception as well, (Adlard & Hazan, 1998; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Manis et al., 1997) such as a difficulty in recognizing certain phonemes (Brady, 1997).

Phonology in adults

The majority of the work done on phonological processing skill and reading ability has been done with pre-literate and literate children. Not as many studies have been done to see how phonological processing influences reading ability during adulthood. Unsworth and Pexman (2003) conducted a study with adult participants, which focused on how reading skill might influence phonological processing tasks. They studied groups of more skilled and less skilled adult readers and the effects each group had on phonological tasks that involved homophones, homographs, and word regularity. They compiled reading scores using the Author Recognition test (Stanovich & West, 1989) and the Nelson-Denny reading test on 75 undergraduate students. The compiled scores were rank ordered and then split into three equal groups of 25 students each. They used the top 25 students to form the more skilled reader group and the bottom 25 to form the less skilled reader group. They found that the more skilled readers were significantly faster and less error prone than the less skilled readers on all tasks. They also found significant homophone effects for both the more skilled and less skilled readers, but only significant regularity effects for the less skilled readers. This research sheds light on how adult readers of different skill levels process phonological tasks differently.

Another study that looked at reader skill and phonological processing ability in adults was done by Binder and Borecki (2008). They looked at the role of phonology during silent reading with a group of adults who were learning to read and a group of skilled college-aged readers. Participants were asked to silently read a paragraph as quickly as possible that contained an incorrect homophone, correct homophone, or a spelling control word. The skilled college readers were not affected by the incorrect or correct homophone in the paragraphs and read them at the same speed. However the adults who were just learning to read took longer to read the paragraphs with incorrect homophones than those with correct homophones. For both groups, reading the paragraphs with the spelling control words took the longest amount of time. Similarly to the results of Unsworth and Pexman (2003), these results suggest that the less skilled readers do use phonology during reading but are not as efficient at it as the more skilled readers who were not affected by the presence of the incorrect homophone.

Studies of phonological processing and dyslexia have been done in other languages as well. A study of Danish speaking normal and dyslexic readers was conducted to see if there are any signs of phonological processing deficits that could indicate the underlying cause of reading dysfunction in adults (Elbro, Nielsen, & Petersen, 1994). They tested 89 dyslexic and 50 normal adult readers on reading tasks such as word, non-word, and pseudoword identification; and auditory language tasks such as phoneme identification, semantic and phonological word knowledge (synonym judgment), and pronunciation distinctness of reading aloud. The dyslexic readers performed less effectively on all tasks compared to normal readers. They were poor readers of novel words they had never seen before and showed difficulty with phonemic awareness tasks. They also confused similar sounding words more often than normal readers and pronounced words less distinctly than normal readers as well.

One study opposes a unitary view of phonological codes, and provides evidence of different phonological codes for reading and for holding phonological information in working memory (Besner & Davelaar, 1982). Besner and Davelaar conducted memory span experiments in which subjects were shown nonwords and psuedohomophones successively on a computer screen and had to repeat back the stimuli in the correct order to the experimenter. During some trials the subjects had to count to 10 out loud while viewing the stimuli, as a way of suppressing phonological processing. Different results were demonstrated that were dependent on phonological suppression and lexical status (pseudohomophones or nonwords). This indicates that there are different phonological codes used during reading and short term memory span. There are phonological codes for memory span that are impaired by suppression, and phonological codes used for lexical access that are not impaired by suppression.

Showing that there is a phonological code used when visually reading words, and a different phonological code used for holding phonological information in working memory, supports the idea that phonological processing is not one unitary form of processing, but that there can be different types of phonological codes for different types of phonological processing.

The phonological deficit model of reading disabilities

The phonological deficit model of reading disabilities predicts a difficulty in word recognition for individuals with phonological difficulties. This is due to segmental language representation at the phonological level, affecting the knowledge of phonemes and skill of processing them (Elbro, 1996; Fowler, 1991; Goswami & Bryant, 1990; Liberman & Shankweiler, 1985; McBride-Chang, 1995a; McBride-Chang, 1995b; McBride- Chang, 1996; Metsala, 1997; Olson, 1994; Stanovich, 1986; Stanovich, 1991). This can result in poor spelling-to-sound translation when learning to read.

This model is based on Coltheart's (1978; 1993; 1994; 2001) dual route model for reading which proposes that when the sub-lexical route (phonological, grapheme-to-phoneme conversion) is impaired, compared to the lexical route (whole word lexical access), poor spelling to sound translation occurs and results in reading difficulties. Experiments used to test this are done by using pseudowords that use spelling-to-sound translation in order for the word to be read. Testing for regularity effects using regular spelled words and exception words is another method typically used to show how the dual route model works.

Regular words use spelling-to-sound translation and the sublexical route, where as exception words must be learned as a whole and must be accessed through the lexical route during reading.

Metsala and colleagues (1998) did a meta-analysis to see if adults with reading difficulties demonstrate a regularity effect and if the effect size would be different from normal readers. The meta-analysis included 17 studies and had a total of 1116 participants (536 with reading disabilities, 580 normal readers). They found that both groups showed regularity effects and the effect size was not significantly different between groups.

These results were not in line with the expectations based on Coltheart's (1978; 1993; 1994; 2001) dual route model of reading, which predicts that readers with disabilities would show an absent or reduced regularity effect compared to normal readers. However, the data does fit with Seidenberg and McClelland's (1989) computational model that performed well on single word reading tasks but was criticized for poor performance on pseudoword reading (Besner, Twilley, McCann, & Seergobin, 1990). Better pseudoword performance could be obtained by having more fine-grained input at the level of graphemes and phonemes. This lack of fine-grained phonemic information could be why individuals with reading disabilities typically have problems with pseudowords, but still show regularity effects just like normal readers.

Limitations of previous studies

Previous studies have been done on phonological processing, auditory non-linguistic processing, and reading ability. However, there are existing issues that these studies have not addressed. To date, no studies have looked for a relationship between visual phonological processing (such as during reading) and auditory phonological processing (such as during listening). While some studies have considered auditory non-linguistic processing and its relationship to reading ability, no studies have compared this with auditory phonological processing and reading ability. Very few studies have been done to rule out the possibility that effects may be due to a general cognitive visual processing mechanism. No studies have been done that also included auditory phonological processing tasks in comparison to auditory non-linguistic tasks.

Goals of present studies

To address the limitations of the previous research and investigate this research idea further, there are four goals for this dissertation. The first is to determine if there is a relationship between visual phonological processing (as in reading) and auditory phonological processing (as in listening) of language (Ch.2). Second, to see how the difference between auditory and visual phonological processing is related to language processing tasks (Ch. 3 & 4). The third goal is to rule out that the difference between auditory and visual processing is due to general auditory processing skills (Ch. 5). Finally, the fourth goal is to test that the difference between auditory and visual phonological processing is not due to a general cognitive processing mechanism (Ch.6).

Chapter 2

The relationship between reading ability and listening ability

The goal of Chapter 2 is to establish that there is a correlation between reading speed and listening speed; that is, faster readers can also understand faster speech. The literature review from Chapter 1 reveals that no experimental studies have been done to explicitly test this relationship. However, there is much evidence that suggests that a relationship between reading and listening skills may exist.

The study in Chapter 2 looks at the relationship between visual phonological processing during reading and auditory phonological processing during listening. As mentioned earlier, reading skill can be influenced by auditory non-linguistic processing ability in children who are learning to read and have reading disorders. One study (Ahissar et al., 2000) has looked at this auditory non-linguistic influence on reading in adults who had reading disabilities in childhood, but no studies have looked at the relationship of reading skill and auditory linguistic processing ability. There is much work (see Chapter 1 for review) that suggests auditory linguistic processing contributes to reading ability, but the relationship between auditory phonological processing during listening and visual phonological processing during reading has not been explicitly tested.

The experiment in Chapter 2 was conducted in order to test the hypothesis that reading speed is correlated with listening rate of speech. In this experiment the listening speed task represents auditory linguistic processing ability, and the reading speed task is a proxy for visual phonological processing skill. The hypothesis is that better readers, who are defined by having faster and more accurate reading scores should be able to listen to and comprehend faster speech than readers who are slower and less accurate.

Methods

Participants

The participants were students from the University of Alberta, who participated in the psychology research pool for course credit in an introductory psychology course. In order to participate in the studies described in this dissertation, students must have acquired English as a first language, and were right-handed.

There were 206 participants (79 males, 127 females) who were included in the analysis of the listening and reading speed tasks. In order to be included in the analyses participants had to score within 2 standard deviations of accuracy and latency scores for both the reading and listening task. This requirement removed 10 participants from an original 216 (5%). The average [standard deviation (SD)] age was 19 [1.9] and ranged from 17 to 30. All of the participants reported in this dissertation did the reading and listening tasks reported in this chapter. Subsets of this group of participants also did other tasks such as visual and auditory linguistic tasks (Ch. 3, 4), auditory non-linguistic tasks (Ch.5), and general cognitive tasks (Ch. 6) that are covered in the remaining chapters of this dissertation.

Stimuli

Reading speed task. The stimuli for the reading speed task used reading passages 1, 3, and 5, from the Nelson-Denny Reading Test (Brown, Bennett, & Hanna, 1981), as well as the comprehension questions for each of these passages. Passages 1, 3, and 5 were used instead of all six passages in order to shorten the length of the reading speed task. Split-half reliability testing was previously done (Westbury, 2011, personal communication) with 503 participants who read all six passages. The correlation between the whole test scores and scores of only passages 1, 3, and 5, was nearly perfect, r (503) = .98, $p < .0001$. A nearly perfect correlation was also found between the whole test scores and scores for only passages 2, 4, and 6, r (503) = .97, $p <.0001$. In other words, there is no statistical difference or advantage to doing the longer version of the test with all six passages, rather than using only the scores from the shorter test with just three passages.

There were 8 or 9 sentences in each passage and each sentence had an average of 25 words in it. See Table 1 for details.

PASSAGE	SENTENCE	WORDS	LETTERS
1	1	29	165
1	2	41	226
1	3	21	125
1	4	16	98
1	5	24	160
1	6	40	240
1	7	23	143
1	8	18	130
1 Average		26.5	160.9
3	1	15	75
3	2	20	103
3	3	34	188
3	4	26	131
3	5	14	102
3	6	23	156
3	7	17	120
3	8	46	263
3 Average		24.4	142.3
5	1	16	94
5	2	15	90
5	3	15	100
5	4	19	121
5	5	35	216
5	6	13	69
5	7	43	302
5	8	23	143
5	9	27	174
5 Average		22.9	145.4
Overall Average		24.5	149.4

Table 1. Number of letters and words in each sentence of each passage used in the reading speed task.

Listening speed task. Auditory narratives collected from www.librivox.com were used in the listening speed task. Audio clips from a variety of audiobooks were used in the experiment (see Table 2 for details). A different male speaker narrated each audiobook.

Author of the text	Title of the text	Time (mins:secs)
First part of the experiment:		
Bill O'Reilly	The O'Reilly Factor	4:46
Charles Dickens	A Tale of Two Cities	2:14
Arthur Conan Doyle	A Study in Scarlet	4:54
Chris Anderson	Free: The Future of a Radical Price	4:59
Rafael Sabatini	Scaramouche	5:01
Second part of the experiment:		
Thomas Bullfinch	Bullfinch's Mythology	approx. 0:20 per clip
Joseph Devlin	How to Speak and Write Correctly	approx. 0:20 per clip
Franz Kafka	The Metaphorphosis	approx. 0:20 per clip
H.G. Wells	The War of the Worlds	approx. 0:20 per clip
Jonathan Swift	A Modest Proposal	approx. 0:20 per clip
Henry Thoreau	On the Duty of Civil Disobedience	approx. 0:20 per clip
Corey Doctorow	Down and Out in the Magical Kingdom	approx. 0:20 per clip

Table 2: Auditory books used in listening speed task.

Procedures

Reading speed task. In the current experiment, each participant saw three sets of passages and comprehension questions (1, 3, and 5). The passages were presented on a computer monitor one sentence at a time. Participants were instructed to read the sentence on the computer screen and then press the spacebar, which caused the current sentence to disappear and the next sentence to appear. They were encouraged to read through the sentences as quickly as possible but to make sure they fully understood each sentence before pressing the spacebar because they would be asked comprehension questions at the end of each passage. Four multiple-choice questions (with five answer choices) were given one at a time after each passage to ensure comprehension of the passages.

Participants were instructed to click on their answer choice using the mouse, and the next question with possible answers appeared. After 4 comprehension questions the next passage began.

Listening speed task. In the first part of the task, participants listened to passages of audiobooks that were sped up to 2.1 times normal speed. While they were listening, they pressed the computer up or down arrow keys to adjust the speed of the speech to try to get to the fastest speed they could understand. Each press of an arrow button decreased or increased the speed by 1%. Once participants felt they attained a speed in which it was as fast as they could hear but could still comprehend they clicked on a button on the screen with the computer mouse and moved on to the next passage. They followed this procedure for five different audio clips. The audio clips were on a continuous loop and did not stop until the participant chose to move on. The speed that was self-selected for these clips in the first part was considered their self-paced listening speed score and was used to calibrate the speed in which auditory clips were presented in the second part of the experiment.

In the second part of the experiment, participants listened to a number of short audio clips and answered a comprehension question after each clip. These audio clips started out at a rate of speed 10% higher than the average self-paced speed of the clips in the first part of the experiment and could not be slowed down, sped up, or repeated by the participants. Participants had to listen to the auditory clip and then answer a multiple-choice question about the information heard in the clip. This was to determine if comprehension of the audio clip at that particular speed was achieved. The last answer choice for each question was always *too fast to comprehend* and participants could choose this option rather than guessing at an answer if the clip was too fast for them to understand. If the comprehension question was answered correctly, the next audio clip was presented 1% faster. If it was answered incorrectly or *too fast to comprehend* was selected, the next clip was played 1% slower. When participants returned to the same speed three times (by answering correctly and speeding up, and then answering incorrectly and slowing down, two times from any speed), this was considered their measured listening speed score and no additional audio clips or questions were presented. If participants did not return to the same speed three times, the clips and questions continued until the questions ran out (35 questions in total) and that current speed was considered their best measured listening speed. This was done as a check that participants were setting their self-paced speed accurately.

Results

Listening speed measures

There were two scores for the listening speed task: the self-paced listening score from the first part of the task and the measured listening score from the second part of the task. The self-paced listening score was intended to be the dependent measure for listening speed. The measured listening score was done in order to check that participants were adjusting the self-paced scores accurately and not just selecting a fast speed even if they could not understand the speech at that speed. Participants had greater control over their self-paced scores as they were able to speed up or slow down the speech to the exact point they felt they could understand it. Therefore this is likely the most accurate listening score for each participant. The measured listening speed score was less controlled as it depended on a strict guideline for increasing or decreasing the speed of the speech based on answering multiple-choice questions, and therefore the self-paced was intended as the better dependent measure. A Pearson product-moment correlation was done to check for a relationship between the two listening speed scores. There was a strong positive correlation between the self-paced and measured listening speed scores, $r = .80$, $n = 206$, $p < .0001$, reinforcing that participants were accurate at finding their fastest self-paced listening speeds while still able to comprehend the rapid speech. This ensures that it is appropriate to use the self-paced listening score as the dependent measure for listening speed.

The listening scores were transformed to a negative scale by multiplying each score by -1, with smaller numbers indicating faster listening speeds. This was done in order to have the listening score follow the same direction as reaction times (RT) for the reading speed task, with smaller values indicating faster speed. The average [SD] self-paced listening score for all participants was -1.81 [0.19], and scores ranged from -2.14 to -1.13. The scores were standardized using a z-score calculation. These listening speed z-scores were used to compare with reading speed z-scores described below.

Reading speed measures

Reading speed was measured for each participant for how long it took to read each sentence in each passage. Smaller RTs indicate faster reading speeds. Reading accuracy of the comprehension questions was also recorded for each participant. Reading accuracy for all participants had an average of 73.5% correct and a SD of 14.9%. Participants scoring more than 2 SDs below average accuracy (< 43.7%) were not included in the analyses. This eliminated 13 out of an original 219 (6%) participants.

The overall average [SD] reading speed RT of each sentence for all participants was 7424 [2331] milliseconds (ms), and RTs for each sentence ranged from 1966 ms to 14235 ms. Each sentence had an average of 25 words; participants averaged 297 ms per word overall and ranged from 79 ms per word to 569 ms. The reading speed RT scores were standardized using a z-score calculation. In the analyses that follow, z-score RTs are used as the reading speed dependent measure.

Reading speed and listening speed

A Pearson product-moment correlation was computed to investigate the relationship between reading speed z-score RTs and self-paced listening speed z-scores. Reading speed was correlated with listening speed, $r = .23$, $n = 206$, $p < .001$. As predicted, participants who were faster readers were also able to listen to and comprehend faster speech (Figure 3).

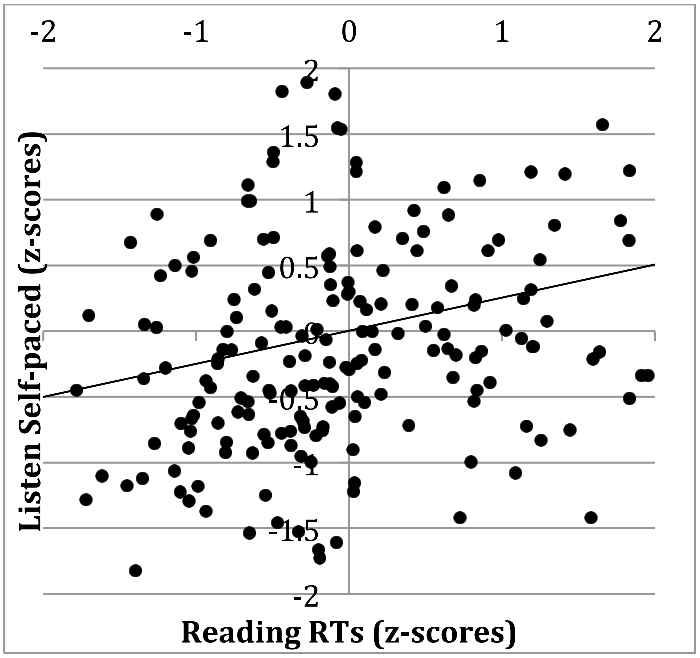

Figure 3: Scatterplot of reading RT z-scores and listening self paced z-scores.

Discussion

The results of the first experiment suggest that there is a significant relationship between reading speed z-scores and rate of listening z-scores. Faster readers are also able to listen to and comprehend faster rates of speech. This demonstrates a connection between these two modalities during language comprehension.

This connection may be due to the phonological processing that occurs during both reading and listening tasks. However, phonological processing in general can be divided into different and more specific aspects, such as phonological access, phonological recoding in lexical access, and phonological recoding in working memory, as demonstrated in Wagner and Torgesen's review (1987) mentioned earlier in Chapter 1. If these specific aspects of phonological processing exist, it may be possible for other aspects of phonological processing to exist as well such as visual phonological processing, auditory phonological processing, and phonological processing that is specifically shared between the auditory and visual modalities.

I propose that the difference between reading and listening to speech, once you take away the phonological processing specific to a single modality, is the phonological processing that is shared between both modalities (Figure 4).

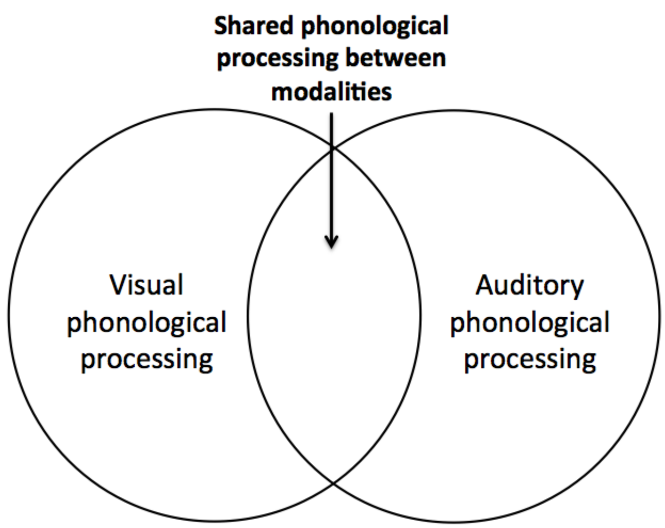

Figure 4. Shared processing between visual and auditory phonology.

This shared phonological processing can be measured by taking the difference between a participant's reading RT z-score and his/her listen-self-paced z-score. This *reading-listening-difference* (RLD) score should indicate how efficiently one processes language across both modalities. A small RLD score indicates that there is a smaller difference between the participant's average reading speed z-score and listening speed z-score (Figure 5). A large RLD score shows that there is a greater distance between the participant's average reading speed and listening speed z-score (Figure 6). Small RLD scores (less distance between modalities) indicate that the participant is quite skilled and efficient in using phonological processing between both modalities to arrive at a phonological representation, whereas participants with large RLD scores (more distance between modalities) are less skilled or not able to use any shared phonological processing between modalities.

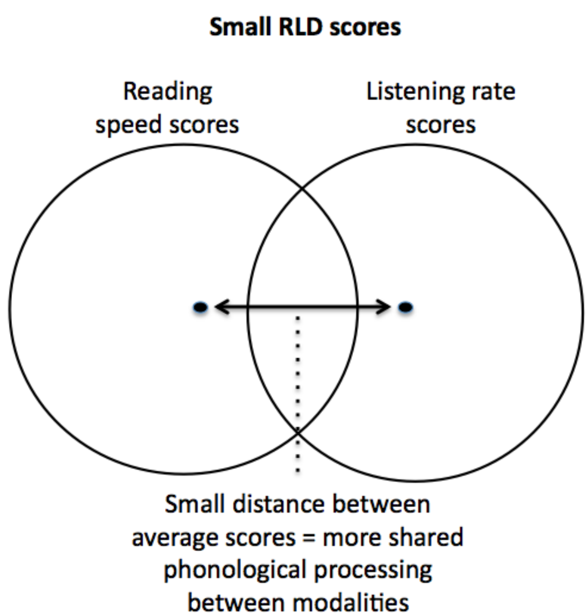

Figure 5. Small RLD scores indicate less distance between reading and listening scores, and more shared phonological processing.

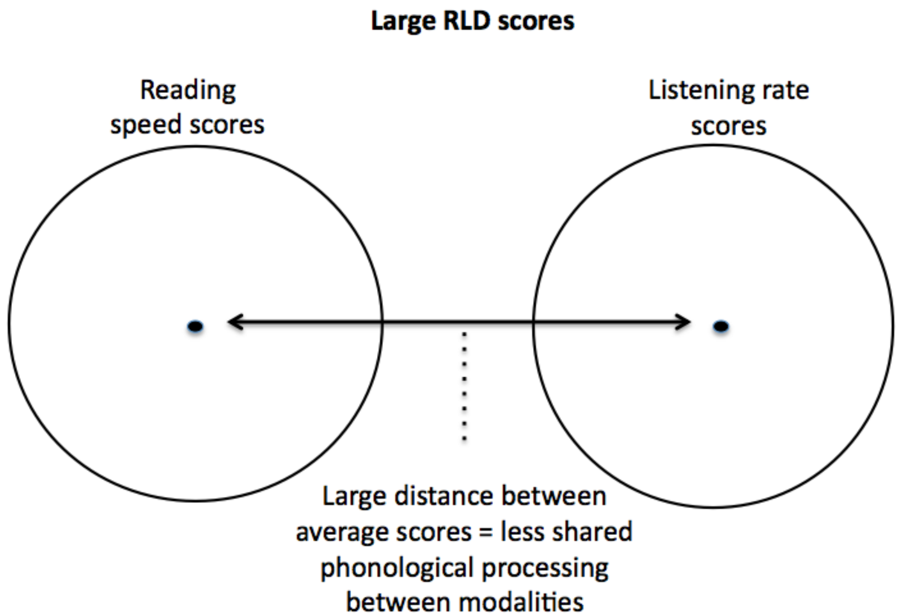

Figure 6. Large RLD scores indicate more distance between reading and listening scores, and less shared phonological processing.

The results from the experiment in Chapter 2 support the hypothesis that reading speed and listening speed are related. Correlational evidence shows that reading speed and listening speed are positively correlated; faster readers are also able to listen to and comprehend faster speech and vice versa. I propose that this correlation is due to shared phonological processing between auditory and visual modalities.

However, one cannot make this claim based on only one correlation. The purpose of this dissertation is to investigate and establish the association between visual phonological processing and auditory phonological processing. The correlation between reading speed z-scores and listening speed z-scores in this chapter is a successful first step in accomplishing this goal, however, further evidence is needed to strengthen this proposed idea. If this correlation exists because of the association between visual and auditory phonological processing, and shared phonological processing between the two modalities allows for better efficiency of language processing, then one should be able to see this efficiency with various language tasks as well.

Shared phonological processing efficiency can be represented by measuring the difference between the reading speed and listening speed z-scores resulting in a RLD score for each participant. Participants with smaller RLD scores have less of a difference between their listening and reading scores, for example, slow readers would also need speech to be slower in order to comprehend it, and fast readers would also be able to understand faster speech. Participants who have larger RLD scores have larger differences between reading and listening skills. They might be very fast readers but not skilled at listening to fast speech and vice versa. This would indicate that they are not able to use phonological information that is shared between modalities very efficiently. Therefore large RLD scores indicate poor efficiency of phonological processing between modalities, and small RLD scores indicate more efficient use of shared phonology between the visual and auditory modality.

Although previous studies have made the assumption that auditory and visual phonological processing are interrelated processes, none have explicitly tested this with respect to reading and listening speed tasks. This study is the first to provide explicit evidence of this relationship, and one of a few studies to investigate phonological processing efficiency involving reading ability in an adult population. The correlation between reading speed z-scores and listening speed z-scores establishes this relationship and allows a new measure to be created: RLD scores. I propose that RLD scores measure the shared phonological processing between the visual and auditory modalities. Smaller RLD scores indicate better efficiency of shared phonological processing which should also aid in better processing of phonological language tasks. This is further investigated in the next chapter.

Chapter 3

The RLD effect and stages of processing

A number of studies (see Chapter 1 for review) have indicated that reading skill, auditory abilities, and phonological processing abilities are associated in different ways. However, no studies have specifically tested the relationship between reading speed skill and listening speed skill. This relationship was tested in the previous chapter, finding a positive correlation: fast readers are also able to listen to fast speech, whereas slow readers need slower speech for comprehension. I propose that this is a result of shared phonological processing between modalities, which could be measured by RLD scores. Small RLD scores (less difference between reading speed z-scores and listening speed z-scores) indicate better efficiency by shared phonological processing. Large RLD scores (larger differences between modalities) indicate less efficient use of shared phonological processing. If this proposed idea is correct, RLD scores should also be associated with efficient processing of phonological language tasks. The goal of this chapter is to test the hypothesis that RLD scores will be related to scores on language tasks that focus on early phonological processing, but not on language tasks that focus on later semantic processing.

The early stage of language processing starts with phonological processing. Phonological processing consists of identifying sublexical items (such as individual phonemes of individual letters) and/or lexical items (whole words) (Coltheart, 1978; Coltheart et al., 1993; Coltheart et al., 2001). Once the word is identified through phonological processes, semantic processing occurs to access information about the meaning of the identified word. Therefore, language tasks that allow for very quick responses are thought to be able to access early phonological stages. Tasks that need judgments based on interpreting meaning, will have already passed through the phonological processing stage in order to first identify the word and are into later stages of semantic processing when a response is made.

Tasks that involve early phonological processing that are used in the study in this chapter include a syllable judgment task, lexical decision tasks in both visual and auditory modalities, and a rhyme judgment task. The task in this study that is used to capture the later language processing of semantics is the auditory synonym judgment task (ASJ). More details on each of these tasks follow.

The syllable judgment task is used to test phonological processing ability. It requires participants to assess the number of syllables in the stimuli presented. The stimuli are made up of words and non-words, and are controlled on word length so that participants cannot simply assume that longer looking words have more syllables. This method requires phonological processing rather than visual orthographic processing.

Lexical decision tasks are commonly used in many psycholinguistic studies. In this task, participants are presented with a word or non-word and must quickly decide if it is a word or not. This task tests the ability to access the lexical representation of a word and can be used in both the visual and auditory modality. Although semantic effects have often been shown in lexical decision, many previous studies have used lexical decision tasks to investigate phonological processing in the visual modality (for example Coltheart et al., 2001), auditory modality (for example Ziegler, Muneaux, & Grainger, 2003), or both (Westbury & Moroschan, 2009).

The rhyme judgment task requires participants to see a word or non-word on the computer monitor and then decide which of two choices, also presented on the screen, rhyme with the target. The rhyme judgment task from the Alberta Language Function Assessment Battery (ALFAB) (Westbury, 2006a, 2006b, 2010) is unique in that it presents stimuli that match orthographically but not phonetically (ex. Does *danger* rhyme with *hanger* or *ranger*?) or match phonetically but not orthographically (ex. Does *watch* rhyme with *each* or *scotch*?). This ensures that participants must use phonological coding rather than just visual letter matching in order to successfully complete the task.

The ASJ task was originally created in the ALFAB to test access to semantics, specifically the meanings of concrete and abstract words. The participant hears a word and is asked to choose which of two words is closest in meaning. Both phonological and semantic foils are used in the experiment and the stimuli consist of concrete and abstract words. The ASJ task allows one to test if there is a difference between the processing of phonological and semantic foils, and also tests to see if there is a difference between processing the meaning of concrete and abstract words. This task requires semantic processing of word meaning in order to arrive at a correct answer, therefore, this task was used in the present study as a way of testing overall semantic processing ability.

Methods

Participants

The participants in this study were a subset of the participants described in Chapter 2. There were 107 participants to start in this group. In order to be included for the analyses in this study, participants had to be within 2 SD of the average accuracy and latency for *each* task in this study. This eliminated 13 participants (12%) leaving 94 participants in the study. The average age [SD] for this group was 19 [1.7] and there were 57 females and 37 males.

Stimuli

Reading speed and listening speed tasks. The stimuli in the reading and listening speed tasks were exactly the same as described in Chapter 2.

Syllable judgment task. The stimuli in the syllable judgment task consisted of 36 words and 36 pronouncable non-words for a total of 72 trials. The stimuli were controlled for length (4, 5, 6, 7, 8, or 9 letters) and number of syllables (1, 2, or 3), therefore it was not the case that longer words necessarily had more syllables and vice versa.

ALFAB tasks. The visual lexical decision (VLD), auditory lexical decision (ALD), rhyme judgment, and ASJ tasks were taken from the ALFAB (Westbury, 2006a, 2006b, 2010). The ALFAB was created to test many aspects of language ability in aphasic individuals (those having language deficits due to stroke or brain injury) and has also been normed on a large number of non-braininjured individuals matched on age. These tasks were chosen from the ALFAB in order to test language abilities of the participants of this study. The ALFAB tasks and all other tasks in this dissertation were run on custom built software called ACTUATE (Assessing Cases: The University of Alberta Testing Environment) (Westbury, 2007). ACTUATE is a flexible and fully customizable data-gathering environment that can deliver a range of stimulus types and take a range of millisecond-accurate timed responses.

VLD task. There were 40 words and 40 non-words used in the VLD task to create 80 trials. However, only reaction times for correct responses to words were used in the analyses. All the words were low frequency (0-15 number of occurrences per million words of text) and were controlled for phonological neighborhood size (high and low), length (short and long), concreteness (abstract and concrete words), and regularity (regular and irregular words). These distinctions are already built into the task from the ALFAB, although for this study, only the latency of correct words is used in the analyses.

ALD task. Just as in the VLD, 40 words and 40 non-words were used in the ALD task to create 80 trials, with only the correct responses to words used in the analysis. The ALD task also used low frequency (0-14 per million) words that were controlled for phonological neighborhood size, length, regularity, and concreteness. As above, only the reaction times for correct words are used in the analyses and no additional analyses were done with other factors such as concreteness since that is not the focus of the current study.

Rhyme judgment task. The rhyme judgment task consisted of 40 trials, with 20 words and 20 non-words. The foils were either orthographically matched or unmatched with the target, and also either orthographically matched or unmatched with each other. Only correct responses were included in the analysis.

ASJ task. The stimuli for the ASJ task consisted of all words and had 40 trials. These consisted of semantically related foils and phonologically related foils to a given target.

Procedures

Reading and listening speed tasks. The procedures for the reading and listening speed tasks were the same as described earlier in Chapter 2. RLD scores were calculated for each participant using their z-scores on the reading and listening tasks. These RLD scores were used as the dependent measure for shared phonological processing between modalities in the analyses that follow.

Syllable judgment task. Participants saw a word or non-word on the computer screen and then saw a number on the screen. They had to decide if the number matched the number of syllables in the presented stimulus. If it did, they were instructed to press the *c* key for *correct*, and if not, to press the *x* key for *incorrect*. They were instructed to go as quickly as possible and RTs and accuracy scores were recorded.

VLD task. Participants saw a string of letters presented on a computer screen and had to decide if it formed a real word or not, as quickly as possible. If it was a real word, they were instructed to press the *c* key on the keyboard for *correct*, if it was not a real word they were instructed to press the *x* key for *incorrect*. RT was recorded for each response, from the time the stimulus appeared on the screen until the time the button was pressed by the participant.

ALD task. The procedures for the ALD task were the same as those described above for the VLD task, with a minor alteration for the auditory procedure of listening to the spoken stimuli through headphones instead of viewing visual stimuli on the computer screen. Reaction times were recorded from the onset of the presentation of the auditory word until a button was pressed by the participant to indicate the response.

Rhyme judgment task. Participants saw a target word or non-word and were visually given two stimulus choices. They had to decide which of the choices rhymed with the target.

ASJ task. This task required participants to listen to a word and think about its semantic properties in order to compare its similarity to other words. In this way, this task goes through a deeper level of semantic processing that determines the meaning of the word, than LD tasks that require lexical access and only enough semantic processing to determine that the stimuli is a word or not, but not full meaning. Participants heard a word presented through headphones. After the initial word was given, they were asked if it means the same as word choice 1 or word choice 2. If they thought it meant the same as the first word choice they heard they pressed the *x* key (because it is the first key when reading left to right on the keyboard), and if they chose the second word they heard to be the synonym they pressed the *c* key (because it is the second key in the sequence when reading left to right on the keyboard).

Results

Analyses were done using linear mixed effects (LME) models (Baayen, 2008; Baayen, Davidson, & Bates, 2008). Using LME provides a way to account for the variability due to different subjects and different items by treating these as random effects and treating the different variables as fixed effects. Subjects and items should be treated as random effects because they are randomly sampled from populations of people and words. Variables tested with the different tasks are treated as fixed effects because they are not randomly sampled but specifically chosen. LME, or linear mixed effects, models provides a statistical analyses that includes both random and fixed effects. This was done for the RLD scores in each experiment; each trial for each subject was included in the analysis, and subjects and items were entered as random effects with the task variable entered as a fixed effect. RLD scores and the scores for the specific task being studied were entered into each LME model. The LME analysis provides a t-value for the fixed effect in each model. P-values given for each t-value were calculated using a Monte Carlo Markov chain (MCMC) procedure (Baayen et al., 2008).

Syllable judgment. As predicted, LME analysis showed that RLD scores compared to syllable judgment RTs on correct responses were significant, $t = 3.07$, $p < .002$. As RLD scores get larger (less efficient processing), RTs on the syllable judgment task get longer (see Figure 7).

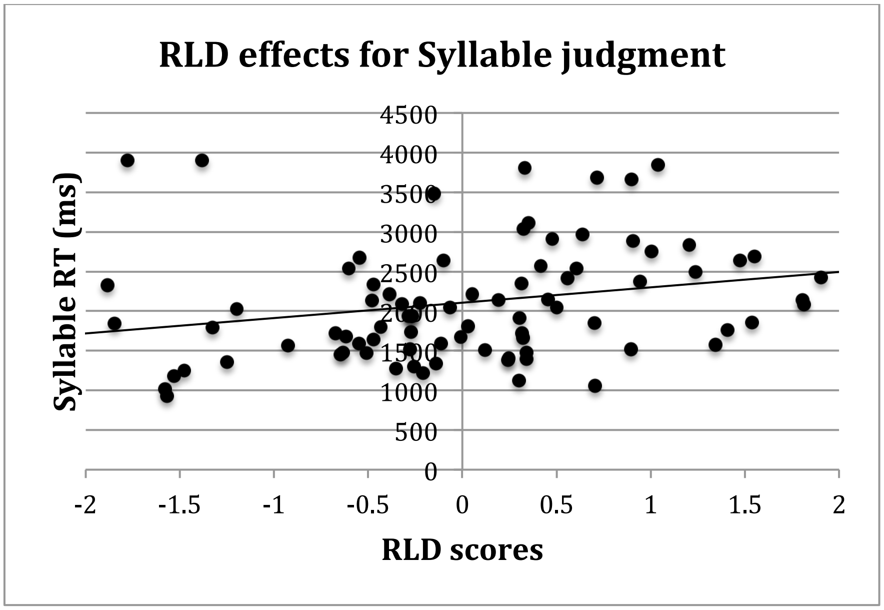

Figure 7. RLD scores with syllable judgment RTs.

VLD task. The VLD RT scores for correct words were entered as fixed effects in the model. LME analysis showed a significant fixed effect for RLD scores with VLD scores of correct words, $t = 3.11$, $p < .002$, demonstrating that as VLD RTs for correct words get longer, RLD scores get larger (see Figure 8).

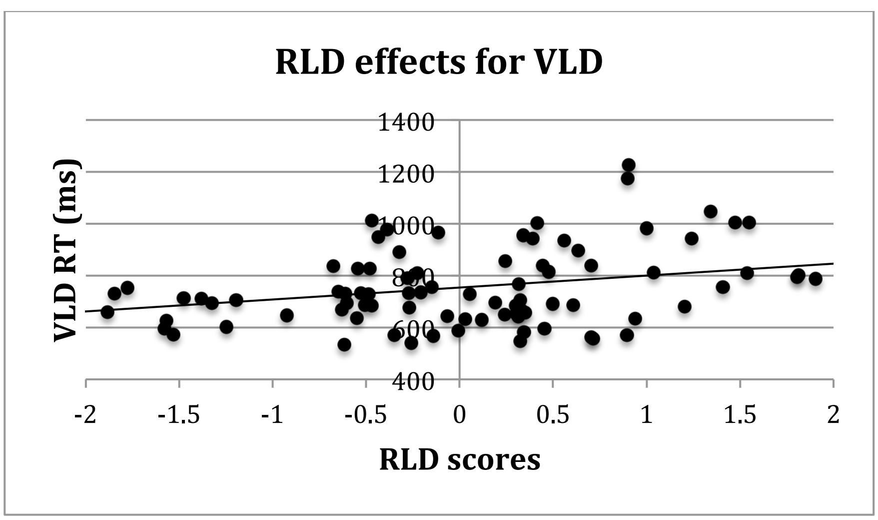

Figure 8. RLD scores with VLD RTs.

ALD task. The LME model for ALD consisted of RLD scores entered as random effects and ALD RT scores for correct words entered as fixed effects. As expected, and just like results from the VLD task, LME analysis showed that RLD scores and ALD RTs for correct words were significantly related, $t = 2.3$, $p < .02$. RLD scores increased as ALD RTs increased.

Rhyme judgment task. Unexpectedly, the results for the rhyme judgment task did not show a significant relationship between rhyme judgment RTs and RLD scores, $t = 1.04$, $p < .01$. Further analyses were carried out by splitting the RLD scores into two equal groups, those with small RLD scores and those with large RLD scores, in an effort to see if the effect was with the small RLD group who are more efficient at shared phonological processing and not with the large RLD group who are less efficient. A t-test showed that average RTs for choosing correct words in the rhyme judgment task were significantly different between small (M = 1513 ms) and large (M = 1759 ms) RLD groups, $t = -7.12$, $p < .001$, however there was no significant relationship between rhyme judgment RTs and RLD scores in the large RLD score group, $t = 0.21$, $p > .84$, or the small RLD score group, $t = -0.68$, $p > .5$. Analyses were also done on rhyme judgment RTs for foils matched on orthography and foils unmatched on orthography with the large RLD score group and the small RLD score group but there was no significant relationship found with either group in either category (large RLD group: $t = -0.04$, $p > .78$ and $t = 0.46$, $p > .78$, respectively; small RLD group: $t = -0.72$, $p > .57$ and $t = -0.65$, $p > .57$ respectively).

ASJ task. The ASJ RT scores were entered as fixed effects in the LME model with RLD scores as random effects. The analysis did not show a significant fixed effect for RLD scores with ASJ scores, $t = 0.44$, $p > .7$, demonstrating that RLD scores are not significantly related to ASJ RTs. Further analysis was done to see if there was a difference between large and small RLD score groups with ASJ RTs. A two sample t-test revealed there was no significant difference of ASJ RTs between small and large RLD score groups, $t = -1.1$, $p > .27$.

Additional analyses on age, gender, and education

Additional LME analyses were done to check for effects of age, gender, and years of education, with RLD scores for all participants reported in this dissertation (n=206). The average [SD] age was 19 [1.9] and ranged from 17 to 30. There were 79 males and 127 females. Years of education were considered to be the total number of years in elementary, secondary, and post-secondary education combined for each participant. This ranged from 12 to 18 years with an average [SD] of 13.7 [1.1] years. None of these analyses were significant (age: $t = 0.86$, $p > .39$, gender: $t = -0.79$, $p > .43$, education: $t = 0.61$, $p > .54$).

Discussion

As predicted, RLD scores were significantly related to scores on early phonological processing tasks such as syllable judgment, VLD, and ALD. This fits with the proposal that RLD scores measure shared phonological processing between modalities and should be associated with other language processing tasks that measure phonological processing.

These results that demonstrate an association between RLD scores and scores on phonological processing tasks fit with models of reading that show phonology occurring in the early stages of processing and semantics occurring at later stages. RLD scores measure efficiency with phonological processing and are significantly associated with other tasks that demonstrate phonological processing in the early stages of reading as well.

Also predicted was that RLD scores were not significant with the semantic processing ASJ task. The ASJ task is used to access semantic processing. This semantic processing happens after phonological processing has already occurred and lexical access is achieved. Since RLD scores reflect the shared phonological processing between modalities, these scores should only be significantly associated with tasks that access early phonological processing stages and not associated with tasks that access later stages of semantic processing. The results of the ASJ analysis with RLD scores agree with this proposed idea. ASJ RTs were not significantly associated with RLD scores. Another analysis was done to make sure there was no difference in ASJ RTs between more or less efficient groups of processors. Participants with small RLD scores should be more efficient at using shared phonological processing between modalities than participants with large RLD scores. There was no difference between large and small RLD groups and ASJ RTs, following the prediction that there is no significant association between RLD scores and latency scores on the semantic task of ASJ.

One unexpected result was that rhyme judgment scores were not significantly related to RLD scores. Rhyme judgment should have to rely on phonological information to decide if one stimulus rhymes with another stimulus so the prediction was that rhyme judgment scores would be related to RLD scores overall, or at the very least, be related specifically to small RLD scores. However RLD scores were not significantly related to rhyme judgment scores overall or when analyzed within large or small RLD score groups.

One possible complication is that foils were used in the rhyme judgment task that matched orthographically but not phonologically, in order to prevent participants from just visually matching the orthography to quickly get the answer: for example *Which rhymes with 'halves'? 'valves' or 'calves'?.* This orthographic interference may go against the facilitation provided by shared phonological processing between modalities. It is possible there was enough interference of orthographic and phonological mismatches in this task that it cancelled out any facilitation provided by the efficiency of the RLD effect. The rhyme judgment task RTs were divided by foil type, matched orthographically or unmatched orthographically and analyzed with small and large RLD score groups as well, but none of the analyses were significant. It is possible that the rhyme judgment task was too complex since it involved the processing of two stimuli at the same time in order to find a rhyme match to the target. Future experiments might be successful with a more simplified rhyme judgment task similar to a lexical decision type task that only requires a response to one stimuli at a time and asks if it rhymes with a given target, requiring only a yes or no answer. This would eliminate the need for foils and may reduce interference and confounding information during processing.

Additional analyses done on age, gender, and years of education demonstrated no significant associations with RLD scores.

No studies prior to this have investigated the relationship between reading and listening skills or shared phonology between modalities, but many studies have looked at reading ability in relation to phonological processing. As mentioned earlier, a great deal of the previous work done on reading ability has focused on children's phonological processing during the period of reading acquisition (see review by Wagner & Torgesen, 1987). Studies that have been done only with children provide limited information on reading ability and other possible factors that may contribute to it during a particular stage in life. Children may acquire reading and language skills at different rates, so testing during a period of reading acquisition may lead to quite variable results. For example, in regards to language acquisition boys are typically slower in phonological development than girls of the same age. However, if tested at a later time when the phonological system is mastered, no gender differences are displayed (see review by Klann-Delius, 1981). In this same way, reading skills may be greatly improved by the time of adulthood after phonological skills have been fully mastered. This is in line with the evidence that no gender differences were found in the current study for reading speed and listening speed z-scores. It is important to know if auditory phonological processing interacts with reading even after reading acquisition is attained and well practiced, and not just influential during the process of acquisition during childhood. The results of the present study give evidence that reading speed is correlated with listening speed and can be represented as a RLD score. This study done with adults demonstrates that visual and auditory processing of language has a relationship that lasts beyond the stage of acquisition; something that we would not know by just relying on previous work done with children alone.

The goal of Chapter 3 was to add support to the proposal that reading and listening are associated tasks that share phonological processing between the visual and auditory modalities. This support is found in the results that RLD scores, being a proxy for shared phonological processing efficiency between modalities, is significantly related to scores on other tasks that access phonological processing but not on a semantic processing task. Most of these results are in line with this proposed research idea, however it was expected that the results of the rhyme judgment task, thought to be a phonological task, would also be significantly related to RLD scores but it was not. In hindsight, the way this task was conducted may have been too complex to provide results that were not confounded by other factors such as accessing multiple lexical entries at a time in order to make a response. Overall the majority of results in this chapter support the main research idea of shared phonological processing between the visual and auditory modality, and demonstrate that this shared processing happens during the early stages of phonological processing rather than the later stages of semantic processing. Now that it has been shown that the RLD effect occurs during phonological processing, the next inquiry is which route in phonological processing does the RLD effect take?

Chapter 4

The RLD effect and different phonological routes

The studies presented so far in this dissertation have established that there in an association between visual phonological processing during reading and auditory phonological processing during listening. This relationship can be measured using RLD scores, which are significantly related to scores on language tasks that access phonological processing. Now deeper analyses needs to done in order to find out which route or pathway do RLD scores represent with regards to phonological processing and theoretical models that attempt to explain reading.

Phonological processing during reading is described in different theoretical models. One well-known model of reading is the DRC (Coltheart et al., 2001). This model uses two routes for processing linguistic stimuli when it is encountered during reading. One route is the sublexical grapheme to phoneme conversion (GPC) rules route. When a word is encountered, the GPC rules are used to match individual letters or *graphemes* to their matching linguistic sounds or *phonemes*. These are blended together to sound out the word. This explains the processing of regular words that have consistent matching of graphemes to phonemes, but it does not explain the processing of irregular words that have inconsistent spellings. The processing of these *exception* words is explained through the other route: the lexical whole word route. In this route words are learned and processed as a whole word and accessed as one lexical unit rather than sublexical pieces that can be blended together through GPC rules. In the

DRC model, both routes are available and can run simultaneously; the route that arrives at the answer first wins. The DRC model explains acquisition of reading in the following way. When children are learning to read they start by primarily using the sublexical route and GPC rules to sound words out. Regular words can be learned in this way of putting pieces together, and once the words are learned and if they are encountered often (high frequency words) they can be remembered and accessed as one unit through the whole word route. Irregular words, on the other hand, always have to use the whole word route as GPC rules will not work to sound out these words correctly. Nonwords or new words that have not been encountered previously always need to use the sublexical GPC rules route as there is no way the word could have been learned as a whole unit previously.

Since nonwords always have to be processed through the sublexical GPC route and other previously acquired words likely use the whole word route, we can compare the results of words and nonwords in psycholinguistic tasks such as VLD, ALD, and syllable judgment to see which route the RLD effect that was demonstrated in previous chapters occurs in. We know from the study in the previous chapter that RLD effects were found for words in the VLD, ALD, and syllable judgment task, but the analyses in the previous study did not investigate if there were RLD effects with nonwords in these tasks as well. If there are RLD effects with words *and* nonwords, then the RLD effect could occur through either route. If the RLD effect is found with words but *not* nonwords then the effect must occur through the whole word route and not use GPC rules.

I propose that RLD effects should use the whole word route rather than the sublexical GPC rules route. The RLD effect represents the shared phonological processing between the auditory and visual modalities. The results from the study in Chapter 3 show that the effect is found with visual tasks such as VLD and syllable judgment, and the auditory task of ALD. Stimuli from the auditory task must be processed through the whole word route because participants only heard each word or nonword and did not see the word on the screen. Therefore auditory words cannot be processed by using GPC rules on pieces of the word, but only as they are heard, in single whole units. Since the RLD effect is significantly related to scores on the ALD task, this would indicate that RLD effects must occur through the whole word pathway. Therefore the prediction for the next study is that that RLD effects will be found with processing of words (that can use the lexical whole word route) but not for the processing of nonwords (that must use the sublexical GPC rules route).

RLD effects: Words versus nonwords

Methods

Participants

There were 94 individuals who participated in all three tasks that compare word processing to nonword processing: VLD, ALD, and syllable judgment. These are the same group of participants who took part in the study in Chapter 3. The average age [SD] for this group was 19 [1.7] and there were 57 females and

37 males. Participants were right-handed University of Alberta students who knew English as a native language.

Stimuli

Reading and listening tasks. The stimuli for the reading speed and listening speed tasks were the same as previously described in Chapter 2.

VLD, ALD, and syllable judgment tasks. The stimuli for the VLD, ALD, and syllable judgment tasks were the same as previously described in Chapter 3.

Procedures

Reading and listening tasks. The procedures for the reading speed and listening speed tasks were the same as previously described in Chapter 2.

VLD, ALD, and syllable judgment tasks. The procedures for the VLD, ALD, and syllable judgment tasks were the same as previously described in Chapter 3.

Results

Analyses were done using LME regression models (Baayen, 2008). Variability due to subjects and items was accounted for in the RLD scores by listing every trial for every subject in the task. The variables in the VLD, ALD, and syllable judgment task were analyzed using an average score (correct trials only) for each subject. All p-values given were calculated using a MCMC procedure (Baayen et al., 2008). RLD scores were calculated for each participant by finding the difference between his/her reading speed z-score and listening speed z-score.

VLD task. As predicted, LME analyses revealed a significant relationship between RLD scores and VLD RT scores on correct words (as RLD scores get larger, VLD RTs get longer), $t = 3.11$, $p < .02$, but not for VLD RT scores on correct nonwords, $t = 1.71$, $p > .09$.

ALD task. Similar to the results for VLD, ALD RT scores for correct words were significantly longer as RLD scores were larger, $t = 2.3$, $p < .02$, but not a significant result for ALD RT scores for correct nonwords, $t = 0.689$, $p > .5$.

Syllable judgment task. The results of the syllable judgment task also follows the results of the VLD and ALD tasks when comparing words to nonwords. A significant result was found when comparing RLD scores to syllable judgment RTs for correct words, $t = 2.43$, $p < .01$, but not when comparing RLD scores to syllable judgment RTs for correct nonwords, $t = 1.08$, $p < .28$. Syllable judgment RTs were longer when RLD scores were larger.

Discussion

As predicted, the results showed that RLD effects were significant with words, but not with nonwords, in the VLD, ALD, and syllable judgment tasks. As RLD scores were larger (less efficient processing), the RTs for correct words in these tasks were longer but there was no relationship on the RTs for correct nonwords in these tasks. These results can be explained using the DRC model through the whole word lexical route. According to the DRC model, words can be processed through the GPC route or the whole word route depending on what level of processing is needed (sub-lexical processing of individual phonemes in the GPC route, or lexical processing in the whole word route). However, nonwords must use the GPC route because they do not have a lexical entry to match to in the whole word route. Because there were no significant effects of RLD scores with nonwords, the effect is not occurring through the GPC route and must only happen with whole word access.

One problem with this interpretation however, is that the DRC model is a model of reading and is not really intended to explain non-visual processing tasks such as ALD. This is a dilemma in that there is no proposed model for shared phonological processing between modalities and the association of reading and listening. However, these RLD effects might be better explained using a different model such as Seidenberg and McClelland's (1989) PDP model.

The connectionist PDP model consists of three types of units: orthographic units, phonological units, and semantic units. The routes between these three types of units are bi-directional, meaning that information can feedback or feed-forward between the units. The proposed idea of shared phonological processing between modalities could be represented in the PDP model as bi-directional processing between visual phonological processing and auditory phonological processing. What I specify as visual phonological processing in this dissertation refers to the phonological processing that occurs during reading. In the PDP model, this processing could be represented by orthographic units, phonological units, and the bi-directional pathways between them. Auditory phonological processing in this dissertation refers to the processing that occurs during listening to speech, and could be represented by the phonological units in the PDP model. Since there is not a current model that describes both reading processes and listening processes for linguistic stimuli, the next best thing might be to modify or incorporate this information into an existing model. The PDP model may be able to explain RLD effects if it was extended to be a model of listening as well as reading. If this were the case, RLD effects would relate to the efficiency of processing between the orthographic and phonological units in the PDP model. I propose that individuals with small RLD scores are more efficient with phonology between reading and listening, and this efficiency could be represented in greater bi-directional processing between orthographic and phonological units in the PDP model.

Other studies have described efficiency between these units of the PDP model in terms of more or less skilled readers (Seidenberg & McClelland, 1989; Strain & Herdman, 1999; Unsworth & Pexman, 2003). The individual differences between reading skill described in these studies could be similar to the individual differences found in RLD efficiency in this dissertation. A study by Unsworth and Pexman (2003) used VLD to look at how reader skill influences phonological processing. They found a main effect of *reader skill level*: more skilled readers responded faster than less skilled readers. They did not find a main effect of regularity, but using planned comparisons they did find that the less skilled readers had slower response times for exception words than for regular words.

These same results are predicted for the current study using RLD scores, rather than the reading scores used by Unsworth and Pexman. Participants with larger RLD scores are not as efficient in using the shared phonological processing between modalities and therefore may be more hindered when encountering exception words that do not follow the grapheme to phoneme rules that regular words do. Therefore the prediction for the next study in this chapter is that a regularity effect will be seen with participants who have large RLD scores but not for participants who have small RLD scores.

RLD effects: Irregular words versus regular words

Methods

Participants

There were 150 participants who undertook the VLD task that measured regularity effects. These participants were a subset of the 206 participants described in Chapter 2. To be included in the analyses each participant had to be within 2 SD for average accuracy and latency scores in the VLD task. This eliminated 6 participants (4%) and resulted in 144 participants included in the analyses for this study. Each participant had learned English as a native language and was right handed. The average [SD] age of the participants was 19.2[1.8] and ranged from 17 to 27. There were 54 males and 90 females.

Stimuli

Reading and listening tasks. The stimuli for the reading speed and listening speed tasks were the same as previously described in Chapter 2.

VLD task. The stimuli for the VLD task were the same as previously described in Chapter 3.

Procedures

Reading and listening tasks. The procedures for the reading speed and listening speed tasks were the same as previously described in Chapter 2.

VLD task. The procedures for the VLD task were the same as previously described in Chapter 3.

Results

RLD score groups. RLD scores for 144 subjects were divided into two equal groups of small RLD scores (ranging from -4.32 to 0.11) and large RLD scores (ranging from 0.12 to 4.22). Each group had 45 females and 27 males with an average [SD] age of 19 [1.8].

VLD task. The results of the VLD task on these participants show a significant difference in VLD latency between large RLD and small RLD score groups, $t(142) = -2.39$, $p < .02$. Participants with small RLD scores responded faster than participants with large RLD scores (728 ms compared to 821 ms on average, respectively). There was no overall effect of regularity (regular words faster on average than irregular words) in the VLD task, $t(142) = -1.1$, $p > .2$, but as predicted and similar to what Unsworth and Pexman (2003) found with reading skill, there was a regularity effect with participants who had larger RLD scores (less skilled at efficient phonological processing), $t(71) = 2.6$, $p < .01$, but no effect for the group with small RLD scores (more efficient at processing), $t(71) = 1$, $p > .33$. The large RLD group had an average [SD] RT of 845 [241] ms for irregular words compared to an average [SD] RT of 796 [204] ms for regular words. The small RLD group had an average [SD] RT of 736 [187] ms for irregular words and an average [SD] RT of 719 [156] ms for regular words.

Discussion

The results of this study were as predicted. A regularity effect was found with individuals who had large RLD scores but not with individuals who had small RLD scores. Large RLD scores indicate a larger difference between reading scores and listening scores, and therefore a less efficient use of the shared phonological processing between modalities. Small RLD scores demonstrate less of a difference between reading and listening scores and indicate that phonological processing between the two modalities is used, resulting in greater efficiency. This is comparable with Unsworth and Pexman's (2003) study that found similar results using VLD and reading skill scores. They attributed slower reaction times on exception words for less skilled readers to having less efficient mappings between orthographic and phonological units in the PDP model (Unsworth & Pexman, 2003).

The results of the current investigation can also fit with the PDP model in a similar way. Slower times for irregular words for individuals with large RLD scores indicate less efficiency of the use of shared processing between reading and listening.

Chapter 5

The RLD effect and auditory non-linguistic processing

Now that the relationship between reading and listening has been established and an effect has been found between RLD scores and phonological linguistic tasks, it is necessary to rule out any confounding factors that may have contributed to the results. One such confounding variable is general auditory processing skill. In other words, the RLD effect could be related to general *non-linguistic* auditory processing skills rather than auditory phonological processing skills that are specific to language. The goal of Chapter 5 is to rule out this possibility. Results from earlier chapters reveal that RDL scores are significantly related to auditory phonological tasks such as ALD. The hypothesis for the next study is that RLD scores will not be significant with auditory non-linguistic task scores such as tone discrimination, formant discrimination, and gap detection.

Many previous studies have investigated auditory processing and reading using non-linguistic auditory stimuli with children, especially those with reading disabilities or SLI (see for example, McArthur & Hogben, 2001; Stark & Tallal, 1979; Stark & Tallal, 1988; Stark & Tallal, 1988; Talcott et al., 1999; Tallal et al., 1993). A variety of mixed results are demonstrated in these studies that may be due to many different factors (see Chapter 1 for review of this literature).

The basis of research for this chapter is to show that the relationship between visual phonological processing as demonstrated in reading skill and auditory phonological processing as demonstrated in listening skill is not due to general auditory processing skills. Since this is the first study to make this kind of comparison there are no previous studies to compare to. However there are many studies that have investigated the relationship between reading skill and auditory non-linguistic tasks and one would think the present study that uses reading speed to calculate RLD scores might have similar results with these same auditory non-linguistic tasks. The problem is that there are mixed results in the prior studies. Some studies with children have found a significant relationship between reading ability and auditory non-linguistic processing tasks (see for example Stark & Tallal, 1988; Tallal, 1980; Tallal et al., 1997), while others have found no significant relationship (for example Marshall et al., 2001). The effects that have been found with children may not be found with an adult population due to the fact that reading has already been mastered and non-linguistic auditory processing may no longer be an essential component for reading as it was during reading acquisition.

Only one study has attempted to test for a relationship between auditory non-linguistic processing and reading skills in adults. Ahissar et al.(2000) recruited adult participants who were self-reported as having a childhood reading disability (CHRD) and tested them on a number of reading, auditory and cognitive intelligence tasks. Using a specialized sample of adults who have a history of CHRD however, can not compare to a normal random sample of adult readers, many of whom may not have ever had a reading disability. We know that reading disabilities in childhood can impose on acquiring efficient phonological processing skills (Talcott et al., 1999; Tallal, 1980; Tallal et al., 1997), so normal phonological skills in adulthood for these individuals may be difficult to attain. As a result, these individuals may need to rely on general auditory processing skills just as children do during reading acquisition.

Normal phonological processing in adults without any history of reading disability should not need to rely on auditory nonlinguistic processing skill and should not show any associative relationship between general auditory processing skills and shared phonological processing efficiency. In the current study participants were not selected based on CHRD and the prediction is that general auditory processing of non-linguistic stimuli will not be significantly related to RLD scores.

The auditory non-linguistic tasks used in the current study are similar to tasks used in previous studies done with children and with adults: tone discrimination, formant discrimination, and gap detection.

The tone discrimination task was used in order to test the spectral aspects of auditory processing. Research done by Talcott and colleagues (1999) showed that children's reading skills could be predicted by how well they could distinguish between tones with different frequencies. Other studies have shown spectral processing skills to be related to reading ability (for example De Weirdt, 1988; Studdert-Kennedy & Mody, 1995 and many others). While these auditory skills might be important for children who are just learning to read and relying on accurate auditory information to learn the sounds of the letters in the words they are reading, general auditory processing skills should not be necessary for adults who have already attained the ability to read. Therefore the prediction for this study is that RLD scores will not be significantly related to auditory non-linguistic tasks such as tone discrimination and others mentioned below.

Ahissar and colleagues (2000) suggest that formant discrimination is better correlated with reading ability than pure tone discrimination because formants are closer to sounding more speech-like without actually being linguistic. This is suggested in the text of Ahissar's study but they fail to show this statistically in their paper. If this suggestion is correct, formant discrimination scores may have a relationship with RLD scores even if tone discrimination scores do not. Despite Ahissar's suggestion, the prediction for this study is that formant discrimination will not be significantly related to RLD scores. The formant discrimination stimuli are very similar to the tone discrimination stimuli, with the only difference being that complex spectral tones are used rather than pure tones as in the tone discrimination task. The purpose of the formant discrimination task is to rule out Ahissar's suggestion that formant discrimination may be more word-like than tone discrimination and may draw similar results to results from linguistic stimuli.

Finally, gap detection was included as an auditory non-linguistic task in order to rule out any temporal aspects of auditory processing. Previous studies with children have shown that temporal auditory processing skills are highly correlated with reading decoding skills during reading acquisition (Stark & Tallal, 1979; Stark & Tallal, 1988). This has lead to the *auditory temporal processing* view that children with SLI or dyslexia have problems with reading that are due to deficits in processing rapid auditory stimuli (McArthur & Hogben, 2001; Tallal &

Piercy, 1973; Tallal, 1980). Again, this effect should not be expected to show up for adults who have already acquired reading ability and no longer rely on auditory non-linguistic information to learn appropriate matches from letters to phonemes.

The current study will test whether the relationship between auditory processing and RLD is due to being purely acoustic in nature by testing if non-linguistic auditory tasks influence RDL in adults, the way auditory non-linguistic tasks can influence reading skill with children and adults with CHRD. The expectation is that non-linguistic auditory processing will be ruled out as a possible explanation for the RLD effect with adults, as normal adult readers have successfully acquired the phonological skills used in reading and listening to speech and do not need the general auditory non-linguistic decoding skills used during reading acquisition. Therefore, the hypothesis for the study in this chapter is that the auditory non-linguistic processing tasks will have no significant relationship with RDL scores.

Methods

Participants

The participants were a subset of the 206 participants described in Chapter 2 who took part in the reading and listening tasks. This subset consisted of 48 undergraduate students (16 male, 32 female) who ranged in age from 17 to 25 with an average [SD] age of 19.2 [1.8]. These participants were within 2 SD of scores on reading, listening, and cognitive tasks. This requirement eliminated 2 out of an original 50 participants (4%).

Stimuli

Reading speed and listening speed. The stimuli for these tasks are previously described in Chapter 2. RLD scores were calculated as described previously.

Tone discrimination. There were 64 trials in the tone discrimination task, 32 trials used tones that were matched on frequency and 32 trials used tones with different frequencies. For the tone trials with different frequencies, the differences were either close (1/8 of a tone step up in frequency) or far (1/2 of a tone difference in frequency). All of the trials were also counter-balanced by pitch (higher frequencies or lower frequencies). The high pitch frequencies ranged between 440 – 554 Hz and the lower pitch frequencies were between 135 – 182 Hz.

Formant discrimination. The formant discrimination task used spectral formants of four harmonics and eight harmonics instead of pure tones. The formants were created using PRAAT software. There were 96 trials in total consisting of 48 trials where different spectral formants were presented and 48 trials where the same spectral formants were presented. For the trials with different spectral formants, 16 trials used formants that were close together (1/8 tone apart), 16 trials used formants that were farther apart (1/2 tone), and 16 trials used formants that were created with the same frequency but had either four harmonics or eight harmonics. The pitch of frequencies for these stimuli ranged from 135 – 540 Hz.

Gap detection. There were 108 trials in the gap detection task. Forty-eight trials did not have a gap in the stimuli, and 60 trials did have a gap. Out of the trials that did have a gap, these were further divided by how long the gap in the stimuli was. The gaps were 6, 8, 10, 20, 30, 40, 50, 60, 70, or 80 ms of silence. The tones on either side of the gap were always 1/2 tone apart and were all within a lower pitch (130-262 Hz.).

Procedures

Reading speed and listening speed. The procedures for these tasks are the same as previously described.

Tone discrimination. Participants heard two tones presented one after the other through headphones. Each tone was presented for 500 ms with an ISI of 1000 ms. Participants were asked to decide if the two tones sounded exactly the same or not. If they were the same (i.e. same frequency), participants were instructed to press the *c* key for *correct*, and if they were not the same, they pressed the *x* key for *incorrect.* They were encouraged to go as quickly and accurately as possible. RTs and accuracy scores were collected on all trials.

Formant discrimination. This task is identical to the tone discrimination task described above with the only difference being that participants heard spectral formants instead of pure tones.

Gap detection. In the gap detection task participants listened to auditory stimuli through headphones. They heard two tones that were played one right after the other. Some of them had a short gap of silence between the two tones, and others had no gap between the tones. If participants thought they heard a gap between the tones they were told to press the *c* key for *correct* or *gap.* If they thought there was no gap they were asked to press the *x* key for *incorrect* or *no gap*. Participants were instructed to place emphasis on both speed and accuracy in making their decision. Accuracy scores and reaction times were collected.

Results

Analyses were done using LME regression models (Baayen, 2008). As described in previous chapters, variability due to subjects and items was accounted for in the RLD scores by listing every trial for every subject in the task. The tone discrimination, formant discrimination, and gap detection tasks were analyzed using an average score (correct trials only) for each subject. Calculation of p-values for the LME analyses was done using a MCMC procedure (Baayen et al., 2008).

Tone discrimination. The LME regression analysis entered tone discrimination as a fixed effect while subjects and items of the RLD scores were entered as random effects. The analysis showed that tone discrimination was not significantly related to RLD scores, $t = 0.71$, $p > .48$.

Formant discrimination. Just like tone discrimination, formant discrimination was also not significantly related to RLD scores, $t = 0.94$, $p > .35$, in the LME regression analysis with formant discrimination scores entered as fixed effects and subjects and items of the RLD scores entered as random effects.

Gap detection. Analysis was done, entering RLD scores for subjects and items as random effects, and gap detection scores as fixed effects. There was no effect of gap detection and RLD scores, $t = 1.32$, $p > .19$.

Discussion

The purpose of the study in Chapter 5 was to rule out the confounding variable of general auditory processing speed. Chapter 2 established a correlation between reading speed and listening rate of speech z-scores. From this information, RLD scores were used as a proxy for the shared phonological processing going on between the visual and auditory modalities. The study in Chapter 3 showed that RLD scores have a significant relationship with scores on language processing tasks including auditory phonological tasks such as ALD. Some previous studies however, have found that auditory non-linguistic processing tasks are related with reading ability. These studies have mainly been done with children learning to read and those with reading disabilities. I predicted that RLD scores should not have a significant relationship with auditory non-linguistic tasks because the participants in my study were a random sample of adult readers; not children or those specifically selected as having a reading disorder or history of reading disorder.

General auditory processing can affect children who are learning to read and especially those with reading disorders because it affects the correct acquisition of matching acoustic sounds, to phonemes, to phonological representations, which influences reading ability. With normal adult readers, acquisition of these matches to phonological representations and reading ability has already been attained so general auditory processing should not have any influence anymore. In order to test this in my study, auditory non-linguistic tasks similar to those done in other studies with children and adults with reading disabilities were done, such as tone discrimination, formant discrimination, and gap detection. The results show that scores on the non-linguistic auditory tasks were not related with RLD scores of normal adult participants. This indicates that the reading-listening effect found in adult readers is specifically linguistic and not due to a general auditory processing skill used for processing non-linguistic auditory stimuli.

The results in the current study do not exactly follow the results from similar types of experiments done with children and adults with reading disabilities, although these studies did not investigate the reading-listening difference effect or use a sample population of normal adult readers as in the current study. However, the basis behind the prediction that RLD scores and auditory non-linguistic tasks are not related does fit with these studies.

Tallal and colleagues (1980) tested children with and without reading disabilities on various auditory non-linguistic perceptual tasks and a phonics skills task (nonsense word reading). They hypothesized that auditory perceptual deficits on these tasks would be related to “difficulty in learning the sounds-symbol relationships that are the basis of phonics rules” for reading-impaired children

(Tallal, 1980, pg. 195). They found a significant correlation for the reading – impaired children between auditory perceptual deficits and phonological skills needed for processing language. They also found that children with reading impairment had more errors on auditory perceptual tasks than children without reading impairment when the rate of presentation was increased. This indicates that problems with low-level auditory perception affects the ability to learn to use phonics skills adequately (Tallal, 1980). If children do not have any auditory perceptual deficits, they will be able to use the phonological skills necessary to acquire reading, and auditory non-linguistic processing should not have any influence on reading or the shared phonological abilities between the visual and auditory modality as accounted for in the RLD scores.

For adults who had a history of reading impairments as children the results are mixed. Ahissar et al. (2000) found no significant correlations between gap detection and reading accuracy scores, however they did report a significant correlation for tone discrimination (called frequency discrimination in their study) and reading accuracy for adults with CHRD. They also state that frequency discrimination and formant discrimination were highly correlated with each other which is to be expected, however, correlations of the formant discrimination task and reading accuracy did not indicate significance in the table of data presented in the paper.

There are some key differences between the current study and that done by Ahissar et al. (2000).

Ahissar et al. (2000) recruited participants for their study by advertising for adults with self-reported CHRD. They asked each participant to bring along a friend or family member who did not report having a reading disability in childhood. This is how the control group and experimental group was set up and compared in analyses. So their experiment is not testing if non-linguistic auditory skills may or may not contribute to reading ability, but rather that non-linguistic auditory skills might contribute more in a group of participants who had reading difficulties as children compared to a group of participants who did not have reading difficulties. The present experiment did not select adults who had reading disabilities as children and compare them to adults who did not. It looked at adult reading in general and whether auditory processing tasks that are not linguistic influenced RDL scores. In Ahissar et al.'s paper as well as in other studies with children, auditory non-linguistic processing *deficits* have correlated with reading *disability*, but no studies have looked at reading speed with normal adult readers to see if non-linguistic auditory processing skills correlate with reading after the stage of acquisition has passed. The fact that non-linguistic auditory deficits at a young age may disrupt the rate and difficulty of reading acquisition in childhood for some individuals does not necessarily mean the opposite; that non-linguistic auditory processing skills will facilitate reading speed skills, or as in the current study RLD scores, in adulthood.

Ahissar and colleagues (2000) used accuracy scores for reading single words and non-words out loud as their measure of reading skill rather than reading full sentences. In their analyses, they focused mainly on the non-word reading counts and admit that if reading *speed* were taken into account (by measuring how long it took participants to read the items) it may have lead to different results. The current study used reading speed as the dependent measure of visual phonological processing ability, and had participants read sentences and passages of text. This is a better representation of linguistic behavior in the real world than reading single words or non-words out loud (something people usually only do in an experiment). It measured speed and comprehension (a better way of measuring accuracy), rather than just accuracy alone (measured by testing whether participants could pronounce a word or non-word).

From the mixed results and differences between Ahissar et al's (2000) study and the current study, one is not able to make conclusions based on a direct comparison of the two studies. However, this does not provide any evidence against the predictions of the current study. The current study predicts that a random sample of adult readers will not show a significant relationship between shared phonological processing between modalities and auditory non-linguistic tasks.

The results of this chapter show RLD scores not significant with auditory non-linguistic tasks, although they were significant with an auditory phonological task (the ALD task) in previous chapters. This is more evidence that the reading-listening relationship is due to a language component specific to phonology: the shared phonological processing across the auditory and visual modalities. If this reading-listening relationship was strictly due to visual phonological processing, we should not see the effect with auditory processing tasks at all (linguistic or non-linguistic). If the relationship was only due to auditory phonological processing we should not see it significant with visual linguistic tasks such as VLD. However another pontential confounding factor needs to be addressed: whether the effect is the result of general cognitive processing abilities. Chapter 6 will address this issue.

Chapter 6

The RLD effect and general cognitive processing ability

When considering the reading-listening effect, a potential confounding variable that needs to be addressed is general cognitive processing ability. It is important to rule out that the reading-listening effect that was found in the previous experiments was not due to an overall general processing mechanism. In other words, we need to know that participants have lower RLD scores specifically because they are more efficient at using the phonological information between visual and auditory modalities, and not simply because they are efficient at processing cognitive tasks in general. The study in Chapter 6 tests the hypothesis that cognitive non-linguistic tasks are not related to RLD efficiency.

Since adult participants are used in the studies in this dissertation, I chose to use cognitive tasks that are not linguistic in nature, that have been previously tested within adult populations. The tasks that were done in the present study were the mental rotation task, digit symbol substitution task, and the arrow-matching task.

The mental rotation task is traditionally used as a proxy for spatial cognitive processing ability and was first developed by Shepard and Metzler (1971). Since then, versions of the mental rotation task have been used in many studies (for example, Burton, Henninger, & Hafetz, 2005; Hegarty & Waller, 2004; Peters, Lehmann, Takahira, Takeuchi, & Jordan, 2006; Peters & Battista, 2008; Vandenberg & Allan, 1978) and applications. A review of these applications by Peters and Battista (2008) describe Shepard and Metzler's (S/M) (1971) mental rotation task to be evidence of fundamental neurocognitive mechanisms of spatial perception (Peters & Battista, 2008). Participants see two 3D line drawings of a set of connected blocks. Participants have to choose if the drawings are either the same set of blocks rotated in different ways or drawings of two different sets of blocks. Some applications of the task have been used to show a relationship between mathematical scientific interests and spatial ability (Casey, Nuttall, & Pezaris, 1997; Geary, Gilger, & Elliott-Miller, 1992; Peters et al., 2006) and to predict ability in surgical fields (Anastakis, Hamstra, & Matsumoto, 2000; Brandt & Davies, 2006; Hedman et al., 2006; Wanzel et al., 2003).

In some but not all cases, the mental rotation task has shown gender differences between spatial and verbal cognitive abilities (Burton et al., 2005). A study by Burton et al. (2005) set out to investigate hormonal effects through finger-length ratios and cognitive skills. Two of the cognitive tasks they used were the Vandenberg and Kuse (V/K) version of the mental rotation task (Vandenberg & Allan, 1978) and the Chicago Word Fluency task (Thurstone, 1962). The V/K version of mental rotation task uses the same stimuli as described above in the S/M version but participants have one target drawing to look at and then 4 choices of drawings to match or not. The Chicago Word Fluency task requires participants to write down as many words that begin with the letter s as they can in five minutes, and then write as many four-letter words as they can in four minutes that start with the letter c. They found that males did better (more correct) at the V/K mental rotation task than females, and females did better (produced more words) at the verbal fluency task. Other studies have found the same gender differences with mental rotation (Halpern, 2000; Linn & Petersen, 1985) and with the Chicago Word Fluency task (Heaton, Grant, & Matthews, 1991; Kolb & Whishaw, 1996). However, Peters and Battista (2008) point out that gender effects are only found with the V/K version of the mental rotation task and not with the S/M version. They attribute this to the fact that the V/K version of the task demands a larger memory load for the comparisons of four drawings to the target compared to only a pairwise comparison in the S/M version of the task. Also, some evidence has been found that women typically pay attention to more detail than men. Silverman and colleagues (2007) observed that females take in more information from certain stimuli than males. In this case, women would spend more time taking in more details in the multiple drawings of the V/K version than the two drawings of the S/M version of the mental rotation task. Since gender differences are not one of the research questions for the current study, and the S/M version of the mental rotation task is a lighter load on memory, the S/M version of the task was used in this study.

The digit symbol substitution task uses visual processing of letters and digits. This is a pencil and paper test in which participants must match numbers with an assigned letter and fill in the answers according to the given key as quickly as possible (see below for details). This task has been used for many years as a predictor of age related intelligence, and is included as one of the tasks in the Wechsler Adult Intelligence Scale (WAIS) (Salthouse, 1992). Salthouse (1992) claimed that using the digit symbol substitution task was an important way to understand cognitive processes because it was highly correlated with adult intelligence and negatively correlated with age (as age increases, digit symbol substitution scores decrease). Wechsler also thought the digit symbol substitution task was an excellent indication of cognitive abilities and included it as a subtest in his intelligence batteries, the WAIS and WAIS-R (Wechsler, 1955; Wechsler, 1981). When used in these batteries, the digit symbol substitution test is reported to have correlations with full intelligence scores between .51 and .74 (Wechsler, 1955; Wechsler, 1981). Gender differences in the digit symbol substitution task were found in a study by van der Elst and colleagues (2006). They found that women's scores on the task were significantly higher than men's. This has been found in other studies as well (Beres & Baron, 1981; Salthouse, 1992). However, since the prediction of the current study is to not find any significant relationship between RLD scores and digit symbol substitution scores, there is no reason to look for gender differences in the digit symbol substitution task in this study.

The arrow-matching task has been shown to be one of the best predictors of verbal ability (Wiedel & Schwartz, 1982). In this task, participants see two arrows and must say if they are pointing in the same direction or not. Wiedel (1982) used an arrow-matching task, in addition to other tasks, to investigate the relationship between verbal ability and mental processing speed in adults. He found the arrow-matching task to be the most highly correlated with verbal I.Q. measures, and determined that the arrow-matching task was a good indicator of general mental processing ability.

The purpose of the experiments reported in this chapter is to rule out the confounding variable of general processing ability. If the RLD effect is not due to general cognitive processing abilities, then there should be no relationship with tasks of non-linguistic visual processing that test general cognitive skills. Therefore, the hypothesis for this study is that mental rotation, digit symbol substitution, and arrow matching tasks will not be significantly related to RLD scores.

Methods

Participants

Participants were a subset of the 206 participants from Chapter 2. The subset was 48 (18 male, 30 female) undergraduate students from the University of Alberta who participated for partial course credit. All learned English as a first language and were right handed. The average [SD] age of these 48 participants was 20 [2.3] and ranged from 18 to 30. These participants also did the tasks mentioned in Chapter 5 and were all within 2 SD on all scores.

Stimuli

Reading and listening speed. The stimuli in the reading speed and listening speed tasks are exactly the same as described earlier in Chapter 2.

Mental rotation. The mental rotation task consists of 108 trials, with 64 trials that have matching stimuli and 64 trials that have non-matching stimuli. For both matching and non-matching trials, there were an equal number of easy stimuli (rotated in one dimension, the y plane, Figure 9) and difficult stimuli (rotated in one of two other dimensions, the x plane or z plane).

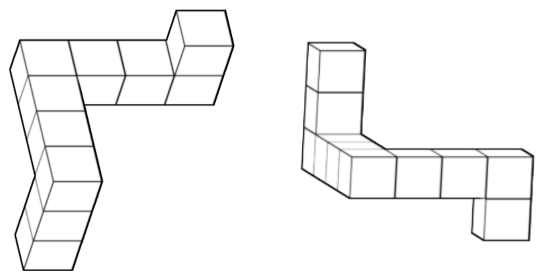

Figure 9. Example of the same set of blocks rotated in the y plane (Shepard & Metzler, 1971).

Arrow judgment. There were 112 trials in the arrow-matching task, with 56 matching trials and 56 non-matching trials. Arrows were presented pointing in one of eight different directions: up, up right, up left, down, down right, down left, right, and left. The 56 matching trials used each direction seven times. The 56 non-matching trials used all possible combinations of the eight different directions.

Digit symbol substitution. Participants were given a one page worksheet that had a set of letters that were each matched to a number across the top. The rest of the worksheet consisted of letters with blank spots beneath them where participants could fill in the appropriate matching number.

Procedures

Reading and listening speed. The procedures for the reading speed and listening speed tasks were the same as described in Chapter 2.

Mental rotation. Participants saw two line drawings of a set of 3-D connected blocks presented visually on the computer monitor. They had to decide if the two drawings represented the exact same set of blocks that had been rotated (see Figure 9) or if they were two different sets of blocks. If they thought both sets of blocks were the same and just rotated differently, participants pressed the *c* key for *correct* or *same*. If they thought the blocks were two different sets, they pressed the *x* key on the keyboard for *incorrect* or *not the same*. Participants were encouraged to be accurate and take their time with the task. Accuracy scores, and RTs were recorded.

Arrow judgment. Two arrows were presented visually on a computer screen. Participants were asked to decide if both arrows pointed in the same direction or not. If they pointed in the same direction, participants were asked to press the *c* key for *correct* or *same direction*. If the arrows pointed in different directions, participants were asked to press the *x* key for *incorrect* or *not the same direction*. They were encouraged to go as quickly and accurately as possible, and accuracy scores and RTs were collected.

Digit symbol substitution. Participants were given the worksheet and asked to fill in the blanks with the appropriate number using the key at the top of the page. After a brief practice trial to ensure comprehension, participants were given 60 seconds to fill in (in consecutive order) as many blanks with the appropriate number as possible. Their score was how many correct responses they completed in 60 seconds.

Results

LME regression models (Baayen, 2008) were used in the analyses of Chapter 6. Using LME, variability was accounted for subjects and items in the RLD scores by listing every trial for every subject in the task (see Chapter 2 for more details). P-values were calculated using a MCMC procedure (Baayen et al., 2008).

Mental rotation. The mental rotation task was analyzed using an overall accuracy score for each subject. RLD scores were entered into the LME model with subjects and items as random effects and mental rotation accuracy scores as fixed effects. The mental rotation accuracy scores were not a reliable predictor of RLD scores, $t = 1.41$, $p > .16$.

Arrow-matching. Arrow-matching RTs were entered as fixed effects and revealed no significant effect on RLD scores, $t = -0.32$, $p > .75$.

Digit symbol substitution. The digit symbol substitution scores ranged from 23 – 65 and had an average [SD] of 43[7]. They were entered as fixed effects in the LME analysis and were not reliably related to RLD scores, $t = -0.6$, $p > .55$.

Discussion

As expected, the results from the experiments in Chapter 6 show no relationship between RLD scores and other tasks that test for general cognitive processing ability such as mental rotation, digit symbol substitution, or arrow-matching tasks. This eliminates the possible confounding variable of general processing ability with regards to the RLD effect.

Many studies with children have also ruled out cognitive abilities or IQ as an indicator of reading ability (see review by Wagner & Torgesen, 1987). As mentioned previously, Ahissar et al. (2000) tested the relationship between reading and auditory processing with adults who had a history of reading disability. They included some cognitive intelligence tests in addition to their experimental tests and showed that their effects were not due to general intelligence or general processing ability.

Ahissar et al. (2000) had adults as participants in their study, yet they used cognitive tests designed mostly for children. It may have been better for Ahissar et al. to use cognitive tasks that had been tested with adult populations to ensure that general cognitive processing effects had truly been ruled out.

The general cognitive processing tasks used in Ahissar et al.'s (2000) study were the Matrix Analogies Test – Expanded Form (MAT) (Naglieri, 1985), and the word memory subtest of the Woodcock-Johnson Tests of Cognitive Ability (Woodcock & Johnson, 1989). The MAT was developed for children ages 5 to 17 years of age and tests their reasoning, pattern, and spatial abilities without using verbal responses (Naglieri, 1985). The Woodcock-Johnson Tests of Cognitive Ability (Woodcock & Johnson, 1989) can be used as early as age 2 and although most testing is done with children, it can be used up to and including adulthood (90 years +). The word memory subtest from this battery measures auditory memory span of linguistic stimuli (Schrank & Wendling, 2009).

The results of Ahissar et al.'s (2000) cognitive tasks (which reported an inconsistent result) are rather vague and confusing. No results were given for the word memory subtest of the Woodcock-Johnson Tests of Cognitive Ability although it is mentioned as a cognitive ability test in the methods section of the study. The other cognitive measure used was the MAT. Only a subset of participants (n=56) did the MAT and out of that subset only 36 participants were selected for use in the analysis. The participants were split into 2 groups: better in reading and poorer in reading. Ahissar et al. report that the poorer in reading group did better than the better in reading group on the MAT and provide a figure for reference but no statistics are reported.

The vagueness of the results for cognitive ability correlations with reading ability tasks in the Ahissar et al. (2000) study does not provide a satisfying answer in regards to ruling out the confounding variable of cognitive processing, although the authors state that reading ability is not due to cognitive ability in their study. The current study used the mental rotation task, digit symbol substitution task, and arrow-matching task; all tasks previously tested with adult participants, rather than tests for children.

The present study gives a much clearer demonstration that cognitive abilities are not related to shared phonological processing between modalities in adults. This was achieved by using various cognitive tasks that tap into different types of non-linguistic cognitive functions, and by using tasks that have been constructed for use with an adult population instead of with children.

Chapter 7

General discussion

The final chapter in this dissertation will look all the findings from the conducted studies and discuss how these results can be interpreted, the implications, the limitations, and ideas for how future research might be conducted on this topic. The chapter ends with final conclusions.

Current findings

Phonological processing is used while reading and also when listening to speech, however no previous studies have been conducted to investigate the shared phonological processing that occurs across both modalities. The current study has shown that reading speed and listening rate of speech are correlated: faster readers are also able to listen to a faster rate of speech while still attaining comprehension. A possible commonality between reading and listening could be the processing of phonological codes to reach a phonological representation.

Reading primarily uses visual phonological processing by matching orthographic stimuli (text) to phonological codes. Listening primarily uses auditory phonological processing by matching auditory phonemes (sounds) to phonological codes. The phonological codes lead to a phonological representation for every word. The phonological representation of a word does not depend on the modality of presentation, and is the same representation whether it was heard or seen. However, this does not mean that the phonological code in each modality that leads to the representation needs to be the same. Phonological codes created through the visual modality (reading) can be different from phonological codes attained through the auditory modality (listening to speech). Other research (see Besner & Davelaar, 1982) has established that there can be different phonological codes for reading versus for phonological working memory; therefore it should also be plausible that there are different phonological codes for reading versus listening to speech. The phonological codes from both modalities converge and the shared phonological information that is provided by both modalities may lead to the phonological representation in a more efficient way (see Figure 10). This might be experienced as imagining how a word sounds when it is read, or thinking about how a word looks when it is heard, although a conscious awareness of this processing is not a requirement.

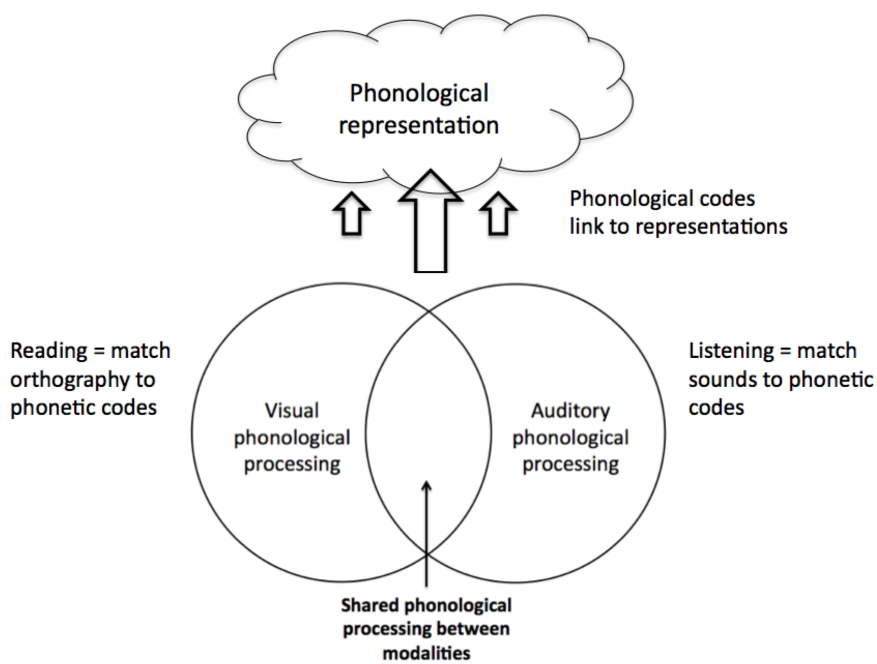

Figure 10. Shared phonological processing provides a stronger link to the phonological representation.

Establishing phonological representations can be thought of in the same way as establishing a memory of an experience. The more ways of linking to that memory, such as remembering the sight, sound, taste, smell, feel of the experience, the richer that representation of the memory will be. Learning phonological representations through different phonological codes can be thought of in the same way. Linking phonological codes through different modalities can lead to a stronger connection to a richer mental phonological representation.

Although no theoretical models to date have been proposed that explain both reading and listening processes in one model, one might imagine how an existing model such as the PDP model for reading (Seidenberg & McClelland, 1989) might incorporate the phonological processing that occurs during listening and how this processing is associated with phonological processing during reading.

The PDP model (Seidenberg & McClelland, 1989), also known as the triangle model, is composed of three types of units: orthographic units, phonological units, and hidden units. There is bi-directional processing between these units, so during reading for example, there is feed-forward processing that goes from the orthographic units to the phonological units (seeing the letter strings and matching the orthography to the phonemes). There is also feedback processing from the phonological units to the orthography units. This is demonstrated when processing homophones. Phonology feeds back to orthography and activates other orthographic units that slow processing (because the orthographic representations compete) and cause a homophone effect (homophones take longer to process than non-homophones do).

This bidirectional processing between orthography and phonology can also apply to RLD effects. Reading accesses orthographic units through visual identification of the letter strings. This gets processed forward to the phonological units and matched to phonemes. Listening to speech could be described in this model by the phonological units, because phonemes are accessed first during listening. Then feedback to orthography could occur (much the same way that it does for homophones, for example). With homophones all orthographic possibilities are activated by feedback from phonology . Listening could also activate the orthographic representation of the word through feedback from phonology. If the PDP model was expanded to include auditory phonological processing (within the phonological units) that is experienced during listening to speech, it could explain the RLD effects through a stronger association between orthographic units and phonological units by way of bidirectional processing.

For reading, feed-forward processing from orthography to phonology is necessary. For listening, however, feedback from phonology to orthography is not *necessary* (because people who can't read can still listen and understand speech), but it is helpful if it is *available*, and adds to efficiency in processing. Therefore, people who can utilize this bidirectional processing between the orthographic units and the phonological units of the PDP model will be more efficient at processing language.

People who are better at integrating the shared phonological information between modalities should also be better or more efficient at other language tasks that require phonological processing. In the present study, shared phonological processing between the auditory and visual modalities is represented with an RLD score: the difference between a participant's reading speed z-score and listening speed z-score. Participants with larger differences between reading speed and listening rates are not as skilled at utilizing the shared phonological processing between both modalities as participants with smaller differences between scores. As predicted, RLD scores were significantly related to scores on phonological language processing tasks such as VLD, ALD, and syllable judgment, but not with a semantic task of ASJ. Other factors were ruled out as having an association with RLD scores: age; gender; years of education auditory non-linguistic tasks such as tone discrimination, formant discrimination, and gap detection; and general cognitive tasks such as mental rotation, arrow matching, and digit-letter substitution. This theory of shared phonology between modalities and the evidence from the results of this study can also explain the results of previous research.

Deaf reading. Studies of deaf readers show that on average they are not as skilled as hearing readers of the same age (Allen, 1986). Traditional phonological skills are learned through hearing the sounds that each phoneme makes, which is not available to deaf individuals. There are alternative ways for deaf individuals to learn phonological information however. This includes instructional tools such as Visual Phonics, Cued Speech, speech reading, and articulatory feedback (Wang et al., 2008). Individuals who learn to read using these methods become better readers (Narr, 2008; Trezek & Malmgren, 2005; Trezek & Wang, 2006; Trezek et al., 2007; Wang et al., 2008). This fits with the theory of shared phonology because deaf readers are only able to use visual phonological processing skills that have been learned through alternative methods and do not have access to auditory skills in phonological coding of information. Therefore they will not be as skilled at reading as people who have access to both modalities and have become skilled at using the shared phonological processing between those modalities to get to the phonological representation of a word more efficiently. Therefore, for deaf individuals, reading will not happen as efficiently as for hearing individuals and will be reflected in lower than average overall reading ability.

Children and auditory processing. The theory of shared phonological processing that leads to phonological representation also explains the correlation between auditory processing deficits and children with reading impairments. Some studies by Tallal and others have found that children with reading disorders such as dyslexia or SLI also have difficulties processing auditory stimuli (Merzenich et al., 1996; Nagarajan et al., 1999; Stark & Tallal, 1988; Tallal & Newcombe, 1978; Tallal, 1980; Tallal, Stark, & Mellits, 1985; Tallal et al., 1993; Tallal et al., 1996; Tallal et al., 1997). If auditory processing deficits are present, then children who are trying to learn phonological skills will have a difficult time linking the correct phonological code to the phonological representation because the phoneme that gets matched to the phonological code might be heard incorrectly. If the correct phonological codes are not acquired they lead to poor or *fuzzy* phonological representations, which lead to poor reading ability. A study by Tallal et al. (1997) demonstrated that if given appropriate training, children with these auditory deficits can learn the proper phonological representations for each phoneme and have more distinct rather than fuzzy representations (Tallal et al., 1997). After the proper phonological codes are acquired these children can go on to learn to read much in the same way that normal children do. This fits with why auditory processing deficits might be significantly related to reading ability for children with reading impairments, and also for adults with CHRD as in the study by Ahissar et al. (2000), but not in the current study with normal adult readers using RLD scores. Children and adults with reading impairments, may have had auditory processing deficits that prevented distinct phonological representations from being established, which resulted in poor reading skills. Normal adult readers, on the other hand, have likely had the opportunity to acquire phonological representations using phonological codes from both modalities without impairment in one modality or the other. Those who are more skilled at using phonological information from both modalities (i.e. those with small RLD scores) are likely to be more skilled at other language tasks, especially those that focus on phonological processing skills.

Blind speech perception. The results of studies with blind individuals and speech perception abilities can also be explained by the current theory. Research has shown that blind children have a much later acquisition of mastery of phonology (Mills, 1983; Mills, 1987), and have difficulties with different elements of speech perception (Lezak & Starbuck, 1964; Mills, 1983; Mills, 1987; Wills, 1970). Blind individuals do not have access to visual phonological processing and can only take advantage of auditory processing of phonological codes to representations. Therefore, this would result in weaker links between phonological codes and representations than if both modalities could be used. These weaker links to representations means it takes blind children longer to be able to learn phonological processing because only one modality is involved in acquisition of those skills and shared phonological information between modalities is not available.

Pure word deafness. Pure word deafness can also be explained using the model of shared phonological processing (Figure 11).

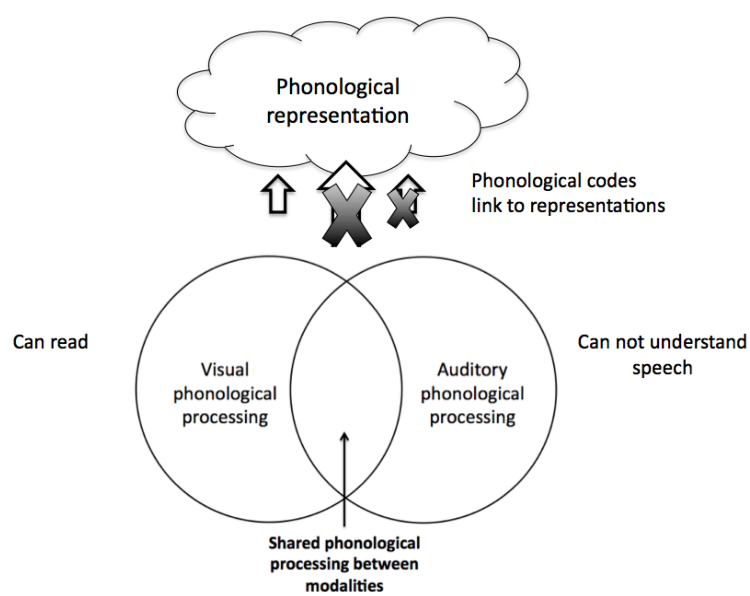

Figure 11: In pure word deafness, access to phonological representations is only through visual codes, leaving individuals able to read but not able to understand spoken speech.

Pure word deafness is the result of damage to the temporal lobe and results in the inability to understand spoken language even though hearing is still intact (Geshwind, 1965). Individuals with pure word deafness can still understand written language, so reading and writing are spared. The model of shared phonological processing can explain the outcomes of pure word deafness. Damage to certain areas of the brain impairs auditory phonological processes, which makes it impossible for shared phonological processing between visual and auditory codes to take place. Visual phonological processing is still intact though, so reading still occurs normally. Pure word deafness also gives evidence that auditory phonological processing used for processing language is separate from general auditory processing, since individuals can still hear but cannot understand spoken speech. This also fits with the results of the current study that the shared phonological processing between the visual and auditory modalities is separate from auditory processing used in non-linguistic tasks, as seen in Chapter 5.

Implications

One of the possible implications of this research includes how we consider reading skill and phonological processing in future studies. Many studies have investigated phonological processing during reading without considering the contribution of phonological processing during listening. When we consider both contributions we can use this as a measure of phonological processing efficiency. Phonological processing efficiency may be a better measure than current methods, such as lexical decision scores, when investigating phonological processing because it accounts for visual and auditory phonological processing skills at the same time. The measure of shared phonological processing between modalities may be better at representing phonological processing overall than measuring phonology based on one modality at a time. This could change the way researchers describe phonological processing in the future. Phonological processing is not just seen in separate modalities but there is a shared processing between modalities as well that enables individual differences in overall phonological processing efficiency.

Individual differences in reading skill have been found in previous studies. When these differences are accounted for, we see different results in phonological processing experiments (see for example Unsworth & Pexman, 2003). These individual differences can be described in terms of efficiency of processing between the orthographic and phonological units in Seidenberg and McClelland's (1989) PDP model. The current research could also fit with a PDP model in terms of efficiency. If the description of the PDP model was extended to include processing during listening as well, the RLD effect found in this study could be explained in terms of efficiency of processing between reading (use both orthographic and phonological units) and listening (use phonological units). Better efficiency would be represented by better mappings between the orthographic and phonological units.

Limitations

As with any research, there are some limitations of the current studies. First of all there were many different experimental tasks used in the studies in this dissertation. Not all participants did all the same tasks throughout all studies. The participants always did the reading and listening tasks, but due to time constraints not all of the other tasks were completed by every participant, therefore subgroups of participants did different groups of tasks. This means that analyses of the data could only be compared for the tasks that were done by all the same participants, and not across all tasks for all 206 participants. Although this is a minor statistical limitation, it is possible that other effects might have been found if comparisons were done with every task overall.

Because there were so many different tasks, not all the tasks had the same number of trials and items in them. This is a limitation with respect to the analyses using LME. In the LME analyses, only the reading task could account for the variability due to items for each subject. The other tasks could not be analyzed using items because LME needs an equal number of items between all the tasks. Instead, averaged scores were used for each participant in all other tasks. It would be statistically optimal to be able to use a full LME model accounting for all items in *all* tasks (not just the reading task) in order to account for more variability.

Another possible limitation may have been with the rhyme judgment task in that it may have been too complex. The lack of RLD effect in this task was a surprising and perplexing result. It was predicted that an RLD effect would be found with the rhyme judgment task as it requires phonological processing in order to respond correctly. The problem may have been that two stimuli were presented as choices to match to a target. This made processing more complex and required more time for a decision to be reached. During this extended time other types of processing may have had a chance to take place such as semantic processing. A simpler task with only one stimulus to make a yes or no decision on might have been a better procedure. If done again in the future, this might be a better task to try because it requires attention to only one stimulus at a time which allows for faster processing that may correlate with early an phonological stage of processing.

A limitation that often occurs with research done at universities is that the participants were mostly young adults; a typical university population. This research may have ended up with different results if the tasks were done with children who are at different stages of reading acquisition, or possibly even older adults. For now, the results of this study can only generalize to a population of young adults. Future research may consider other populations.

Future research

As mentioned in the previous section, future research may include data from other populations. A developmental longitudinal study could be conducted in order to find out if RLD effects as adults correlate with reading acquisition rates as children. This would shed light on RLD effects and whether the effects are different during the stages of reading acquisition and reading fluency. Other questions to be formally investigated might include: when does RLD efficiency occur, can RLD efficiency be learned or is it an innate language skill, or how does the RLD effect relate to language/reading disorders? Future research in these areas might be important to developing treatments for disorders, as well as influence how reading and language skills are taught. More emphasis may need to be put on listening skills in order to help children become skilled readers.

Predictions about individuals with pure word deafness can be made and could be tested in future studies. Since pure word deafness might be explained by the theory of shared phonological processing (see above) based on RLD effects,one might predict that individuals with pure word deafness would not be as skilled as normal individuals on reading tasks that use whole word lexical processing, but may be as skilled as normal individuals on sublexical tasks since RLD effects are not found with sublexical processing.

Another future area of research could be neurological studies. Studies using neurological techniques such as fMRI, event related potentials (ERP), or even transcranial magnetic stimulation could be conducted to investigate which areas of the brain are implicated in the RLD effect. Based on the results in this dissertation, RLD effects occur with processing of whole words and not with nonwords indicating that RLD effects are found in the whole word lexical processing route rather than sublexical routes described in the DRC model. Based on this evidence, one would expect neurological studies to show activations of the RLD effect in areas of the ventral whole word route rather than areas of the dorsal sublexical route .

Conclusion

It has been demonstrated that reading skills and listening skills are associated, and proposed that this association is because of shared processing efficiency between visual phonological processing and auditory phonological processing. The studies described in this dissertation all support this theory of shared phonological processing between modalities. This theory is also supported and works with the evidence from many different sources such as deaf readers, children with reading disabilities, adults with CHRD, other psycholinguistic studies of phonological processing efficiency with skilled and less skilled readers, blind speech perception, and aphasia examples like pure word deafness. Individuals that are skilled at integrating phonological information from both the auditory and visual modalities become more efficient at phonological processing and language processing in general. Other factors such as age, gender, number of years of education, general auditory processing skill, or general cognitive processing skill, have been ruled out and are not associated with the RLD effect. The implications of this research are that researchers must consider the association of reading skill and listening skill and the individual differences in processing efficiency when studying phonological processing.

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