LETTER PROCESSING IN CHILDREN WITH NAMING SPEED DEFICITS

By

NICOLE JANET CONRAD, B.A. (Honours)

A Thesis

Submitted to the School of Graduate Studies

in Partial Fulfillment of the Requirements

for the Degree

Doctor of Philosophy

McMaster University

DOCTOR OF PHILOSOPHY (2002) | McMaster University
(Psychology) | Hamilton, Ontario

TITLE: Letter Processing in Children with Naming Speed Deficits

AUTHOR: Nicole Janet Conrad, B.A. (Honours.) (St. Mary's University)

SUPERVISOR: Dr. Betty Ann Levy

NUMBER OF PAGES: x, 125

ABSTRACT

Research has clearly established that naming speed on a rapid automatized naming (RAN) task is related to reading. However, the nature of this relationship is unclear. Debate continues as to the underlying process or processes that are indexed by the RAN task. The present thesis addressed this issue by exploring the nature of the deficit(s) exhibited by children with slow naming speed on the RAN task. Both orthographic and letter processing skills were examined.

The first three experiments used a probe task to examine the letter processing abilities of children with slow naming speed. Levels of orthographic knowledge were also measured. All three experiments indicated that children with slow naming speed on the RAN task are characterized by deficits in orthographic knowledge and in processing individual letters in a sequence. Results suggest that these two deficits may be independent, as difficulties in processing individual letters in a sequence were observed whether or not orthographic structure was present (Experiment 1 and 2). In addition, children with naming speed deficits were able to use the orthographic structure present in a string to aid processing (Experiments 2 and 3b).

The processing difficulties exhibited by children with naming speed deficits were not a result of inadequate processing time alone (Experiment 3a and 3b). Providing longer time for these children to encode a letter string did not alleviate the problem. A more fundamental problem in representing individual letters may result in poor or slow

processing of letter strings. It is this underlying problem that needs to be corrected in order for letter processing speed to improve.

A training study (Experiment 4) illustrated the importance of orthographic pattern recognition training for children with naming speed deficits. Training children to recognize orthographic units within a word facilitated learning of these words, and enabled them to read new words that shared the same orthographic units. Orthographic training also had an impact on the speed with which children identified individual letters in a sequence. Training to increase the speed of letter identification was successful only when it was preceded by training in orthographic pattern recognition. Training children to recognize larger orthographic units within words may foster an awareness that orthographic consistencies exist within words. When searching for these consistencies within a letter string, children may process the internal elements more efficiently, resulting in an increase in the speed of letter identification when letters are presented in a sequence. Therefore, orthographic training may be beneficial not only in its own right, by addressing the orthographic deficits of children with slow RAN performance, but orthographic pattern recognition training may also be the route through which we can improve processing of individual letters.

ACKNOWLEDGEMENTS

As with any great achievement, there are a number of people who deserve a thank you for their help – not only those who helped me to finish the thesis, but also those who helped me to believe that I could.

My supervisor, Dr. Betty Ann Levy. Thank you for sharing your love of research with me. I have learned, and continue to learn so much from you. You have become a true mentor to me, in many different ways. Thank you for guiding me along this journey.

I'd also like to thank the other two members of my supervisory committee, Dr. Bruce Milliken and Dr. Geoff Norman. I thank you both for your patience, your guidance, and your jokes at the beginning of my committee meetings. Bruce, I've always felt you were on my side, and that made a difference.

A thank you also goes to the various members of the Levy Lab over the years – Derrick, Chris, Sima, Sandi, Samantha, Sara, Carolyn, Bryan, and Ellen. You've all contributed in different ways, either with data collection, or by making the lab a fun place to be. A special thanks to Derrick Bourassa for the marathon sessions of NTN and the stimulating discussions at the Thirsty Cactus; Carolyn Breukelman, for being the calming presence in the lab; Sandi Martin-Chang and Sara Graydon for their friendship. Thank you also to Wendy, Sally, Erie and Gary, you are the heart of the department.

The camaraderie within the department is rare, and wonderful. I have met some truly great people. Thank you Lori Francis, for your friendship, and for waking me up the morning of our first stats exam. Thank you Karmen Bleile for your friendship, and for making the basement the "place to be".

My gratitude is endless for "The Hamilton Girls" – Amy Branscombe, Carrie Sniderman, Christine Tsang, Lynne Honey, Nicole Anderson, Sandra Hessels, and Vicki LeBlanc. Who would have thought that a bunch of totally different people could become right good friends. I was once told before I came here that the friends I made in grad school would remain friends forever. I didn't believe it. I do now. You have had such an impact on me, and have contributed more than you might imagine to my success in so many different ways. I thank you all for all the new experiences, the expanded vocabulary, the fantastic annual road trips, the bitching sessions, the ability to pack up my entire home in 5 hours, for taking care of me during those situations I needed looking after (i.e., Ottawa, 2001), but most of all for being there to listen, to help, to pep talk, and to celebrate. And in Christine's case, for letting me move in – thanks roomie! I came here for a Ph.D. I'm leaving with something far more valuable. Thanks.

Dr. Darryl Bruce, thank you for seeing the spark within me that I had not yet seen for myself. Without your belief in me I never would have achieved all that I have.

And mostly, my parents, Bob and Louise, you have been my rock throughout this difficult journey. You have my gratitude, and my love, for teaching me to dream, to strive, to laugh, to love, to live. It's all over, Mom!

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

Research has clearly established the importance of phonological processes in reading acquisition. Studies have indicated that phonological abilities can predict later reading ability (e.g., Bradley & Bryant, 1983; Wagner & Torgesen, 1987) and that training in phonological skills produces benefits in reading development (e.g., Ball & Blachman, 1991; Bradley & Bryant, 1991; Levy & Lysynchuk, 1997). As a result, deficits in phonological processing are now considered to be central problems that impede the development of reading skill. However, as reading is a multi-faceted skill, deficits in other component skills of reading may also contribute to problems in reading acquisition. Although phonological interventions generally produce favorable results, there are often "treatment resisters" who do not benefit from training in phonological skills (Blachman, 1994; Torgesen, Wagner, & Rashotte, 1994), supporting the notion that deficits in other skills also contribute to impaired reading.

Bowers, Wolf and colleagues (e.g., Bowers & Wolf, 1993; Wolf & Bowers, 1999; Wolf, Bowers, & Biddle, 2000) have postulated a potential second core deficit, indexed by naming speed on a rapid automatized naming (RAN) task. They argued that the process or processes that underlie naming speed on the RAN task contribute to reading ability independently of phonological processing. Deficits in both processes can contribute separately to problems in reading ability. According to this double deficit hypothesis, it is possible for children with poor reading skills to have a single deficit in phonological processing, a single deficit in naming speed, or a double deficit in both skills. Because of the impact of this second deficit on reading ability, it is important to have a clear understanding of the process or processes that underlie it. Unfortunately, the exact nature of this deficit is unknown. This thesis will first discuss the relationship between RAN performance and reading, focusing on several factors that affect this relationship, such as the characteristics of the samples studied, the specificity of RAN deficits to reading disability, and whether the relationship is mediated through other skills that are related to reading ability. Next, several theories with supporting evidence that attempt to account for how RAN performance is related to reading will be discussed. Finally, four experiments will be presented that examine the nature of the deficit(s) that characterize children with slow naming speed on the RAN task (hereafter to be referred to as slow RAN children). Both theoretical and educational implications of these experiments will be discussed.

Sample Characteristics and Their Effect on the Relationship Between RAN Performance and Reading

A rapid automatized naming task (RAN) measures naming speed of simple visual symbols such as letters, digits, colors, and objects (see Figure 1 for an example of a RAN task). In a classic experiment, Denckla and Rudel (1976) used a continuous naming task that consisted of five target items repeated in arrays of five rows of ten items. There were four different types of displays that contained one of five letters, five digits, five colors, or five simple line drawings of objects, repeated randomly throughout the display. The results indicated that although all groups of children made few errors, children with dyslexia were slower to name visual symbols than average readers. These findings suggested that naming speed for visual symbols could differentiate poor readers from average readers.

3	**8**	**4**	**1**	**5**	**2**
4	**9**	**6**	**3**	**5**	**2**
2	**8**	**1**	**9**	**5**	**6**
1	**8**	**4**	**9**	**2**	**6**
9	**5**	**3**	**2**	**1**	**9**
8	**5**	**3**	**5**	**1**	**2**
4	**2**	**9**	**6**	**5**	**3**
9	**6**	**4**	**5**	**2**	**1**

Figure 1: Example of RAN-digit task display

Since this time, many further studies have demonstrated that a relationship exists between RAN performance and reading ability. Faster naming speed on a RAN task is related to better reading ability (e.g., Blachman, 1984; Cornwall, 1992; McBride-Chang & Manis, 1996; Meyer, Wood, Hart, & Felton, 1998). RAN performance can differentiate poor readers from average readers during childhood (e.g., Bowers & Swanson, 1991; Watson & Willows, 1995; Wolf, 1982; Wolf, 1997; Wolf, Bally, &

Morris, 1986), and into adulthood (Felton, Naylor, & Wood, 1990). In addition, RAN performance is predictive of later reading ability (e.g., Meyer et al., 1998; Scarborough, 1998; Wolf, Bally, & Morris, 1986). It is clear that a relation does indeed exist between performance on the RAN task and reading.

However, studies have indicated that the strength of the relation between RAN performance and reading may be affected by the age and the reading ability of the sample of children used in studies (e.g., McBride-Chang & Manis, 1996; Meyer et al., 1998; Scarborough, 1998). Some researchers have argued that the relation between RAN performance and reading is strongest for readers of low skill, either young children in the early stages of reading development, or older impaired readers (McBride-Chang & Manis, 1996; Wolf & Bowers, 1999). There is support for this argument. Blachman (1984) measured RAN performance in children of all levels of reading ability in Kindergarten and Grade 1 and found naming speed on the RAN task to be negatively related to word identification scores; that is, children with lower (faster) RAN scores had higher word identification scores. Wolf, Bally, and Morris (1986) found similar results. They measured RAN performance in Kindergarten and found that for both average and poor readers, RAN performance predicted grade 2 reading scores. These studies suggest that for young, inexperienced readers, RAN performance is related to reading for children across all levels of reading ability.

With older children the relationship between reading skill and RAN performance is less straightforward. Although it appears that across all ages, poor readers are slower on the RAN task than are average or good readers (e.g., Bowers & Swanson, 1991;

Felton, Naylor, & Wood, 1990; Wolf, 1982; Wolf, 1997; Wolf, Bally, & Morris, 1986), it has been argued that the predictive power of RAN performance diminishes for normally achieving children as they get older, while RAN performance remains a strong predictor of later reading skill for poor readers (McBride-Chang & Manis, 1996; Wolf & Bowers, 1999). In support of this argument, Cornwall (1992) examined the relation between RAN performance and reading ability in a group of older children reading below grade levels. She found that for poor readers aged 7 to 12 years old, the children with the fastest RAN scores were the children with the highest word identification scores. This study showed that the relation between RAN performance and reading continues to exist in older less skilled readers. It is unclear from this study whether the relation continues to exist in normal achieving readers who are older.

McBride-Chang and Manis (1996) directly examined the differential relation between RAN performance and reading ability in normally achieving and poor readers in Grades 3 and 4. These children were older than those studied by Wolf, Bally, and Morris (1986) and Blachman (1984). They found that for the poor readers, the children with the slowest RAN scores were the children with the poorest reading scores on two measures of word identification. However, for the normally achieving readers, there was no relationship between RAN performance and reading ability. Other studies have also found little relation between RAN performance and reading ability in average or good readers. Scarborough (1998) found that RAN scores measured in Grade 2 were predictive of Grade 8 word identification scores, but only for poor readers. RAN scores were not predictive of reading ability for average readers. Meyer, Wood, Hart, and

Felton (1998) found similar results. Grade 3 RAN scores were predictive of word identification scores in both Grade 5 and Grade 8, but again only for the poor readers. For the average readers, RAN scores were not predictive of later reading scores. On the basis of these studies, it can be argued that RAN performance is a poor predictor of later reading ability for normally achieving children as they become more fluent at reading, whereas it remains a strong predictor for poor, non-fluent readers.

In addition to the sample characteristics, the type of RAN task used may also affect results of studies that examine the RAN-reading relationship. Following from the initial study of Denckla and Rudel (1976), researchers generally use one of four versions of the RAN task. While the format of the RAN task remains the same, different studies use different items. These items are either all digits (RAN-digits), all letters (RAN-letters), all color patches (RAN-colors) or all simple line drawings of common objects (RAN-objects). Although there are other versions of the RAN task used (see for example Wolf, 1986), these four versions are most common. Wolf, Bally, and Morris (1986) questioned whether results would be the same across the four different versions of the RAN task. They measured all four RAN types for both average and impaired readers in Kindergarten, Grade 1 and Grade 2. They found that for both average and impaired readers, all four RAN measures taken in kindergarten predicted Grade 2 reading scores. However, when measured in Grade 1, only RAN-digits and RAN-letters continued to predict Grade 2 reading scores, and RAN-objects and RAN-colors lost their predictive power as children got older. That the relationship between RAN-objects/RAN-colors and reading diminishes as children become older has also been found by Cornwall (1992) with 7-12 year old children, by Watson and Willows (1995) with children in Grade 1, by Bowers, Steffy, and Tate (1988) with 8-11 year old children, and by van den Bos, Zijlstra, and lutje-Spelberg (2002) with Dutch speaking children. On the basis of these studies, it appears that as children get older, RAN-letters and RAN-digits remain related to reading, while RAN-objects and RAN-colors do not.

Other researchers found different results. Scarborough (1998) found that RAN-colors and RAN-objects measured in Grade 2 were predictive of Grade 8 word identification scores, but only for impaired readers. Likewise, Meyer, Wood, Hart, and Felton (1998) found that all four versions of the RAN task taken in Grade 3 predicted word identification scores in Grade 5 and Grade 8; but again, this was only for poor readers. It may be that for normally achieving children, fluency in identifying objects and colors is achieved earlier than for impaired readers, thus decreasing the relationship between RAN-colors/RAN-objects with reading for these children. While it is unclear whether RAN-colors and RAN-objects remain predictive of later reading ability for all children, it is clear that the alphanumeric versions of the RAN task do remain related to reading, as is evident by the innumerable studies that continue to use RAN-digits or RAN-letters for all age groups (e.g., Ackerman & Dykman, 1993; Bowers, 1989; Bowers & Swanson, 1991; Bowers, Steffy et al., 1988; Levy, Bourassa, & Horn, 1999; Lovett, Steinbach, & Frijters, 2000; Manis, Doi, & Bhadha, 2000; McBride-Chang & Manis, 1996; Meyer et al., 1998; Semrud-Clikeman, Guy, Griffen, & Hynd, 2000; van den Bos et al., 2002; Watson & Willows, 1995). It is for this reason that RAN-digits was used in this thesis.

The above studies indicate that RAN performance is related to reading in a number of different ways. RAN performance can both differentiate poor readers from average readers and predict later reading ability. The strength of this relationship appears to be affected by the characteristics of the sample and the version of the RAN task used. For young children, RAN performance is related to reading for readers of all ability and with all versions of the RAN task. For older readers, RAN performance is most robustly related to reading for impaired readers and when either RAN-digits or RAN-letters are used.

Specificity of RAN Deficits to Reading

It is not known from the studies described above whether a naming speed deficit on the RAN task is specific to reading disability or whether children with other types of learning disabilities also exhibit a deficit in naming speed. To address the question of specificity of naming speed deficits to reading, Denckla and Rudel (1976) examined RAN performance in a group of children from a special education school. Some of these children were classified as having reading disabilities (dyslexia), while other children were found to have unspecified learning disabilities that were not related to reading. RAN scores were compared between these two groups of children, and to a control group of children with no disabilities. Denckla and Rudel found that performance on the RAN task not only differentiated dyslexic readers from normally achieving readers, but that it also differentiated dyslexic readers from children with other non-reading related learning disabilities. Children with dyslexia had slower RAN times than both controls and children with non-reading related learning disabilities. Other researchers have found that performance on the RAN task can also differentiate children with reading disabilities from children with other learning disabilities such as Attention Deficit Hyperactivity Disorder (ADHD). Felton, Wood, Brown, Campbell, and Harter (1987) examined naming speed on the RAN task for four groups of children, those with a reading disability (RD) and ADHD, those with only a RD, those with only ADHD, and children with neither ADHD or RD. They found that only those children with a reading disability had a naming speed deficit and that the occurrence of ADHD was unrelated to naming speed deficits. Other researchers have replicated these results (e.g., Ackerman & Dykeman, 1993; Semrud-Clikeman et al., 2000). These studies all point to the specificity of naming deficits to reading.

Waber (2001) argued that deficits in naming speed on the RAN task are more generalized, and that children with other learning disabilities also exhibit naming speed deficits. She described a study in which she used a sample of children with learning impairments who had been referred for evaluation because of problems in school. Waber did not include in her sample any children with specific co-morbidities such as ADHD or neurological impairment. These children were not classified as learning impaired on the basis of academic scores or achievement tests; that they were having problems in school was sufficient to classify them as learning impaired. From this sample children were classified as either poor readers or adequate readers. The percentage of poor readers with RAN deficits and the percentage of adequate readers with RAN deficits were examined. Eighty-five percent of the poor readers had RAN deficits, and 60% of the adequate readers also had a RAN deficit. As a large proportion of children with learning impairments who were adequate readers had a naming speed deficit, she concluded that naming speed deficits are more generalized and not specific to reading disability.

However, a second study described by Waber (2001) questioned this conclusion. Within this sample of learning impaired children, there were both average readers and poor readers. Waber found that although the average readers in this sample were performing below expectations on the RAN task (based on unpublished norms), they were still faster on the RAN task than were the poor readers. Thus, even within this sample of learning impaired children, RAN scores were able to differentiate average readers from poor readers. This finding is consistent with the work described above of Denckla and Rudel (1976) in which not only did the children with dyslexia have slower RAN scores than the children with unspecified learning disabilities, this latter group of children performed slower on the RAN task than a group of control children with no learning disabilities. Taken together, these studies suggest that although some learning impaired children (but not all, see studies on ADHD) may have deficits in naming speed, learning impaired children with reading disabilities have greater deficits than do learning impaired children without reading disabilities. This suggests that the connection between RAN performance and reading cannot be fully explained by a general slowing down of cognitive speed due to some form of damage to the brain. There is a specific connection between RAN performance and reading.

What we do know thus far is that RAN performance is related to reading. We do know that RAN performance can differentiate poor readers from average readers, and from children with other learning disabilities. RAN performance is predictive of later reading skill. The strength of the relationship between RAN performance and reading differs depending on the age and ability of the sample studied. What we do *not* know is the underlying mechanism for this relation. We do not know *how* RAN performance is related to reading. One possibility is that RAN performance is related to reading through some other skill that contributes to reading ability. It is this question that is next addressed.

Relationship Between RAN and Phonological Processing

Although the relationship between RAN performance and reading is well established, it is unclear what underlying processes are driving this relationship. Torgesen, Wagner and colleagues (Torgesen & Wagner, 1998; Torgesen, Wagner, & Rashotte, 1994; Torgesen, Wagner, Rashotte, Burgess, & Hecht, 1997) have argued that the RAN task is a measure of phonological processing abilities, such as the ability to understand, manipulate and access the sound properties of spoken and written language. They have argued that performance on the RAN task is an index of the ease and speed with which one can access phonological information from long term memory. However, there is sufficient evidence to suggest that although performance on the RAN task shares some variance with performance on phonological tasks, it is not necessarily this shared variance that mediates the relationship between RAN and reading (Bowers & Wolf, 1993; Wolf & Bowers, 1999; Wolf, Bowers, & Biddle, 2000). The shared variance between phonological tasks and naming speed may be a result of the need to access the sound representations and articulate the names of symbols in both tasks (Manis, Seidenberg, & Doi, 1999; Wolf, Bowers, & Biddle, 2000). However, the RAN task accounts for unique variance in reading ability that is not accounted for by phonological tasks.

There are several different lines of evidence to suggest that the RAN task is not a measure of phonological processing, but rather is an index of a process or processes that make independent contributions to variance in reading ability. The first hint of evidence to support this assertion comes from cross-linguistic studies, with languages that have a more regular orthography than English. Orthography refers to the spelling pattern of words; however, orthography is not simply the visual symbols that represent letters, it is the systematic relationships between letters in a sequence that represent the phonological properties of the word (Ehri, 1980). Thus, a language with a regular or shallow orthography is one in which there is a consistent, or one-to-one mapping between graphemes and phonemes. A language with an irregular or deep orthography, such as English, is one in which the mapping between graphemes and phonemes is not consistent, and can map one grapheme to many phonemes. For example, in English, vowels can be mapped to many different pronunciations (e.g., the "a" in cave, cat) and the same letter is sometimes pronounced (e.g., the "p" in potato) and sometimes silent (e.g., the "p" in psychology). As a result, the structure of words in a regular orthography can be decoded using lower levels of phonological skills than that which is needed to decode the structure of words in an irregular language like English. Whereas in an irregular language like English, young and/or poor readers tend to show deficits in phonological abilities, in languages with a regular orthography like German, poor readers tend to show greater deficits in fluency or speed of reading (Wimmer, 1993; Wolf, Pfeil, Lotz, & Biddle, 1994). This finding suggests that deficits in phonological ability are not at the root of reading problems in German-language speaking children who are able to master the shallow orthography easily, but that some other process is impeding their reading ability, which manifests as deficits in reading fluency. There is evidence to suggest that this fluency problem is predicted by performance on the RAN task.

Studies have examined RAN performance in children who speak German and Dutch, both of which are languages with a more regular or shallow orthography than English. Wimmer (1993) studied German-speaking children in Grades 2 and 4. He found that performance on the RAN task was a better predictor of reading ability than performance on phonological processing tasks. In addition, children with dyslexia had slower RAN scores than did normally achieving readers, indicating that the RAN task can differentiate average from poor readers in the German language. Wolf and colleagues (1994) replicated these results with a larger sample of German-speaking children. In a subsequent study, Wimmer, Mayringer, and Landerl (2000) found that German children classified as having a naming speed deficit upon school entry, continued to show naming speed deficits at the end of Grade 3. These children also showed deficits in reading speed compared with children with no naming speed deficit. That naming speed deficits are associated with impaired reading ability is also evident in other languages with a regular orthography, like Dutch (van den Bos et al., 2002). Van den Bos and colleagues studied the relation between RAN performance and reading in several groups of Dutch speaking people, ranging in age from 8-years old to 16-years old and adults. Using a full range of reading ability, they found that naming speed on RAN-digits and RAN-letters correlated with speeded word identification for all age groups, including adults. These studies indicate that in languages where the phonological requirements are less demanding, RAN performance has a strong relationship with reading ability. Cross-linguistic studies such as these begin to suggest that the RAN task is not simply a measure of phonological processing ability, but that RAN may in fact be measuring a process that contributes to reading fluency independently of phonological abilities.

Stronger evidence for the independence of RAN performance and phonological processing abilities comes from many studies that have illustrated that naming speed on a RAN task explains unique variance in reading ability, separate from the variance accounted for by phonological processing tasks (e.g., Bowers, 1989; Bowers & Kennedy, 1993; Bowers & Swanson, 1991; Manis, Seidenberg, & Doi, 1999; Manis, Doi, & Bhadha, 2000). These predictor studies used hierarchical regression analyses as a statistical method to partial out the variance in reading measures attributed to phonological processing and RAN performance. The variables are entered into the regression equation in a fixed order. Typically in these studies the phonological variables are entered first, followed by the RAN variables. The increase in variance associated with the last variable entered into the regression (the RAN variable in this case) represents the unique contribution of that variable; that is, RAN performance accounts for an increase in the proportion of explained variance in reading measures.

Manis, Seidenberg, and Doi (1999) examined whether RAN performance and phonological processing skills measured in Grade 1 would predict unique variance in Grade 2 reading skills. Children from a range of reading abilities were tested. They found that RAN performance accounted for unique variance in word recognition, separate from that accounted for by phonological processing skills. In addition, RAN performance continued to explain unique variance in Grade 2 word identification after accounting for the earlier reading levels of the children, indicating that RAN performance is directly related to later reading as opposed to indirectly related to later reading because of its relation with earlier reading skills. Bowers (1989) found similar results with children across a range of reading ability in Grade 4. Thus for children across a range of reading ability, RAN performance accounts for unique variance in reading ability after the effects of phonological processing skills have been considered.

Whereas both Manis and colleagues (1999) and Bowers (1989) examined the relation between RAN performance, phonological processing and reading in a sample of children from the full range of reading ability, McBride-Chang and Manis (1996) examined the relation in poor readers and average readers separately. They found that for children in Grades 3 and 4, RAN performance predicted unique variance in two measures of word identification only for poor readers, and not for average readers. The differing predictive ability of RAN performance for good and poor readers was seen in other results reported by McBride-Chang and Manis (1996) and Scarborough (1998) that have already been described. In any case, it is clear from the studies described here that RAN performance contributes unique variance to reading ability that is separate from that of phonological processing abilities, further supporting the assertion that the RAN task is not simply a measure of phonological processing ability.

Further evidence to support the independence of naming speed and phonological abilities was provided by Bowers (1995). She followed a group of readers from Grade 2 to Grade 4 and categorized these children into four groups, those with no deficit in either phonological tasks or naming speed, those with only a naming speed deficit, those with only a phonological processing deficit, and those with a "double deficit" in both naming speed and phonological abilities. Both single deficit groups of children were moderately poor readers, with the double deficit group having the most profound reading disability. Bowers argued that this study supports the idea that the RAN task is not a measure of phonological processing abilities for two reasons. First, that poor readers can be characterized by naming speed deficits in the absence of phonological processing deficits suggests that they are separate. Second, because the children classified as having a double deficit had greater reading impairment than either single deficit group alone suggests that not only does each deficit affect reading ability, but also the two deficits combined have an even larger impact on reading ability.

Other researchers have also classified children on the basis of the presence or absence of naming speed deficits and phonological processing deficits. Wolf (1997) replicated Bowers' (1995) findings with a larger sample of children. Several researchers have found similar results with severely impaired readers (Lovett et al., 2000; Manis et al., 2000; Manis & Freedman, 2001; Wolf, Goldberg-O'Rourke, Gidney, Lovett, Cirino, & Morris, 2002). Wimmer, Mayringer, and Landerl (2000) found the same results with German-speaking children. Each study found poor readers characterized by naming speed deficits in the absence of phonological deficits. Each study also found that poor readers exhibiting both deficits had the most severe reading impairments, supporting the argument that naming speed contributes independently to reading ability.

To summarize, cross-linguistic studies have found that RAN performance is related to reading in languages where phonological demands are reduced. RAN performance has been found to explain unique variance in reading ability, separate from that accounted for by phonological processing tasks. Other studies have found that naming speed and phonological abilities make separate and combined contributions to reading ability, and that poor readers can have deficits in naming speed without a corresponding deficit in phonological processing. All these studies point to the independence of naming speed from phonological processing, suggesting that the relationship between RAN performance and reading is not mediated through phonological processing skills. However, there are other processes that are related to reading that may account for the relation between RAN performance and reading.

Relationship Between RAN and Other Reading Subskills

Many studies have shown that RAN performance makes a contribution to reading independently from the contributions of other predictors of reading such as verbal ability, IQ, and memory (e.g., Bowers & Swanson, 1991; Bowers, Steffy, & Swanson, 1986; Bowers, Steffy, & Tate, 1988; McBride-Chang & Manis, 1996; Meyer et al., 1998). Bowers, Steffy, and Tate (1988) directly examined the relation between naming speed on a RAN task, verbal and performance IQ, and memory span. Memory span was measured with a digit span test and a sentence memory test. For the latter, sentences of progressively longer lengths were orally presented to be repeated by the children. Verbal

IQ and performance IQ were both assessed by the Wechsler Intelligence Scale for Children – Revised. Both RAN-colors and RAN-digits were measured, but as they found no differences between poor readers and average readers on RAN-colors, only RAN-digit scores were used in the analysis. Children of all reading ability were included in this study and ranged in age from 8 years old to 11 years old. IQ was controlled both statistically and by selection criteria. When both verbal IQ and performance IQ were entered into a hierarchical regression first, RAN continued to account for unique variance in word identification scores. Even when a sample of children with a restricted range of IQ scores was used, RAN continued to account for unique variance in word identification scores, after accounting for IQ. Other researchers have supported this finding. RAN performance still differentiates poor readers from average readers after controlling for differences in IQ (e.g., McBride-Chang & Manis, 1996). RAN performance continues to predict later reading skill once IQ is controlled (e.g., Meyer et al., 1998; Cornwall, 1992) and RAN performance continues to contribute variance to reading scores that is separate from that contributed by phonological processing, once the variance accounted for by IQ has been considered (e.g., Bowers, 1989; Bowers & Swanson, 1991; McBride-Chang & Manis, 1996; Wolf et al., 2002). These studies all suggest that it is not IQ that mediates the relationship between naming speed on the RAN task and reading.

Bowers, Steffy, and Tate (1988) also found that RAN continued to make a unique contribution to reading scores after accounting for the effects of both IQ and memory span. Although others have found significant positive correlations between RAN performance and memory span (e.g., Spring & Perry, 1983), these authors argue that verbal IQ may not have been strictly controlled and the overlap may be a result of the shared contribution of verbal ability to both the RAN task and memory span tasks. Others researchers have supported the results of Bowers and colleagues (Bowers, Steffy, & Swanson, 1986; Wagner et al., 1993), indicating that memory span is not the process through which RAN performance is related to reading.

Denckla and Cutting (1999) described a study in which they examined the relation between RAN performance and a number of other factors related to reading. In addition to examining predictors of reading such as phonological awareness, orthographic awareness, and memory span, they also examined two factors possibly related to RAN performance - general processing speed and articulation rate. For a group of normal readers in Grades 1, 2, and 3, they found that although some of the variables shared some variance with RAN performance, none of the variables tested could fully explain RAN's contribution to word reading. RAN performance continued to contribute unique variance to reading words even after accounting for all other variables. This suggests that RAN performance impacts reading independently from phonological awareness, orthographic awareness, memory span, articulation rate and general processing speed. This finding supports the previous studies that have found RAN performance to make unique contributions to reading above that contributed by phonological processing skills, and also supports the findings of Bowers, Steffy, and Tate (1988) in regards to memory span.

Studies have supported the results of Denckla and Cutting (1999) further. Neuhaus, Foorman, Francis, and Carlson (2001) examined two cognitive components shared by the RAN task and reading, articulation rate and pause length. Using children in

Grades 1 and 2 they measured both of these components on the RAN task to determine whether differences in these components could account for the differences on the RAN task between readers of differing skill. Articulation rate was defined as the time to articulate the name of the symbols on the RAN task. Pause length was defined as the duration of time between the articulations of the stimulus names. The authors suggested that differences in either of these measures could account for the differences found on the RAN task for readers of differing skill, and may provide information concerning how RAN performance is related to reading. They found that although pause time between naming letters was predictive of reading ability, articulation speed was not. Differences in pause time between impaired and average readers may reflect the extra time needed by impaired readers to relinquish the name of one symbol and move on to processing the next symbol. Wolf and Bowers (1999) described similar results showing that differences on the RAN task between impaired readers and average readers were not due to differences between the groups in articulation rate. These results suggest that the differences found between impaired readers and average readers on the RAN task are not a result of poor readers' slower ability to articulate the names of the symbols.

On the basis of these findings, it can be argued that naming speed on the RAN task is related to reading independently of other well established predictors of reading. This would suggest that RAN performance is tapping into another distinct process that can also interfere with the development of reading ability. However, an understanding of what process or processes do account for the variance in reading ability that is captured by the RAN task remains unclear. Several theories have been presented that attempt to explain how RAN performance is related to reading ability. These theories and related evidence will now be reviewed.

Theories of RAN's Relation to Reading

Researchers agree that the RAN task is an index of the ability to make a connection between a visual symbol and a verbal output (Bowers & Wolf, 1993; Denckla & Cutting, 1999; Klein, 2002; Manis, Seidenberg, & Doi, 1999; Wolf & Bowers, 1999). However, opinions differ among researchers on where in this process a breakdown occurs, and how this breakdown subsequently affects reading. Bowers and Wolf (1993; Wolf & Bowers, 1999) were among the first to propose a theory as to the relation between RAN performance and reading ability. Bowers and Wolf first suggested that RAN is related to reading through its effects on orthographic knowledge; that is, RAN performance is associated with the ease of building up orthographic representations. In fluent reading, letter patterns in a word are recognized as a single unit, rather than sounded out letter by letter (Ehri, 1992; Perfetti, 1992). These multi-letter units become represented in the processing system through the repeated processing of letters that frequently occur together. Concurrent processing of letters that frequently occur together enables associations to form between these letters. Once these associations are formed and represented in the processing system, these multi-letter units are retrieved as a whole from the lexicon to support fluent reading. Recognition of these letter patterns is quicker than decoding or sounding out phonemic units of the same words (Barker, Torgesen, & Wagner, 1992). Bowers and Wolf (1993; Wolf & Bowers, 1999) suggested that children with slow naming speeds are unable to establish these good quality orthographic representations that are needed to support fluent reading. This deficiency in forming orthographic representations results from individual letters in a word being processed too slowly to enable their concurrent processing so that associations form between letters. As a result of this lack of knowledge of letter patterns, these children do not develop representations of orthographic patterns that commonly occur in written English. Deficits in orthographic representations result in slow word recognition and impair reading development (Ehri, 1992; Perfetti, 1992).

Wolf and Bowers (1999) have also speculated as to the mechanisms underlying the inability to process letters close enough together in time to form associations between letters. Based on evidence from neurological studies, they have proposed two non-exclusive hypotheses to explain this deficit. The first of these hypotheses suggested that the breakdown occurs with the visual identification of a symbol that then is to be connected to a verbal label. Wolf and Bowers proposed that this breakdown might be related to deficits in the magnocellular stream of the visual system, which is one of two pathways that carry information from the retina to the visual cortex.

The magnocellular pathway and the parvocellular pathway are each sensitive to different characteristics of the visual display (Livingstone & Hubel, 1988). The parvocellular pathway transmits information slowly, predominates in central vision and responds to color and high spatial frequencies. High spatial frequencies provide information about fine details. In contrast, the magnocellular system does not respond to color, predominates in peripheral vision, has neurons with larger receptive fields than the parvocellular system, processes information faster than the parvocellular system, and responds to low spatial frequencies. Low spatial frequencies provide information about the global shape or form of objects in the visual display. The two pathways process information in parallel, but processing in the magnocellular system begins 90 to 120 milliseconds prior to processing in the parvocellular system (Chase, 1996; Keen & Lovegrove, 2000; Livingstone & Hubel, 1988). Therefore, perceptual identification of a symbol or an object begins with low frequency information, such as the global shape, and the high frequency information, such as fine details, is gradually filled in. As reading begins with the perceptual identification of letters, any deficit within the visual system could have an effect on reading ability.

Several studies have reported visual perceptual deficits for individuals with dyslexia (e.g., Williams & Lecluyse, 1990), and specifically, deficits within the magnocellular system (Chase, 1996; Demb, Boynton, Best, & Heeger, 1998; Livingstone, Rosen, Drislane, & Galaburda, 1991). For instance, Livingstone and colleagues (1991) found reduced cell and axon size, and a reduced number of cells in the magnocellular system in the brains of adults with dyslexia. Livingstone argued that these cellular abnormalities would affect the speed with which visual information was processed. In support of this argument, Chase (1996) examined processing speed in both the magnocellular system and the parvocellular system of individuals with dyslexia using a flicker fusion study and found that adults with dyslexia were slower to process information through the magnocellular system than were controls, but that processing speed in the parvocellular system was the same. These results lend support to the argument that deficits in the magnocellular system may play a role in reading disability, and provide the foundation for the hypothesis suggested by Wolf and Bowers (1999).

This hypothesis suggests that when the underlying rate of processing in the visual system is disrupted, the formation of orthographic representations that support fluent reading is disrupted, and this is indexed by naming speed on the RAN task. This disruption in visual processing occurs in the magnocellular stream of the visual system, which is responsible for processing low-spatial frequency components that give information about the shape and form of stimuli. This difficulty processing shape and form results in problems recognizing individual letters, and the need for more time to do so. If the speed and quality of visual information at the level of low spatial frequencies were compromised, efficient letter identification is prevented, which in turn impairs the establishment of good quality orthographic representations necessary to support fluent reading. Indeed, Chase (1996) has argued that when low spatial frequencies are processed too slowly, the ability to make rapid visual discriminations and to establish representation of letters and letter clusters in memory is impaired. This is because efficient visual perception requires the integration of information from both the magnocellular system and the parvocellular system, and precise timing is necessary for this integration. Bowers and Wolf have argued that this slowed processing of information through the magnocellular system would result in slower serial naming speed on the RAN task, as well as interference in making connections between letters that commonly occur together in words. Therefore, if naming speed and the acquisition of orthographic representations are affected by the same underlying process, this would explain why naming speed is a good predictor of reading ability.

The second hypothesis put forth by Wolf and Bowers (1999) suggests that slow naming speed is indicative of a more general timing deficit exhibited by individuals with dyslexia that impairs performance across a number of domains. Studies have shown that individuals with dyslexia have a number of processing speed deficits in the perceptual, linguistic, and motoric domains, especially when complex tasks are used that involve some integration of multiple subprocesses (e.g., Farmer & Klein, 1995; Chase, 1996; Tallal, 1980; Stein, 1993). Wolf and Bowers (1999) conceptualize the naming process as a multi-component process that involves the integration of a number of subprocesses including attention, visual processing, integration of visual information with stored orthographic representations and phonological representations, access and retrieval of phonological labels, activation and integration of semantic and conceptual information, and motoric activation leading to articulation. Therefore, they suggest that slow naming speed may result from a deficit within a larger, more general system of timing deficits that carry across domains. As the subprocesses involved in naming speed are also hypothesized to be components in reading, this would explain the relationship between naming speed and reading.

If naming speed deficits are a result of a more general timing deficit, there are a number of ways in which the naming process could break down. Precise timing is necessary for a number of the sub-processes shared between the RAN task and reading. As noted earlier, precise timing is involved in the processing of visual information in the magnocellular system. Timing requirements are also involved in the integration of subprocesses, such as the rapid integration of low-level visual processes with lexical access or lexical retrieval. Therefore, deficits in timing in any one subprocess, or a deficit in a combination of subprocesses, could result in slow naming speed. As reading also involves the integration of the same low-level perceptual processes with higher linguistic and conceptual processes, a general timing deficit could also impair reading ability.

As stated earlier, the two hypotheses put forth by Wolf and Bowers (1999) are not mutually exclusive. A breakdown in one subprocess such as visual processing of low spatial frequencies, may affect only the development of orthographic representations. However, a more general timing deficit, as proposed by their second hypothesis, could affect not only visual processing, but other subprocesses as well. For example, Tallal (1980) argued that deficits in phonological processing are related to problems in auditory temporal processing. Therefore, a child with reading difficulties could have a breakdown in one subprocess such as visual processing of low spatial frequencies, which would affect only the development of orthographic representations, or a breakdown in several subprocesses such as visual processing and auditory processing which could affect the development of both orthographic and phonological representations. This explanation would support the "double deficit hypothesis" proposed by Wolf and Bowers (1999) in which poor readers can have a deficit in either naming speed or phonological abilities without a deficit in the other, or poor readers could have a deficit in both processes, leading to the most severe reading impairments because these children would not have a compensatory route available to them.

Several predictions are suggested from the theory of Bowers and Wolf (1993; Wolf & Bowers, 1999). If RAN performance is related to reading through its effect on orthographic knowledge, then it would be expected that (1) because children with slow naming speed on the RAN task are slower to make associations between letters in a word, they would require more practice or exposure to a word in order to establish an adequate orthographic representation to support fluent reading and (2) that slow RAN children would be both less sensitive to large orthographic patterns within words and would also show deficits in orthographic knowledge compared with children with fast naming speeds.

Studies have examined these issues. In regards to slow RAN children requiring more practice or exposure, studies have found somewhat inconsistent results. Bowers and Kennedy (1993) studied both poor and average readers in Grade 2 and found that naming speed for words presented in isolation was related to naming speed on a RAN task. Slow RAN children were slower than fast RAN children to read an isolated word after 10 repetitions, even after controlling for word reading speed on the first trial. That is, they gained less speed with each exposure to the word than the fast RAN children. These results suggest that the slow RAN children did not show equivalent improvement to that of fast RAN children with the same amount of practice. Bowers and Kennedy concluded that slow RAN children benefited less than other children with each practice repetition of the words. Bowers (1993) found similar results using repeated readings of text. These results support the idea that slow RAN children may need more exposure or practice with a word to show the same benefits as other children.

Levy and colleagues (Levy, Abello, & Lysynchuk, 1997; Levy, Bourassa, & Horn, 1999) examined this issue more extensively. In one study, Levy, Abello and Lysynchuk (1997) examined the benefits of single word practice on the reading fluency of poor readers with slow and fast naming times. Both groups of readers were trained on 90 content words that would be included in the text readings used to measure fluency. Texts were at a grade level below the child's grade, thus ensuring that these words would be easy for the children to learn. Each child received five repetitions of the 90 words on each of four days for a total of 20 repetitions. In this training phase, although slow RAN children had slower word identification times than the fast RAN children, there was no difference in gains of word recognition speed between fast RAN and slow RAN groups. That is, in the training phase, both slow RAN and fast RAN groups decreased their word naming times over repetitions. Text readings that incorporated these 90 trained words were then used to measure reading fluency. Both groups again showed decreases in reading time over repetitions, and in fact, it was the slow RAN group who showed a slight tendency to benefit more from practice than the fast RAN group. These results provide little support for the hypothesis that readers with slow naming speeds require more practice than do readers with fast naming speeds to show equal gains in reading fluency.

However, Levy, Bourassa, and Horn (1999) provide some support that readers with slow naming speeds do *not* show equal gains from the same amount of practice. In contrast to the previous study in which easy words were used and the children were trained for speed, this study used words that were unfamiliar to the children, and their acquisition was measured over training trials. Different training methods were used in this study to examine whether fast RAN readers and slow RAN readers were differentially responsive to these training regimes. Each child received training on 48 words, in one of three conditions. Training methods included onset-rime training (e.g., ch-ide, chide), phoneme segmentation training (e.g., p-l-a-n-k, plank), and a whole word method in which words were not broken down into smaller units. Results indicated that across all training conditions, the fast RAN group acquired more words (total words read correctly) per trial than the slow RAN group, thus showing faster word acquisition. This finding provides support for the hypothesis that readers with slow naming times need more practice. But, of particular interest in this study was the response of the slow RAN readers to the whole word training condition. In both segmentation conditions, once the pretest differences in word recognition were partialled out, the fast and slow RAN children did not differ in the final number of new words acquired. Therefore, although the slow RAN group acquired fewer words in the first few training trials than did the fast RAN group, by the end of training the slow RAN groups had caught up to the fast RAN group. However, the slow RAN children showed much slower word acquisition when trained with the whole word method, and by the end of training were still far behind the fast RAN group in total words acquired. This result indicates that children with slow naming speed do not show the same benefit with the same amount of practice as do children with fast naming speed. Taken together, the results of these studies suggest that the *type* of practice slow RAN children have with words may have differential effects on their gains.

Deficits in orthographic knowledge have also been found with slow RAN children. Bowers, Sunseth, and Golden (1999) examined orthographic skill in children in Grade 3 who had a single deficit in naming speed or a single deficit in phonological processing skills. Children with a naming speed deficit performed less accurately than children without a naming speed deficit on two measures of orthographic knowledge. Manis, Seidenberg, and Doi (1999) found that for children in Grades 1 and 2, performance on the RAN task correlated better with three measures of orthographic skill, than with measures of phonological awareness. These results support a relation between performance on the RAN task and orthographic skills, one of the basic tenets of Bowers and Wolf's (1993; Wolf and Bowers 1999) theory.

Other research findings have questioned the relation between performance on the RAN task and orthographic skill. Bowers, Sunseth and Golden (1999) examined whether slow RAN children were less sensitive to letter patterns within a word. In a series of studies, they devised a "quickspell" task that required readers to report as many letters as they remembered from briefly displayed four letter arrays that varied in their orthographic structure, real words (e.g., name), pseudowords (e.g., pake), and illegal nonwords (e.g., tmln). According to the Wolf and Bowers' (1999) position, lack of orthographic knowledge as a result of slow letter identification should have led to less sensitivity to the orthographic structure in words and pseudowords, for slow RAN children, compared with fast RAN children. Therefore, slow RAN children would be less accurate than fast RAN children across all letter strings, and they would show little benefit in reporting letters from real words and pseudowords over unrelated letter strings.

However, the results reported by Bowers and colleagues (1999) indicated that performance on the RAN task was related to the number of letters reported only in orthographically *illegal* letter strings. Slow RAN children reported fewer letters in the illegal letter string condition than fast RAN children, but these groups did not differ from each other in reporting letters from words and pseudowords. These results indicated that slow RAN children were using the orthographic redundancy in words and pseudowords to aid in letter processing. Bowers (2001) describes similar sensitivity to orthographic structure in a number of tasks for slow RAN children. These results are inconsistent with the idea that naming speed on the RAN task is related to reading through its effect on the growth of orthographic knowledge as postulated by Bowers and Wolf (1993; Wolf & Bowers, 1999).

Based on the results reported by Bowers, Sunseth, and Golden (1999), Bowers (2001) recently suggested that the processes underlying the RAN task are not responsible for the deficit in orthographic knowledge, but rather contribute to poor reading independently of level of orthographic knowledge. She refined the RAN theory proposed by Wolf and Bowers (1999), suggesting that slow naming speed on the RAN task reflects incomplete processing of letter strings with little orthographic structure. She suggested that this is a low-level visual identification deficit. Processing of letter strings with little orthographic structure she terms a "baseline" upon which the additive effects of orthographic knowledge build. Therefore, this problem in the baseline speed of letter processing, plus reduced orthographic knowledge, contribute independently to reading skill. Further, orthographic knowledge gained from sources such as print exposure, add to the perception and more complete processing of letter strings with orthographic structure. What is important to note is that this baseline deficit does not contribute to orthographic knowledge as originally proposed by Bowers and Wolf (1993; Wolf & Bowers, 1999), but rather affects reading ability independently of orthographic skill. Although individual differences in orthographic knowledge can alter the perceptibility of letters in a word, both speed of processing individual letters and orthographic knowledge independently contribute to variance in reading ability.

This revised theory is more consistent with the quickspell results reported by Bowers, Sunseth, and Golden (1999). Bowers (2001) argued that slow RAN children were able to use orthographic structure to improve performance on the quickspell task, where accuracy was better for words and pseudowords than for illegal letter strings. The differences in performance on the illegal letter strings would be a result of differences in the proposed baseline deficit. Put another way, Bowers states that both slow RAN children and fast RAN children will benefit from the higher level of orthographic structure found in words and pseudowords compared with nonwords. However, the help that orthographic structure provides starts at a much lower baseline level in slow RAN children, reflecting their deficit in baseline speed of processing letter strings of little orthographic structure.

Manis, Seidenberg, and Doi (1999) have also speculated as to the relation between RAN performance and reading. These authors also suggested that slow performance on the RAN task reflects a deficit in making the connection between a visual symbol and a verbal output, but they argue that it is a verbal labeling problem. They argue that slow RAN performance results from difficulty in making arbitrary associations between a symbol (e.g., digit) and its name. This deficit in making arbitrary associations is related to the learning of arbitrary orthographic knowledge about words, and therefore affects sight word reading. In particular, they argued that RAN performance is related to exception word reading (e.g., island, have). Arbitrary, word specific orthographic knowledge is required to read exception words because they do not follow spelling-sound correspondences and cannot be read through knowledge of other words. Manis and colleagues tested this idea and found that RAN performance was negatively correlated with exception word reading for children in Grade 1 and 2. Children with the highest (slowest) RAN scores read fewer exception words. By itself, this result appears to support the notion that RAN performance reflects the ability to make arbitrary associations. However, they found a similar relationship between RAN performance and other measures of orthographic skill, and therefore, it could be argued that these results support Wolf and Bowers' (1999) theory that RAN performance is related to reading through its effects on orthographic knowledge.

At present there is considerable debate as to how RAN performance is related to reading. Bowers and Wolf (1993; Wolf & Bowers, 1999) argued that the underlying process(es) that RAN taps into are causally related to orthographic knowledge and thus affect reading ability through this knowledge. Bowers (2001) later argued that RAN performance is a measure of a baseline speed of processing letters, and that this process contributes to reading independently from orthographic knowledge; that is, there is no causal relationship between RAN performance and orthographic knowledge. Manis and colleagues (1999) suggested that RAN performance reflects the ability to make arbitrary associations, and that an inability to make these associations can affect sight word reading. In order to discriminate among these theories, it would be beneficial to examine the abilities and deficits of children with slow naming speed on many tasks that measure different reading-related skills. This thesis focused on the letter and letter pattern processing abilities of slow RAN children to answer several specific questions generated by the proposed theories.

Overview of Experiments

The first three experiments of this thesis used a paradigm adapted from the work of Berninger (1987) to examine the difficulties slow RAN children have in processing letter patterns of different sizes in both words (Experiments 1 and 3a) and nonwords (Experiments 2 and 3b). This task consisted of presenting a word or a nonword for a fixed amount of time, followed one second later by a probe. The probe was a single letter, a letter cluster, or a whole word/nonword. Children judged whether or not the probe had been present in the preceding word/nonword. Berninger used this task to examine different types of visual information readers extract from a word, and how this might change with development. The task was used here to examine the nature of the units within words that slow RAN children have difficulty processing. Experiment 1 in Chapter 2 examined the size of the orthographic unit within a word that slow RAN children have difficulty in processing. According to Bowers and Wolf (1993; Wolf & Bowers, 1999), slow RAN children should show deficits in processing individual letters, and even larger deficits in processing orthographic units larger than a single letter. This hypothesis was addressed by using real words and probing different sized orthographic units.

Experiment 2 in Chapter 2 questioned what role orthographic structure plays in the processing difficulties exhibited by slow RAN children by examining whether slow RAN children showed similar deficits as in Experiment 1 when orthographic structure was absent. This was done using orthographically illegal letter strings. Further, because Bowers and Wolf (1993; Wolf & Bowers, 1999) argued that slow RAN children have deficits in orthographic knowledge, it follows that they would not benefit to the same degree as fast RAN children from the orthographic structure found in real words. Therefore, for slow RAN children, performance for real words and orthographically illegal nonwords may show little difference. Experiment 2 examined this issue by directly comparing performance on words with orthographic structure and nonwords without orthographic structure.

Chapter 3 explored a possible reason for the processing difficulty exhibited by the slow RAN children in Experiments 1 and 2. Experiment 3a and 3b questioned whether a longer time to study the initial letter string would compensate for the slower processing of letters in a sequence by slow RAN children and improve the memorial representation of that sequence. If inadequate processing time alone accounts for the difficulty that slow RAN children have in processing letters in a sequence, performance would improve if they had more time to process the initial words and were able to establish a better representation to compare with the probe. Both real words (Experiment 3a) and nonwords (Experiment 3b) were examined to explore whether a longer study time would differentially affect the processing of words and nonwords.

Chapter 4 describes a training study designed to answer two major questions. As the previous four experiments indicated that slow RAN children have difficulty processing individual letters in a sequence, I wondered whether I could train these children to process individual letters more efficiently, and if so, what effect this would have on their reading skills. In addition, the training study examined Bowers (2001) theory that training in *either* speeded letter recognition or orthographic pattern recognition would improve reading skills, and that theoretically, training in both would provide an even greater benefit. This training study examined the separate and combined effects of training in each of these skills for slow RAN children; poor readers with slow naming times on the RAN task. A crossover design was used in which children first received either training in speeded letter recognition or orthographic pattern recognition. Upon completion of this phase of training, children were tested on a variety of reading measures to examine the separate effects of each type of training. Following this testing period, children then received the other type of training. Reading measures were again administered upon completion of this final phase of training to examine the combined effects of both training regimes on reading skills.

Chapter 5 discusses the theoretical and educational implications of the studies described in this thesis.

A Note on Statistical Analyses

The statistical analyses used in the experiments reported in this thesis were basic mixed design repeated measures analyses of variance with both between-subject factors and within-subject factors. Except where indicated, post-hoc analyses were conducted using the Newman-Keuls test with alpha set at .05. A Newman-Keuls test allows for multiple pairwise comparisons without increasing the chance of a Type I error above the alpha level that has been set. Therefore, with alpha set at .05, there is a less than 5% chance of rejecting the null hypothesis when it is true, or saying that a difference exists between means when in reality there is no difference. This test solves for the smallest difference between means needed to be considered statistically significant.

CHAPTER 2

The Effect of Orthographic Structure on Letter Processing

Experiment 1: Sensitivity to Letter Patterns with Orthographic Structure in Slow and Fast RAN Children

In light of the debate concerning the role of orthography in the relation between RAN performance and reading, Experiment 1 explored the nature of orthographic units that present problems for slow RAN children. This experiment used a probe task to examine differences in the rapid processing of orthographic units of varying size for three groups of children differing in reading skills. To relate performance on this task to naming speed deficits, two groups of poor readers were chosen. These two groups of poor readers differed only on RAN performance. One group of poor readers had a naming speed deficit (slow RAN group) while the other group of poor readers did not have a naming speed deficit (fast RAN group). Because most poor readers also have a deficit in phonological processing, the slow RAN group used here was most akin to Wolf and Bowers' (1999) double-deficit group. The fast RAN children were most akin to their single phonological deficit group. Performance of these two poor reader groups was contrasted with the performance of a group of average readers. This enabled identification of which deficits were related to poor reading skills, and more specifically, which deficits were related to naming speed deficits. Participants were briefly presented a word, followed by a probe of varying size, either a single letter, a 2-letter cluster, or a whole word. Children were to judge whether the probe had been present in the preceding word. If slow RAN children process individual letters too slowly, resulting in poor representation of larger orthographic units as postulated by Bowers and Wolf, then they should show deficits compared with fast RAN children, in recognizing single letters in a briefly presented word. Because of the slow RAN children's deficit in representing larger orthographic units, they should show an even greater deficit compared with fast RAN children in recognizing larger orthographic clusters. As skilled readers do not sound out words letter by letter, but rather recognize letter patterns within a word (Ehri, 1992), average readers should recognize letter patterns in the present task more accurately than both poor reading groups.

The present experiment also compared blocked versus scrambled presentation of probe types in order to examine the use of strategy. By blocking probe types together, information about the size of the unit to focus on when processing the initial word was available. It was questioned whether this information could be used by the slow RAN children to differentially aid their performance. Therefore, the present experiment presented the probe types blocked by unit size for half of the participants, and scrambled for the other half of the participants so that all unit sizes occurred in a random arrangement.

Method

Participants

One hundred and eight children in Grade 2 classrooms of the Hamilton-Wentworth Catholic District School Board were selected for participation in this study. To select these 108 children, 731 children were screened in 43 schools. Permission for participation was obtained from the Board, the schools, and parents. Two selection measures were administered for each child, and on the basis of these results, selected children were divided into three groups. First, each child was administered the word identification subtest of the Wide Range Achievement Test - Third Edition (WRAT-3; Wilkinson, 1993). The WRAT-3 is a standardized test of word identification that begins with simple words such as "in" and "cat" and progresses to more difficult words such as "oligarchy" and "terpsichorean". Students who scored above a standard score of 90 on the WRAT-3 were assigned to the average reader group. Students who scored below a standard score of 90 on the WRAT-3 were assigned to one of two poor reader groups.

Next, each student in the sample was administered a rapid automatized naming (RAN) test, adapted from Bowers and Swanson (1991). This test consisted of two matrices of digits. Each matrix contained eight rows of six digits. For each matrix the digits 1 through 9, excluding the two-syllable "seven", occurred randomly with no immediate repetitions. The digits were presented in white on a black computer screen. The time to name all digits in the matrix was recorded via the computer. Timing began with presentation of the matrix. When the last digit was read, the experimenter pushed a key to erase the display from the computer screen and to stop the clock. The dependent measure was the time required to read all 48 digits. The student's RAN score was the mean naming time in seconds for the two RAN trials.

On the basis of these two selection tests, three groups of 36 participants each were formed. Students identified as poor readers on the WRAT-3 were divided into a fast RAN group and a slow RAN group on the basis of the criteria used in Levy, Bourassa, and Horn (1999). Levy and colleagues administered the RAN task to 128 poor readers in Grade 2 and found the median RAN score on the test used here to be 41.5 seconds. Therefore, in the present study, poor readers with a RAN score equal to or slower than 41.50 seconds were assigned to the slow RAN group. Poor readers with a RAN score faster than 41.50 seconds were assigned to the fast RAN group. Average readers also completed the RAN task. Three of these average readers were dropped from the analyses because their RAN scores were slower than the cutoff for slow RAN poor readers (41.5 seconds). This left a group of 33 average readers with RAN scores above the slow RAN cutoff. Thus, two poor reading groups (a fast RAN group and a slow RAN group) and one average reading group were formed. Table 1 presents mean scores on the selection measures for each of the three groups.

RAN scores and WRAT-3 scores were each subjected to an analysis of variance with reading group as the independent factor to check the reliability of the groupings. For the WRAT-3 scores, there was a reliable effect of reading group, $F(2,97)=178.53$, $MSe=41.37$, $p<.001$. Newman-Keuls post hoc analysis indicated that the average reading group differed from the two poor reading groups. There was no difference between the slow RAN group and the fast RAN group on WRAT-3 scores.

There was also an effect of reading group on the RAN scores, $F(2,97)=108.525$, $MSe=33.08$, $p<.001$. Newman-Keuls post hoc analysis indicated that the average reading group and the fast reading group did not differ in naming speed, but the slow RAN group was significantly slower than the fast RAN group and the average reading group.

Table 1

Means (M) and Standard Deviations (SD) on Selection and Descriptive Measures

Group	WRAT-3	RAN	Phoneme Counting	Rhyme Generation	Digit Span
Slow RAN (n=34)					
M	81.18	51.83	.40	11.9	9.4
SD	5.29	6.63	.18	7.6	3.1
Fast RAN (n=31)					
M	84.10	34.49	.40	15.7	8.9
SD	4.29	4.13	.21	6.7	2.0
Average (n=33)					
M	108.42	33.30	.47	22.3	11.7
SD	8.76	6.07	.20	8.9	2.9

Note. WRAT-3 scores are standard scores (M=100, SD=15), RAN scores are seconds, phoneme counting is percent correct, rhyme generation is the number of words generated, digit span is standard Score (M=10, SD=3).

The experimental task involved the presentation of a word to be retained in memory in order to compare to the probe. Therefore, to ensure that any differences on the experimental task could not be attributed to differences in memory abilities between the groups, memory span was measured using the digit span sub-test of the Wechsler Intelligence Scale for Children - Revised (WISC-R). Standard scores for each group are presented in Table 1 and are based on a mean of 10 and a standard deviation of three. An analysis of variance with reading group as the independent factor indicated there was an effect of reading group, $F(2,97)=9.98$, $MSe=7.39$, $p<.001$. Newman-Keuls post hoc analysis revealed that both poor reader groups differed from the average reader group, but did not differ from each other. This result is consistent with previous research that suggests that poor readers have lower performance than average readers on measures of memory span (e.g., Daneman & Carpenter, 1980; Levy & Hinchely, 1990). In addition, these results indicate that any differences found on the experimental measures between the fast RAN group and the slow RAN group cannot be attributed to differences in memory span, although differences between poor and average readers may be related to memory capacity.

Each child also completed two measures of phonological processing ability. One was a rhyme generation task in which children orally generated words that rhymed with 10 orally presented words (bug, cut, flag, rash, get, tell, hill, lip, mop, not). The dependent measure was the number of rhyming words generated for the set of 10 words. The second task was a phoneme counting task in which the child was instructed to count the number of sounds in each of eight words (paw, who, chill, fit, from, clap, craft, fringe) and eight nonwords (oag, tay, pell, wop, pisk, dest, sconch, blant). The dependent measure was the percent correct. Although most poor readers have problems with phonological processing skills, the extent of the problem in the present study was measured so that differences on this dimension between the groups could be taken into account[1]. Analyses revealed an effect of reading group for both the phoneme counting task, $F(2,97)=1.36$, $MSe=.04$, $p=.26$, and the rhyme generation task, $F(2,97)=14.95$, $MSe=61.13$, $p<.001$. Post hoc analyses revealed that for both measures of phonological processing, there was no difference in performance between the slow RAN group and the fast RAN group. The average reader group performed better than both poor reader groups. Therefore, any differences found on the experimental measures cannot be attributed to differences in phonological processing ability between the slow RAN group and the fast RAN group.

To summarize, three groups of children participated in this study. Two poor reading groups that were matched for reading level but differed on naming speed were included. Performance of these two groups was compared to a group of average readers.

Material and Design

The probe task used in this experiment was a modification of one used by Berninger (1987). Berninger used this task to examine types of visual information readers extract from a word, and how this might change with development. The task involved presenting participants a word and then a probe. Participants were to make a yes/no judgment as to whether the probe had been present in the preceding word. Whereas Berninger presented words of differing length and probed letter clusters of differing lengths, the present experiment used only 4-letter words, and probed only single

[1] Two slow RAN readers and five fast RAN readers were also dropped from the analyses because their scores on a test of phonological processing skills used to match groups on this ability were more than two standard deviations above the mean. This resulted in a group of 34 slow RAN readers and a group of 31 fast RAN readers

letters, 2-letter clusters, or whole words. This task was used to measure readers' ability to recognize letter patterns of varying sizes within a briefly presented word.

The experiment consisted of three conditions that differed only in the size of the probe. In each condition, participants were presented a four-letter word (e.g., land) followed by a probe that was a single letter (e.g., n), a two-letter cluster (e.g., nd), or a whole word (e.g., land). Participants judged whether the probe had been in the preceding letter string. There were 16 trials in each condition, half where the word contained the probe and half where the word did not contain the probe. In addition, the location of the probe letter or letter cluster varied such that on half of the trials the probe was from the middle of the word (e.g., an), and on the other half of the trials the probe unit came from the beginning (e.g., la) or end (e.g., nd) of the preceding word. In the whole word condition, on half of the trials the probe word was the same as the preceding word, and on half of the trials the probe word changed by one letter, but still made a real word. On the trials where the probe word changed by one letter, the position of this letter varied across trials. Half of these trials had the letter change in the interior of the word (e.g., land - lend) and half of these trials had the letter change at the beginning or the end of the word (e.g., name - same, card - cart). This was to ensure that participants would process the entire word rather than focus on one particular location within the word.

Presentation format was also manipulated. For half of the participants the trials of each probe-size condition were blocked. The order of presentation of blocks was counterbalanced across participants. For the other half of participants, trials for all probe-size conditions occurred randomly in the trial sequence.

Stimuli were presented on a computer screen as white words on a black background. Each trial consisted of the presentation of a word on the screen for one second. After a one second interval, a probe followed that remained on the screen until a response was made. Responses were made by pressing a key on the computer keyboard, one key used for "no" and one key used for "yes". Trials where the probe had been present in the preceding word and trials where the probe had not been present in the preceding word were randomly arranged with no more than three trials of one type occurring in a row. The dependent measure for this task was the proportion correct in each condition.

Twenty-four words were used in this experiment. All words were four letters long and at the Grade 2 level (Educator's Word Frequency Guide, 1996). These 24 words were divided into three lists of eight words each. Each participant saw a different list of words in each probe condition. The three lists of words were counterbalanced across participants so that each list occurred an equal number of times in each condition. For the blocked presentation format, words within a condition were presented in a different random order for each participant. For the unblocked condition in which trials in each condition were randomly mixed together, words were also presented in a different random order for each participant. After completion of the experimental task, a reading test was administered in which all children were asked to read each of the words presented during the experiment.

Finally, because of the hypothesized relation between RAN performance and orthographic knowledge, all participants completed an orthographic choice task to measure orthographic knowledge. This task was a version of the task presented by Olson, Forsberg, Wise, and Rack (1994). The test included 15 pairs of words. Each pair consisted of the correct spelling of a target word, and a homophonic nonword spelling (e.g., berry-bairy, boks-box). Children indicated which of the two alternatives was the correct spelling for a target word used in a sentence. The dependent measure was the percent correct.

Procedure

Children were administered the selection measures (WRAT-3 and RAN) in one 15 minute session. The pretest measures (digit span, phonological processing tasks) and the orthographic choice task were administered on a separate day, followed by the experimental task in a session that lasted approximately 30 minutes. Children were all tested during the second half of the school year.

Results and Discussion

Bowers and Wolf (1993; Wolf & Bowers, 1999) have argued that slow RAN children have a deficit in orthographic knowledge as they do not efficiently process units in a word that are larger than a single letter. The results of the orthographic choice task presented here support this argument. Percent correct for the slow RAN children was .70, for the fast RAN children .82, and for the average readers .93. As predicted, the slow RAN group was less accurate on this task than was the fast RAN group. This observation was supported by an analysis of variance. There was an effect of reading group, $F(2,97)=36.36$, $MSe=.01$, $p<.001$. Newman-Keuls post hoc analysis indicated that the slow RAN group performed less accurately than the fast RAN group, which performed less accurately than the average reading group. These results support previous findings that suggested a relation between performance on the RAN task and orthographic knowledge (Bowers, Sunseth, & Golden, 1999; Manis, Seidenberg, & Doi, 1999).

For the probe task, proportion correct for each reading group is presented in Table 2 for letters, letter clusters, and words as a function of blocked or scrambled presentation. Analyses were conducted on both the set of data that contained only words read correctly and the full set of test items. As the results of these analyses were the same, only the analyses of the full set of test items are presented. A 2 x 3 x 3 mixed analysis of variance was conducted with format (blocked/scrambled) and reading group (average, fast RAN, slow RAN) as between subject factors, and probe type (letter, cluster, word,) as the within subject variable. There were significant main effects of probe type, $F(2,184)=8.17$, $MSe=.01$, $p<.01$, format, $F(1,92)=8.08$, $MSe=.03$, $p<.01$, and reading group, $F(2,92)=35.98$, $MSe=.03$, $p<.001$. However, there was also a significant three-way interaction of reading group, probe type, and format, $F(4,184)=2.48$, $MSe=.01$, $p<.05$. To examine this interaction separate analyses were conducted for the blocked and the scrambled conditions.

A 3 x 3 analysis of variance was conducted for each of the blocked condition and the scrambled condition with reading group as the between-subject factor and probe type as the within-subject factor. In the blocked condition, there was a main effect of reading group, $F(2,42)=23.45$, $MSe=.02$, $p<.001$ and no other effects were significant. Newman-Keuls post hoc analysis indicated that across all probe types the slow RAN group was less accurate than the fast RAN group and the average reading group. There was no difference in accuracy between the fast RAN group and the average reading group.

Table 2

Percent Correct for Probe Types as a Function of Blocked/Scrambled Presentation

Probe Type	Slow RAN (n=34)		Fast RAN (n=31)		Average (n=33)	
	Blocked	Scrambled	Blocked	Scrambled	Blocked	Scrambled
Letter						
M	**.73**	.67	**.93**	.79	**.93**	.90
SD	**.16**	.15	**.07**	.14	**.10**	.10
Cluster						
M	**.70**	.67	**.85**	.72	**.91**	.86
SD	**.13**	.17	**.09**	.18	**.08**	.15
Word						
M	**.77**	.72	**.84**	.86	**.96**	.92
SD	**.17**	.12	**.15**	.12	**.08**	.12

In the scrambled condition, there was a main effect of probe type, $F(2,100)=8.136$, $MSe=.01$, $p<.01$, and a main effect of reading group, $F(2,50)=15.80$, $MSe=.04$, $p<.001$. Newman-Keuls post hoc analysis revealed that all three groups were more accurate with the word probe than with the letter or letter cluster probes. Accuracy for letter probes and letter cluster probes did not differ. This finding indicates that all children, even the slow RAN children, exhibit a word superiority effect, suggesting that word level knowledge improves perception of the constituent elements. In addition, post hoc tests revealed that across all probe types, the slow RAN group was less accurate than the fast RAN group, which was less accurate than the average reading group.

Presentation format had an effect on the performance of the fast RAN group, and on sensitivity to probes for all reading groups. With blocked presentation, no differences in sensitivity among probe types were found for any of the reader groups. Although the slow RAN group was less accurate than the fast RAN group, none of the groups found one probe type more difficult than another probe type. In contrast, with the scrambled presentation, all groups found the whole word condition equally easier than the letter or cluster condition. In addition, performance of the fast RAN group was equal to that of the average reading group with the blocked presentation, whereas with scrambled presentation, the accuracy of the fast RAN group was less than that of the average reader group. Presentation format did not differentially affect the performance of the slow RAN group, compared with the fast RAN group. With either blocked or scrambled presentation, the slow RAN group was less accurate than the fast RAN group.

As expected, the slow RAN group did show deficits with single letters compared with the fast RAN group. However, contrary to the hypothesis derived from the Bowers and Wolf (1993; Wolf & Bowers, 1999) explanation, these deficits were not greater for the larger orthographic clusters. The slow RAN group was less accurate than the fast RAN group across probe types with no increase in the difference for larger probe sizes. These results suggest that slow RAN children have difficulty at the level of the individual letter within an orthographic string and this difficulty is not compounded by orthographic unit size. To summarize the main findings of Experiment 1, the slow RAN children compared with the fast RAN children showed a deficit in orthographic knowledge, as indicated by performance on the orthographic choice task. They also showed a deficit in letter processing, but this deficit was unrelated to the size of the orthographic unit. This dissociation of knowledge and processing results led me to question whether the letter processing deficit was in any way dependent on orthography. Experiment 2 directly examined whether slow RAN children show similar deficits on letter strings with no orthographic structure, and whether orthographic structure in the initial letter string aids their processing of letters in a sequence.

Experiment 2: Sensitivity to Letter Patterns with No Orthographic Structure in Slow and Fast RAN Children

The purpose of the second experiment was to examine whether orthographic structure was critical for the effect found in Experiment 1, by comparing the processing of letter strings with and without orthographic structure. The same probe task described in Experiment 1 was used here to examine the differences among groups in processing letter strings without orthographic structure. To directly compare whether orthographic structure provides a benefit in recognizing letter patterns, real words probed with a whole word were also included. As in Experiment 1, differences in sensitivity to the letter probe would be expected here if the slow RAN children are slower to process individual letters as suggested by Bowers and Wolf (1993). However, if the slow RAN group's deficit lies in difficulty processing larger *orthographic* units, as suggested by Bowers and Wolf (1993), there should be little difference in accuracy between the slow and fast RAN groups on both the cluster and nonword probes in the present experiment because there is no orthographic information available to differentially benefit the fast RAN group. Also, if slow RAN children have a deficit in orthographic knowledge, they should show little benefit in processing words compared with letter strings without orthographic structure. This experiment explored these issues.

Methods

Participants

Seventy-two children who participated in Experiment 1 also completed Experiment 2. Group placement was established as in Experiment 1. Of the 72 children who completed Experiment 2, one fast RAN participant was removed from the analyses because of scores on the rhyme generation task that were more than two standard deviations above the mean. Three average readers were also removed from the analysis because of RAN scores that were above the criteria for slow RAN poor readers (41.5 seconds). The readers removed from the present experiment were among those removed from Experiment 1. This resulted in a group of 24 slow RAN readers, 23 fast RAN readers, and 21 average readers. Table 3 presents mean scores and standard deviations for the selection measures for each of the three groups.

RAN scores, digit span standard scores, and WRAT-3 scores were each subjected to an analysis of variance with reading group as the independent factor to check the reliability of the groupings. Once again, the fast RAN group and the slow RAN group were matched for reading ability and both were below the level of reading ability of average readers, $F(2,65)=120.25$, $MSe=42.57$, $p<.001$. RAN scores for the slow RAN group were significantly slower than RAN scores for the fast RAN group, while the fast RAN group was equal to the average reading group, $F(2,65)=94.43$, $MSe=25.79$, $p<.001$. Digit span was equal for the slow RAN group and the fast RAN group, with better performance for the average reading group, $F(2,65)=5.88$, $MSe=6.44$, $p<.01$. These results verify the group placement.

Table 3

Means (M) and Standard Deviations (SD) for Selection and Description Measures

Group	WRAT-3	RAN	Phoneme Counting	Rhyme Generation	Digit Span
Slow RAN (n=24)					
M	82.08	51.83	.41	12.2	10.2
SD	4.92	6.35	.21	6.2	2.9
Fast RAN (n=23)					
M	83.78	35.61	.40	16.0	9.3
SD	4.55	3.79	.20	6.0	2.0
Average (n=21)					
M	109.43	32.81	.49	21.7	11.9
SD	9.37	4.65	.21	8.9	2.6

Note. WRAT-3 scores are standard scores (M=100, SD=15), RAN scores are seconds, phoneme counting is percent correct, rhyme generation is the number of words generated, and digit span is standard scores (M=10, SD=3)

Scores for the rhyme generation task and the phoneme counting task are included in Table 3 for each group. Analysis of variance on each of these measures indicated that performance was equal for all three groups on the phoneme counting task, $F(2,65)=1.24$, $MSe=.04$, $p=.30$. In addition, the fast RAN group and the slow RAN group were matched on the rhyme generation task, $F(2,65)=10.06$, $MSe=50.06$, $p<.001$. Average readers had higher performance on this task than the two poor reading groups. These findings suggest that any differences found on the experimental task cannot be attributed to differences between the slow RAN group and the fast RAN group in phonological processing skills.

To summarize, three groups of children participated in this study. Two poor reading groups that were matched for reading level, but that differed on naming speed were included. Performance of these two groups was compared to a group of average readers.

Material and Design

The design of this experiment was similar to that used in Experiment 1. Three of the conditions in the present experiment were the same as those used in Experiment 1, except that letter strings that were illegal by the rules of English orthography were used (i.e., nonwords). All nonwords contained only consonants. Each nonword consisted of four letters (e.g., lmdn). Bigram frequency norms were used to ensure that these letter combinations did not occur in these positions in any word in the English language, and therefore these were nonwords with no orthographic structure (Mayzner & Tresselt, 1965).

A fourth condition was added to this experiment to directly compare performance on a word with orthographic structure to performance on a nonword with no orthographic structure. This condition was the same as the word condition in Experiment 1. Therefore, there were a total of four conditions: nonword with letter probes (e.g., lmdn - m), nonword with cluster probes (e.g., lmdn - md), nonword with nonword probes (e.g., lmdn - lmdn) and word with word probes (e.g., land - land).

Twenty-four illegal nonwords and eight real words were used in this experiment. The 24 nonwords were divided into three lists of eight each. Again, each participant saw a different list of nonwords in each condition. The three lists of nonwords were counterbalanced across participants so that each list occurred an equal number of times in each of the nonword conditions. All participants saw the same list of eight real words as these words were only used in one condition. Conditions were randomly distributed across the trials and stimuli were presented in a different random order for each participant (only the scrambled, not the blocked format was used in Experiment 2). The dependent measure for this task was the proportion correct in each condition. All other aspects of the design were the same as in Experiment 1.

Finally, all participants completed the orthographic choice task to measure orthographic knowledge.

Procedure

The procedure was the same as that used in Experiment 1.

Results and Discussion

As with Experiment 1, the results of the orthographic choice are consistent with previous research that has found a relationship between orthographic knowledge and RAN performance (e.g., Bowers et al., 1999; Manis et al., 1999). Percent correct for the slow RAN children was .70, for the fast RAN children .80, and for the average readers .93. Analyses indicated a significant difference among groups, $F(2,65)=23.14$, $MSe=.01$, $p<.001$, with the slow RAN group less accurate than the fast RAN group, and the fast RAN group less accurate than the average group. These results replicate the results of Experiment 1 and provide support for the claim that children with a naming speed deficit have poor knowledge of English orthography.

The probe task in Experiment 2 examined whether orthographic structure was critical for the effect found in Experiment 1. The proportion correct for each reading group is presented in Table 4 for letters, letter clusters, nonwords and words. A 3 x 4 mixed analysis of variance was conducted with reading group (average, fast RAN, slow RAN) as the between subject factor and probe type (letter, cluster, word, nonword) as the within subject variable. There was a significant main effect of probe type, $F(3,195)=34.90$, $MSe=.01$, $p<.001$, and a significant main effect of reading group, $F(2,65)=16.68$, $MSe=.03$, $p<.001$. There was no significant interaction. Newman-Keuls post hoc analysis revealed that across all probe types, the slow RAN group made more errors than the fast RAN group, which in turn made more errors than the average reading group. This result indicates that with orthographically illegal nonwords the slow RAN group was consistently less accurate in identifying units that had been present in a briefly presented letter string, regardless of the size of the probe. This result replicates the results found with real words in Experiment 1. These results suggest that slow RAN children have difficulty with processing individual letters, whether or not orthographic structure is present.

Table 4

Percent Correct for Probe Types

Probe Type	Slow RAN (n=24)	Fast RAN (n=23)	Average (n=21)
Letter			
M	.64	.71	.82
SD	.13	.14	.14
Cluster			
M	.63	.68	.77
SD	.12	.15	.15
Nonword			
M	.67	.77	.82
SD	.12	.13	.15
Word			
M	.79	.86	.95
SD	.14	.11	.08

Newman-Keuls post hoc analysis of the main effect of probe type revealed that for all three groups, there was no difference between letter probes and cluster probes, as was found in Experiment 1 with real words. However, whereas in Experiment 1 word probes were more accurate than both letter and letter cluster probes, in Experiment 2 nonword probes were more accurate than cluster probes only. Letter probes did not differ from nonword probes. However, it is important to note that irrespective of probe size, the slow RAN children were less accurate than the fast RAN children, consistent with the results of Experiment 1. There was no interaction of group with probe type indicating that large probe units did not cause greater problems than single letters for the slow RAN group.

Another important finding resulted from the analysis of word compared with nonword conditions. This analysis revealed that all three reading groups showed increased accuracy for the real word condition compared with the three nonword conditions. Thus, even for the slow RAN group, performance for letter strings with orthographic structure was more accurate than performance for letter strings without orthographic structure irrespective of probe size. This finding indicates that the slow RAN group, as well as the other two groups, was making use of the orthographic structure found in real words to aid performance, contrary to predictions from the Bowers and Wolf (1993; Wolf & Bowers, 1999) explanation. Despite their deficit in orthographic knowledge, slow RAN children were able to use orthographic structure to aid in processing letter strings. This result suggests a fundamental problem in processing letters, irrespective of probe size or of orthographic structure.

Discussion for Experiments 1 and 2

There is considerable debate in the literature concerning the role of orthography in the relationship between performance on the RAN task and reading development (e.g., Bowers & Wolf, 1993; Wolf & Bowers, 1999; Bowers, 2001). Bowers and Wolf suggested that performance on the RAN task was indicative of orthographic knowledge and that performance on the RAN influenced reading ability through its effects on orthographic knowledge. Experiments 1 and 2 did not directly address whether slow processing of individual letters causes the deficits in orthographic knowledge that were observed for slow RAN children in the experiments reported here. However, the results of Experiments 1 and 2 suggest that the difficulty shown by slow RAN children is not limited to the processing of orthographic patterns. As with all children, the slow RAN children do make use of the orthographic structure found in real words to aid performance, but this use does not alter their fundamental problem in processing letters.

Taken together, the results of these two experiments suggest that the difficulty with multi-letter displays exhibited by slow RAN children does not appear to be related to orthography per se. Slow RAN children had equal deficits compared with fast RAN children across all probe sizes, whether or not orthographic structure was present in the initial letter string. These results suggest that the difficulty in processing letter sequences is not a result of deficits in processing orthographic units that are larger than a single letter. The differences in performance between the slow and fast RAN groups for all probe types may be a direct result of an underlying problem in processing individual letters, rather than a problem in processing orthographic units per se. This basic deficit may impair performance on larger sequences with or without orthographic structure, but whether this deficit also causes deficits in orthographic knowledge as proposed by Bowers and Wolf (1993; Wolf & Bowers, 1999) is unclear. In fact, the present results are more consistent with the newer model proposed by Bowers (2001). Bowers suggested that the processes underlying the RAN task are not responsible for the deficit in orthographic knowledge, but rather contribute to poor reading independently of level of orthographic knowledge. She refined the RAN theory proposed by Wolf and Bowers (1999), suggesting that slow naming speed on the RAN task reflects incomplete processing of letter strings with little or no orthographic structure. The results of the present experiments can be interpreted within this framework. Despite the deficits in orthographic knowledge found for slow RAN children, they were able to make use of the orthographic redundancy found in real words to improve performance, as suggested by Bowers (2001).

Bowers (2001) suggested that the RAN task is an index of this baseline speed of letter processing deficit, not the deficit in orthographic knowledge. This deficit, according to Bowers, reflects incomplete processing of a letter sequence. To examine this letter processing problem further, in Experiment 3 I asked whether the inefficient processing of letter sequences might lie in representing the initial stimulus item in memory. I examined whether increasing the time available to encode the initial word (Experiment 3a) or nonword (Experiment 3b) would compensate for the slow letter processing and improve performance on the probe task for slow RAN children.

CHAPTER 3

Experiments 3a and 3b: The Effect of Extended Study Time on Letter Processing

The previous two experiments suggested that slow RAN children have difficulty processing letter strings with or without orthographic structure, consistent with Bowers (2001). Bowers and Wolf (1993) also suggested that slow RAN children have a problem with the speed of processing individual letters. They proposed that the ability to represent the sequencing of letters in a word is an important aspect of encoding that word. If slow RAN children process letters so slowly that the letter sequence is poorly represented, then the probe cannot be easily matched to this poor representation. As a result, accuracy of the slow RAN children would be poorer than that of the fast RAN children, as was found in Experiments 1 and 2. Bowers and Wolf suggested that given the same amount of time to study a word, slow RAN children may only be processing part of the word because of their slower processing of individual letters. Therefore, providing a longer study time to enable complete encoding of the initial word may compensate for slow letter processing and enable these children to set up a better representation of the word with which to compare the probe, thus improving performance for all probe sizes. Using the same experimental paradigm as in the previous experiments, Experiment 3a addressed this issue with real words and 3b with nonwords.

Method

Participants

A new sample of seventy-two children in Grade 2 classrooms of the Hamilton-Wentworth Catholic District School Board participated in both Experiments 3a and 3b. To select these 72 children, 494 children were screened in 31 schools. Selection measures and group placement were as described for Experiment 1. An average reading group, a slow RAN poor reader group and a fast RAN poor reader group were formed. Each group consisted of 24 participants. Table 5 presents mean scores on the selection measures for each of the reading groups.

RAN and WRAT-3 scores were each subjected to an analysis of variance with reading group as the independent factor to check the reliability of the groupings. For the WRAT-3 scores, there was a reliable effect of reading group, $F(2,69))=120.30$, $MSe=27.90$, $p<.001$. Newman-Keuls post hoc analysis indicated that the average reading group differed from the two poor reading groups. There was no difference between the slow RAN group and the fast RAN group on WRAT-3 scores.

There was also an effect of reading group on the RAN scores, $F(2,69)=59.96$, $MSe=54.69$, $p<.001$. Post hoc analysis indicated that the average reading group and the fast reading group did not differ in naming speed, but that the slow RAN group was significantly slower than the fast RAN group and the average reading group. These results indicate that group selection was reliable.

Table 5

Means (M) and Standard Deviations (SD) for Selection and Description Measures

Group	WRAT-3	RAN	TAAS	Digit Span
Slow RAN (n=24)				
M	83.21	54.25	1.2	10.0
SD	6.35	11.16	.83	2.9
Fast RAN (n=24)				
M	83.67	34.50	1.1	8.8
SD	3.85	3.56	.90	1.7
Average (n=24)				
M	103.92	33.53	2.4	11.0
SD	5.35	5.19	.88	2.3

Note. WRAT-3 scores are standard scores (M=100, SD=15), RAN scores are seconds, TAAS is Grade Equivalent, and digit span is standard scores (M=10, SD=3)

Unlike the earlier experiments, phonological processing was assessed using a standardized measure. The Test of Auditory Analysis Skills (TAAS; Rosner, 1979) was used instead of rhyme generation and phoneme counting. The TAAS requires the children to repeat a word while deleting a portion of that word (e.g., say "take", say it again without the "t"). Standardized grade equivalent scores are presented in Table 5. Analysis revealed that the slow RAN group and the fast RAN group were matched on this measure. Both poor reading groups were significantly worse on this measure than the average reading group, $F(2,69)=15.49$, $MSe=.76$, $p<.001$. The digit span subtest of the WISC-R was again used to assess memory span. Standard scores based on a mean of 10 and a standard deviation of three are presented in Table 5 for each group. Analysis revealed a main effect of group on digit span, $F(2,69)=5.456$, $MSe=5.57$, $p<.01$. Post hoc analysis indicated that the fast RAN group and the slow RAN group did not differ on digit span. The fast RAN group also differed from the average group on this measure.

To summarize, the same three groups of 24 children participated in Experiment 3a and 3b. Two poor reading groups (a fast RAN group and a slow RAN group) that were matched for reading ability, phonological ability, and memory span, but differed on RAN performance were included. The performance of these two groups was compared to a group of average readers.

Material and Design

The design of Experiment 3a was the same as that in Experiment 1, except for the study time of the initial word. In Experiment 1 the initial word was presented for one second, followed by a probe after an interval of one second. The probe remained on the screen until a response was made. In the present experiment, four different study times were used, 1 second, 1.5 seconds, 2 seconds, and 2.5 seconds. In each case, the probe followed after a 1 second interval and all probe types were tested at all study times. Thus in all there were 12 basic conditions (4 study times x 3 probe types). Each condition was tested 16 times per participant; for half of these trials the probe was present in the word, and for the other half the probe was not present in the word. Therefore, in all, each participant completed 192 trials (12 conditions, 16 times each). In order to accommodate this large number of trials, the experiment was divided into two sessions of 96 trials, conducted on successive school days.

Ninety-six 4-letter words were divided into 12 lists of eight words each. Each participant saw a different list of words in each of the 12 conditions. These 12 lists of words were counterbalanced across participants so that each list occurred an equal number of times in each of the three probe conditions (letter, letter cluster, whole word) at each of the four study times. All study times and probe types were randomly presented in a different random order for each participant.

Experiment 3b followed the same design except that orthographically illegal letter strings (i.e., nonwords) were used. Ninety-six 4-letter nonwords were constructed. Each nonword was checked with bigram frequency norms to ensure that these combinations of letter did not occur together in any words in the English language (Mayzner & Tresselt, 1965). Each participant saw a different list of nonwords in each condition at each study time. In addition, four lists of eight real words were also used to directly compare letter strings with orthographic structure to letter strings with no orthographic structure. Each participant saw a different list of words at each of the four study times. The four lists were counterbalanced across study times and participants.

Once again the orthographic choice task was administered to all participants.

Procedure

Children were administered the selection measures (WRAT-3 and RAN) in one 15 minute session. The pretest measures and orthographic choice task were administered on a different day, prior to the beginning of the experimental sessions. Experiments 3a and 3b were conducted concurrently. Because each experiment was divided into two parts, testing extended over a period of four days. The order of experiments was counterbalanced across participants such that half of the participants started with Experiment 3a and the other half started with 3b. Children were all tested during the second half of the school year.

Results and Discussion

The results of the orthographic choice task replicate the results of the previous two experiments. The slow RAN group (.70) was less accurate than the fast RAN group (.79), which was less accurate than the average group (.92), $F(2,69)=21.25$, $MSe=.01$, $p<.001$. It is clear from the present studies that slow RAN children have a deficit in orthographic knowledge compared with fast RAN children.

Experiment 3a

The proportion correct for each reading group for the probe task is presented in Table 6 for letter probe, cluster probe, and word probe at each of the four study times. Table 6 shows that the results of the previous experiments have been replicated. The slow RAN group was less accurate across all conditions than the fast RAN group. This observation was supported by an analysis of variance with reading group as the between subject factor, and probe type and study time as within subject factors. There was a main effect of reading group, $F(2,69)=29.64$, $MSe=.10$, $p<.001$, and a main effect of probe type, $F(2,138)=22.108$, $MSe=.02$, $p<.001$. Post hoc analysis revealed that the slow RAN group was less accurate than the fast RAN group across probe types and across study times. The fast RAN group was less accurate than the average reading group. This result indicates that across all probe types, and all study times, the slow RAN group was consistently less accurate in identifying whether or not units had been present, irrespective of study time to encode the initial word. These findings replicate the results of Experiment 1 with real words.

In addition, all three groups were less accurate on the cluster probes than the letter or word probes. Accuracy on the letter probes and word probes was equal. This finding partially replicates Experiment 1 in that all readers were less accurate with cluster probes than whole word probes. However, in the present experiment, all groups performed better with letter probes than cluster probes, whereas in Experiment 1 accuracy for letter probes and cluster probes was equal. The important point is that the slow RAN group was equally poor with different sized probes, compared with the fast RAN group.

Table 6

Percent Correct (standard deviation) for Probes by Group (n=24) and Study Time: Real Words

Study Time	Slow RAN	Fast RAN	Average
1 second			
letter	.68 (.14)	.83 (.11)	.92 (.08)
cluster	.63 (.11)	.71 (.13)	.84 (.10)
word	.71 (.15)	.82 (.14)	.90 (.12)
1.5 seconds			
letter	.67 (.14)	.85 (.12)	.90 (.06)
cluster	.65 (.13)	.78 (.14)	.86 (.11)
word	.73 (.14)	.84 (.12)	.89 (.12)
2 seconds			
letter	.68 (.13)	.84 (.14)	.89 (.12)
cluster	.64 (.15)	.79 (.13)	.84 (.13)
word	.76 (.16)	.86 (.11)	.90 (.11)
2.5 seconds			
letter	.70 (.17)	.85 (.13)	.93 (.06)
cluster	.67 (.13)	.81 (.15)	.87 (.09)
word	.76 (.19)	.87 (.11)	.90 (.10)

Of particular interest in this study was the effect of different study times for each of the three reading groups. Analysis revealed that there was a main effect of study time, $F(3,207)=6.723$, $MSe=.008$, $p<.001$, indicating that all three reading groups were more accurate at longer study times. However, this effect of study time did not interact with reader group, indicating that all three reading groups improved equally with longer study times. Although the increases in accuracy appear very small, post hoc analysis revealed that accuracy at the shorter study times (1 second and 1.5 seconds) differed from accuracy at the longest study time (2.5 seconds) for all three groups. This finding indicates that increased processing time does not lead to improved representation of the letter string for slow RAN children relative to the fast RAN children. This result suggests that the letter processing deficit exhibited by slow RAN children is not simply a problem of limited time to form a representation of the word. Even with 2.5 seconds to process the word, slow RAN children were unable to overcome their deficit. This finding suggests that the problem might not lie in forming the initial representation, as was suggested by Bowers and Wolf (1993; Wolf & Bowers, 1999), or if it is in forming an initial representation it is not the availability of processing time per se that is the source of the problem.

Experiment 3b

The proportion of correct responses for each reading group with orthographically illegal nonwords are presented in Table 7. Slight increases in accuracy can be seen with longer study times for all three reading groups. This observation was supported by an analysis of variance with reading group as the between-subject factor, and probe type and study time as the within-subject factor. There was a main effect of reading group, $F(2,69)=31.33$, $MSe=.11$, $p<.001$, a main effect of probe type, $F(3,207)=107.35$, $MSe=.017$, $p<.001$, and a main effect of study time, $F(3,207)=9.61$, $MSe=.009$, $p<.001$. No interactions were significant. Consistent with previous findings, post hoc analysis revealed that the slow RAN group was less accurate than the fast RAN group. There was no difference in accuracy between the fast RAN group and the average group. In addition, analysis indicated that all three groups were less accurate with the cluster probes than with the letter probes and the nonword probes. This result replicates the results of Experiment 3a with real words. Accuracy for real words was greater than for other probes, consistent with the finding of Experiment 2. This indicates that once again, the slow RAN group was making use of the orthographic structure found in real words to aid performance. Finally, all three reading groups showed an increase in accuracy from the shortest study time (1 second) to the longer study times. However, the benefit of increased study time was the same for all groups, with no special benefit for the slow RAN group. Consistent with the results of Experiment 3a, this result suggests that the letter processing problem for slow RAN children is not simply a problem of insufficient time to establish a good quality representation. Again, even with 2.5 seconds to process the letter string, they are unable to offset the processing problem.

Table 7

Percent Correct (SD) for Probes by Group (n=24) and Study Time: Nonwords

Study Time	Slow RAN	Fast RAN	Average
1 second			
letter	.56 (.10)	.75 (.10)	.77 (.13)
cluster	.56 (.14)	.67 (.09)	.64 (.14)
nonword	.61 (.11)	.73 (.11)	.74 (.11)
word	.68 (.14)	.88 (.12)	.92 (.12)
1.5 seconds			
letter	.56 (.12)	.75 (.11)	.80 (.11)
cluster	.57 (.15)	.65 (.13)	.75 (.12)
nonword	.63 (.13)	.74 (.12)	.77 (.15)
word	.74 (.19)	.88 (.13)	.92 (.11)
2 seconds			
letter	.61 (.15)	.76 (.10)	.81 (.11)
cluster	.59 (.12)	.70 (.10)	.73 (.17)
nonword	.65 (.12)	.78 (.13)	.79 (.13)
word	.74 (.14)	.88 (.10)	.93 (.13)
2.5 seconds			
letter	.59 (.13)	.76 (.13)	.79 (.13)
cluster	.56 (.16)	.68 (.12)	.75 (.14)
nonword	.62 (.74)	.80 (.12)	.83 (.13)
word	.74 (.16)	.88 (.13)	.92 (.10)

Discussion for Experiment 3a and 3b

Bowers and Wolf (1993) proposed that slow RAN children have problems with the speed of processing individual letters in a sequence. They further argued that the ability to represent the sequencing of letters is an important aspect of encoding that word. Therefore, if slow RAN children process letters too slowly, the letter sequence is poorly represented, and the probe cannot be easily matched to this poor representation. Experiments 3a and 3b examined whether longer study times to encode the initial word would compensate for the slower letter processing of slow RAN children, and thereby improve performance on the probe task. Results indicated that there were no differential benefits for the slow RAN group with longer time to process the initial letter string, whether with real words or nonwords. All reading groups equally increased performance slightly with longer study times. Providing longer time for the slow RAN children to encode the initial word does not alleviate the problem, suggesting that speed alone is not the problem. A more fundamental problem in representing individual letters may result in poor or slow processing of letter strings. It is this underlying problem that needs to be corrected in order for letter processing speed to improve. This underlying deficit may be related to processing in the magnocellular system of the visual system as suggested by Wolf and Bowers (1999).

As longer processing time did not alleviate the problem for the slow RAN children, I next questioned whether slow RAN children could improve the efficiency of letter processing through training. This issue was addressed in Chapter 4.

CHAPTER 4

Experiment 4: Training Slow RAN Children to Process Letters More Efficiently

The experiments reported in Chapters 2 and 3 of this thesis indicated that slow RAN children have difficulty processing at the level of the individual letter, whether or not orthographic structure is present in the letter string. Increased processing time does not appear to offset the processing problem slow RAN children exhibit. In addition, these studies support the idea that slow RAN children have deficits in orthographic knowledge. Despite these deficits in orthographic knowledge, they are able to use orthographic structure to aid in processing letter sequences. These results are consistent with the model proposed by Bowers (2001) in which speeded letter processing and orthographic knowledge are separate influences on reading ability, and orthographic knowledge can be used to aid perception of letters in a word. It follows that improvement in either of these subskills of reading should produce benefits in reading ability for slow RAN children, and improvement in both of these subskills should theoretically provide an even greater benefit. The present study explored these issues by training slow RAN children in both orthographic pattern recognition and speeded letter recognition.

The ability to quickly recognize orthographic units within words is fundamental to fluent reading (Adams, 1990; Ehri, 1992; Perfetti, 1992). Levy (2001) reported a training study in which learning to read new words was better when words that shared orthographic units were presented in a block, and with the shared orthographic unit color-highlighted in each word, than when words were presented in random order and in random colors. That is, by making the shared orthographic unit obvious, or highly visible in the print, learning was facilitated. The idea that orthographic units within words play a role in learning to read words is consistent with Goswami's (1986; 1988; 1999) theory of reading by analogy. Goswami (1986) found that children were able to make analogies from known words to new words that contained the same orthographic patterns. She concluded that children are able to read new or unfamiliar words if these words contain orthographic units that are familiar to them through known words. In order to make these analogies, children must be able to recognize common orthographic patterns. Children who do not quickly recognize orthographic patterns within words must rely on slower letter-by-letter decoding (Ehri, 1992; Perfetti, 1992).

Several Dutch studies have found that poor readers can be trained to more efficiently recognize orthographic units within words (e.g., Das-Smaal, Klapwijk, & van der Leij, 1996; van Daal, Reitsma, & van der Leij, 1994). Das-Smaal and colleagues trained poor readers to quickly recognize multi-letter units within words by presenting a multi-letter unit followed by words that either contained or did not contain the presented units. Children responded yes or no as to whether the presented word contained the unit. After several trials, they found that children became faster at detecting units within words, suggesting that children can learn to recognize units within words more efficiently.

However, Das-Smaal and colleagues (1996) found mixed results as to whether this skill transferred to benefits in reading ability. Using two different tasks, they measured children's ability to read new words that either contained trained units or did not contain trained units. In an untimed task, children were allotted unlimited time to read words. With this task, they found no differences between reading new words with trained units versus new words with untrained units. However, when reading ability was measured using a speeded task in which children had limited time to read new words, children read more words with trained units than words with untrained units. These results suggest that learning to recognize multi-letter units within words can transfer to reading new words in some circumstances. When time is limited and children must be able to read a word fluently, training to quickly recognize multi-letter units within words can provide a benefit to reading ability.

Using a different task to train children to recognize letter patterns within words, van Daal and colleagues (1994) also found inconsistent results as to whether these training benefits transferred to reading new words. After repeated reading of lists with 4-letter words that shared orthographic units, children were able to read new words with the trained orthographic units faster than new words with untrained units. However, with 3-letter words, they did not find benefits for words with trained units over words with untrained units. In this study, the benefit to reading ability of training orthographic pattern recognition depended on the size of the words used in training. Although both Das-Smaal and colleagues (1996) and van Daal and colleagues (1994) found inconsistent results within studies, the results provide some support for the idea that training children to more efficiently recognize orthographic patterns within words can have an impact on reading ability. The present study used practice with orthographic units through repeated reading of words containing these units as a training procedure. Following studies reported by Levy (2001), words with shared orthographic units were presented in blocks with the shared units colored in red to highlight the orthographic similarities between words.

The other subskill of interest in the present study was speeded letter recognition. It has been suggested that quick letter identification is also a major component of reading fluency (Adams, 1990). However, whether this particular skill can be trained, and if so, whether it benefits reading ability, is unclear. Carver and David (2001) defined letter-naming speed as "cognitive speed" in their model of reading and suggested that cognitive speed is determined by age. They argued that whereas training can influence other factors related to reading ability such as decoding ability and verbal ability, training does not influence cognitive speed. Cognitive speed, or letter identification speed, can be increased only through developmental maturation. Bowers (2001) also speculated that letter identification ability may only improve through development or maturation. However, these speculations have not been directly tested. One goal of the present training study was to explore whether speeded letter recognition can be improved, and whether this would have an impact on reading ability.

The present training study focused on two specific deficits associated with slow RAN children. A cross-over design was used to examine the effects of single and combined training in orthographic pattern recognition (hereafter referred to as orthographic training) and speeded letter recognition (hereafter referred to as letter training). This design enabled examination of whether slow RAN children can learn to become more efficient at letter recognition, and if so, what benefit this would have on their reading ability. Secondly, this experiment explored how a training program that directly addressed two specific deficits associated with slow RAN children would impact their reading ability. According to Bowers (2001), we would expect to see benefits in reading ability following each type of training alone, and even larger benefits when children receive both types of training.

Method

Participants

Forty-four children in Grades 1 and 2 classrooms of the Hamilton-Wentworth Catholic District School Board participated in this study. For the Grade 1 children, an age criteria was set so that there were no children in Grade 1 included in the experiment who were younger than the youngest participant in Grade 2. This age cut-off was used to ensure that all children participating in the study were within the same age range. To select these 44 children, 656 children were screened in 26 schools over a two-year period. Nine more children qualified but were removed from the sample due to excessive absences. Permission for participation was obtained from the board, schools, and a parent. All children who returned consent forms were administered a set of selection measures. First, each child was administered the word identification subtest of the Wide Range Achievement Test – Third Edition (WRAT-3). Students who scored below a standard score of 90 on the WRAT-3 were then administered the RAN task, as used in the preceding experiments. Children were selected as slow RAN readers on the basis of the criteria established in Levy, Bourassa, and Horn (1999). Therefore, children with a WRAT-3 standard score less than 90 and a RAN score slower than 41.5 seconds were selected for participation in the present study. Lastly, in order to measure acquisition of new words, it was necessary that most of the training words used in the present experiment were unknown by the children. Therefore, only children who read less than one third of the training words (12) were eligible for participation. This resulted in a sample of 44 children. All children were reading below grade expectations and had slow naming speed on the RAN task.

Participants were randomly assigned to either one of the two experimental training groups or to the control group. One experimental group first received letter training, followed by orthographic training. The other experimental group first received orthographic training followed by letter training. A control group was used to ensure that any benefits following training were not simply a result of developing reading skill over the three weeks of training, but rather a result of the training regime itself. The control group did not receive either type of training, but participated in an equal number of one-on-one sessions with the experimenter. During these sessions, children in the control group completed arithmetic problems, and were administered the test measures on the same days as the training groups. This resulted in two experimental groups with 15 participants each and a control group of 14 participants.

RAN scores and WRAT-3 scores are presented in Table 8 for each experimental group and the control group. Scores for each test were subjected to an analysis of variance with experimental group as the independent factor to ensure that all groups were matched on these variables. There was no effect of group on RAN, $F(2,41)=.772$, $MSe=54.74$, $p=.47$, and no effect on the WRAT-3 scores, $F(2,41)=.094$, $MSe=31.056$, $p=.91$, indicating that both the experimental training groups and the control group were all matched for reading skill and naming speed.

Table 8

Performance on Selection and Descriptive Measures

Group	WRAT-3	RAN	OC	TAAS	WISC-III
Letter first (n=15)					
M	83.33	49.17	.71	.93	88.80
SD	7.78	7.54	.11	.96	12.21
Orthographic first (n=15)					
M	83.60	49.68	.68	.73	87.33
SD	4.45	6.06	.10	.70	13.04
Control (n=14)					
M	84.21	52.37	.73	.86	88.71
SD	3.38	8.48	.13	.66	9.66

Note. WRAT-3 and WISC-III scores are standard scores (M=100, SD=15), RAN score is seconds, OC is percent correct and TAAS is Grade Equivalent.

A number of skills related to reading were measured to ensure that any differences found as a result of different training regimes could not be attributed to differing levels of reading related skills. Scores for each of these tasks are presented in Table 8. Orthographic knowledge was measured with the same orthographic choice (OC) task used in the preceding experiments. Groups performed equally on this task, $F(2,41)=.79$, $MSe=.01$, $p=.46$. Because the three groups were matched on orthographic knowledge, any differences found as a result of training could not be attributed to initial differences in level of orthographic knowledge.

Phonological processing skill and IQ were also measured for each participant. Phonological processing skill was assessed with the Test of Auditory Analysis Skills (TAAS; Rosner, 1979). There were no differences between groups on phonological processing skill, $F(2,41)=.24$, $MSe=.62$, $p=.78$.

An estimated IQ score was obtained using three subtests of the Wechsler Intelligence Scale for Children – Third Edition (WISC-III). The Information, Vocabulary and Block Design subtests were used. Sattler (1992) examined the psychometric properties of various short-forms of the WISC-III and reported reliability and validity coefficients. For reliability, Sattler reported internal consistency coefficients, defined as an index of how well the various items are measuring different aspects of the same underlying concept, which in this case is intelligence. Concurrent validity was obtained by comparing performance on the short form of the WISC-III with the performance on the full scale of the WISC-III. According to Sattler, the Information, Vocabulary, and Block Design subtests can be used to estimate IQ with a reliability coefficient of .93 and validity coefficient of .88. Using these three subtests, all three groups were matched on IQ, $F(2,41)=.07$, $MSe=138.55$, $p=.93$. Therefore, any benefits in reading outcome measures as a result of training could not be attributed to differences in these other reading related skills.

In summary, three groups of children were used in this study. One group of participants received training in orthographic pattern recognition, followed by training in speeded letter recognition, while a second group received training in the opposite order. Performance was compared with a control group. All three groups were matched on orthographic knowledge, phonological processing skill, and IQ.

Materials and Design

This experiment was a crossover design in which participants first received one type of training, followed by the other type of training. Order of training was counterbalanced across participants in each group. Test measures were administered prior to training, after the first training phase, and following the second training phase. Training consisted of orthographic pattern recognition and speeded letter recognition.

Orthographic pattern recognition training. Two complete sets of stimuli were made so that if participants received orthographic training on one set of stimuli, they then received letter training on a set of stimuli that did not contain any letters of the alphabet that were used in orthographic training. To do this, the 26 letters of the alphabet were divided into two sets, and each set of 13 letters was used to make up one of the two sets of stimuli. Stimulus sets were counterbalanced across participants such that the two sets of stimuli were each used equally often in the orthographic training and the letter training.

For each stimulus set, 40 words were chosen. Each set of 40 words contained ten "families" of words that shared a common orthographic pattern. Each family consisted of four words with the shared orthographic pattern. The common orthographic pattern shared by words in a family was taken from different positions in a word. Thus four families shared an orthographic pattern at the beginning of the word, four families shared an orthographic pattern at the end of the word, and two families shared an orthographic pattern in the middle of the word. Words were of varying length, but average word length was equal across the two stimuli sets. Of the four families that shared a beginning orthographic pattern, two shared a two-letter pattern and two shared a three-letter pattern. Of the four families that shared an ending orthographic pattern, two shared a two-letter pattern and two shared a three-letter pattern. Both families that shared an orthographic pattern within the middle of the word shared a two-letter pattern. Both stimulus sets contained 40 words, and 187 letters. All words within a family had consistent phonological-orthographic correspondences. That is, all orthographic patterns within a family of words sounded the same. Stimuli sets are presented in Appendix A.

Words were presented one at a time on a computer screen with words that shared an orthographic pattern presented one after another. The shared orthographic pattern within a family of words was written in red, to make the orthographic pattern maximally visible. Order of families within a trial and order of words within a family were randomly ordered across participants. Participants were asked to read each word as quickly and accurately as possible. If a participant did not respond within three seconds, or responded incorrectly, the experimenter provided whole word feedback by reading the word aloud. The dependent measures were accuracy and naming time. The experimenter recorded accuracy. Naming times were recorded via the computer. Naming time was defined as beginning with the onset of the word on the computer screen and ending with the onset of a verbal response.

One trial of training was defined as reading through the list of 40 words once. Participants completed five trials a day over six days for a total of 30 repetitions.

Speeded letter recognition training. Two sets of stimuli that corresponded to the stimuli for the orthographic training phase were used for letter training. For each set of stimuli, the 187 letters used to make up the words used in the orthographic training were divided into three matrices. Two of the matrices contained 62 letters and the third matrix contained 63 letters. These three matrices equaled one trial of training in the letter training and corresponded to one trial of the orthographic training. Thus in one trial in either training phase, participants were exposed to the exact same letters, the same number of times. For example, if the letter "g" was used six times in words in one trial of orthographic training, then the letter "g" was used six times across the three matrices in one trial of letter training.

The training matrices of letters were presented on the computer screen. Letters within a matrix occurred in a different random order on each trial for each participant. The time to name all letters in a matrix was recorded via the computer. Timing began with presentation of the matrix. When the last letter was read, the experimenter pressed a key to erase the display from the screen and to stop the clock. The experimenter recorded errors.

The participants' letter training score for a trial was the total naming time in seconds for all three matrices. Stimuli sets were counterbalanced across participants. Children completed five trials a day over six days for a total of 30 trials.

Test Measures. To explore whether training in recognition of orthographic patterns and letters would provide a general benefit in reading efficiency, The Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999) was administered. This is a standardized test of reading fluency that measures the number of words read correctly in 45 seconds. This test was administered at each of the three test periods. The TOWRE contains two equivalent forms, and these two forms were counterbalanced across test periods and participants.

The RAN-digit task as used in participant selection was also administered at each of the three test sessions. This task was administered to determine whether any potential improvement in letter recognition would generalize to an improvement in digit naming speed as measured by the RAN digit task.

A generalization test of word reading was administered at each testing period to determine whether training in recognizing orthographic units or letters would facilitate reading of new words with these trained units/letters. This was a naming task in which both accuracy and speed were measured. Two lists of 40 words each were constructed. Each list contained 20 new words with trained units/letters and 20 new words with untrained units/letters. Each list contained two words from each of the eight orthographic patterns trained. All words were new words that were not included in the training phase. Each list was matched for average length of word. The two lists of words were counterbalanced across testing sessions for each participant. Words with shared orthographic patterns were *not* presented one after another, but were presented in a different random order for each participant. Words were presented one at a time in the middle of the computer screen, in white on a black background. The dependent measures were number of words read correctly and naming time. Naming time was measured from the onset of the word to the onset of the response. Participants read aloud each word as it appeared on the computer screen. The experimenter coded whether the word was read correctly or incorrectly and the computer recorded naming time. A test session consisted of reading one list of 40 words (See appendix B).

Finally, a probe task was administered to determine whether children would be more sensitive to trained units/letters within letter strings compared with untrained units/letters. The probe task used here was similar to that used in the preceding experiments. The task involved presenting participants with a word or orthographically illegal letter string (i.e., nonword) followed by a probe. Participants were to make a yes/no judgement as to whether the probe had been present in the preceding word/nonword.

Sixty words were used in this probe task. Of these 60 words, 30 contained trained units, and 30 contained untrained units for any given participant. From these 60 words, three separate lists were constructed; each with half trained units and half untrained units. These three lists were counterbalanced across participants and testing sessions. In addition, 60 four-letter nonwords were used. All nonwords had bigram frequencies equal to zero, indicating that these letter patterns do not occur in written English (Mayzner &

Tresselt, 1965). Of these 60 nonwords, 30 were made with trained letters, and 30 were made with untrained letters for any given participant. These three lists were counterbalanced across participants and testing sessions. That is, each participant saw a different list of words and nonwords containing both trained and untrained units at each of the three test sessions.

Three conditions were included in each stimuli list. In one condition, participants were presented with a word that was either four or five letters long, followed by an orthographic cluster probe (e.g., grape – gra). Probes consisted of both trained and untrained orthographic clusters. Condition two consisted of a four or five letter word followed by a letter probe (e.g., grade – g). Probes in this condition consisted of trained and untrained letters. The third condition consisted of a four-letter nonword followed by a letter probe (e.g., ywbr – r). Again, probes consisted of trained and untrained letters. Participants judged whether the probe had been in the preceding letter string. There were 40 trials in each condition, 20 of which used a trained unit as a probe, and 20 of which used an untrained unit as a probe. Within the 20 trained and 20 untrained probes, ten of each required "yes" responses where the word/nonword contained the probe unit and ten required "no" responses where the word/nonword did not contain the probe unit. The location of the probe within the initial word or nonword varied across positions. Each participant saw one list of 120 trials. Each list was divided into three blocks of 40 trials each with a break in between blocks. All probe types occurred randomly intermixed within blocks.

Stimuli were presented on a computer screen as white words on a black background. Each trial consisted of the presentation of a word/nonword on the screen for one second and after a one second interval, a probe appeared and remained on the screen until a response was made. Responses were made by pressing a key on the computer keyboard, one key used for "no" and one key used for "yes". Trials where the probe had been present in the preceding word/nonword and trials where the probe had not been present in the preceding word/nonword were randomly arranged with no more than three trials of one type occurring in a row. In addition, trials of trained probes and trials of untrained probes were also randomly presented. The dependent measure for this task was the proportion correct in each condition for trained and untrained probes. Accuracy was recorded by the computer.

Procedure

Participants were administered the selection measures (WRAT-3, RAN, baseline) in one 15-minute session. Following selection, pretest measures (orthographic choice, TAAS, WISC-III subtests) and pretraining test measures (probe task, TOWRE, generalization words) were administered over two 25-minute sessions. Training Phase 1 began and continued with five trials a day over six days. Once training was complete, test measures were administered on a separate day in one 30-minute session. Children then switched to the other training program with the other set of stimuli and training continued with five trials a day over six days. The day following the completion of training Phase 2, the test measures were again administered in one 30-minute session.

Results

Training Results

Orthographic pattern recognition training. Differences in orthographic training alone and orthographic training following letter training were examined by looking at the number of words read correctly across training trials for children who received orthographic training in Phase 1 (orthographic first) versus children who received orthographic training in Phase 2 following letter training in Phase 1 (orthographic second). Number of words read correctly across the 30 trials of orthographic training was collapsed into blocks of five trials each to give a mean score of words read correctly per day of training. Figure 2 presents the acquisition function for both orthographic training first and orthographic training second. Children who received orthographic training second consistently read between 1.5 and 4.5 more words than children who received orthographic training first; however an analysis of variance with training condition (first/second) as the between-subject factor and days of training (1 through 6) as the within-subject factor revealed that this difference was not significant, $F(1,28)=1.27$, $MSe=300.07$, $p=.27$. A main effect of days was significant, $F(5,140)=187.29$, $MSe=9.96$, $p<.001$, but this did not interact with training condition. Bonferroni post hoc analysis revealed that across both training conditions, children read more words correctly each day of training. That is, children were learning to read more words with each day of training, whether they received orthographic training first or second.

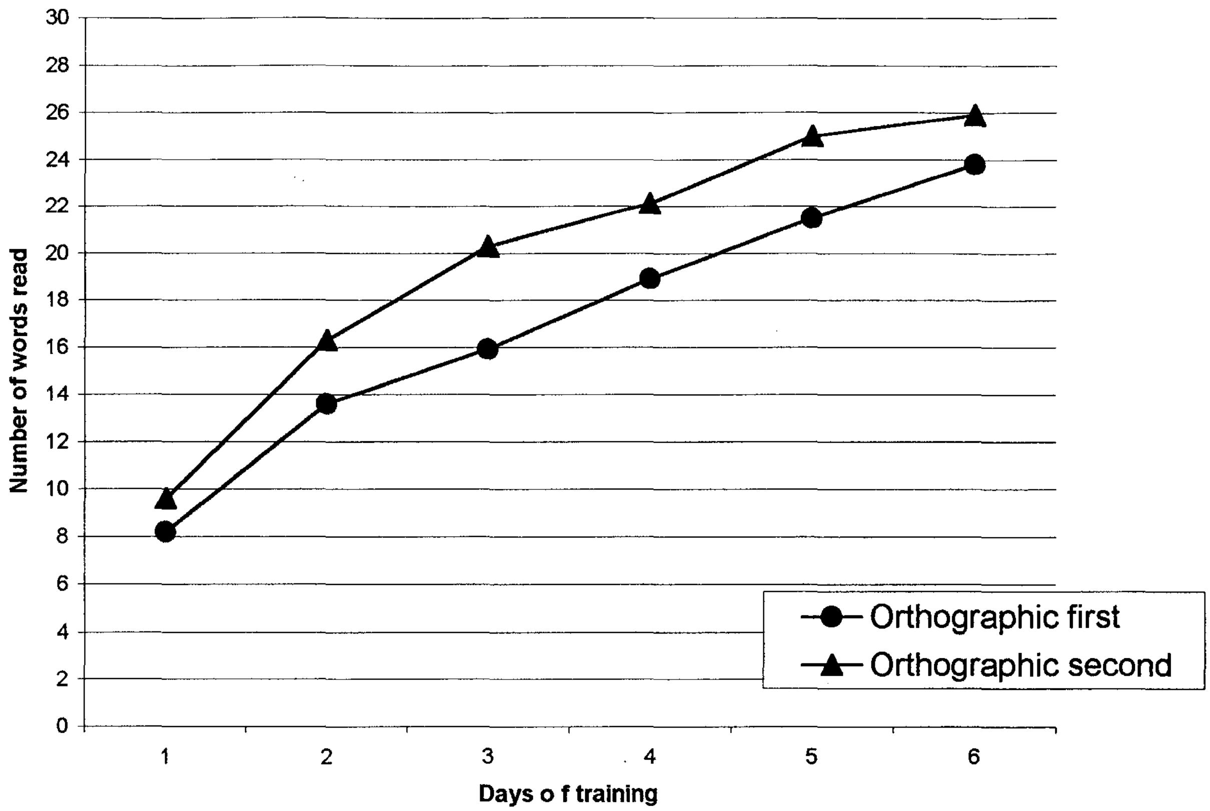

Figure 2: Orthographic training - number of words read correctly

Naming times for words read correctly were also examined. Naming times were collapsed into six blocks of five trials each to give a mean naming speed score per day. Figure 3 presents the naming time function for both orthographic training first and orthographic training second across days of training. These data were subjected to a 2 x 6 mixed analysis of variance with training condition (first/second) as the between-subject factor and days of training as the within-subject factor. As with the accuracy data, there was a main effect of days, $F(5,120)=15.36$, $MSe=.401$, $p<.001$. No other effects were significant. Post hoc analysis revealed that regardless of training condition, children were slower to name words on day 1 of training, and that naming times then leveled off on the remaining days of training. Therefore, children in both training conditions became both more accurate and faster at reading these words as training progressed. There was no difference in this improvement between the two training conditions, indicating that first receiving letter training provided no additional benefit to word reading speed.

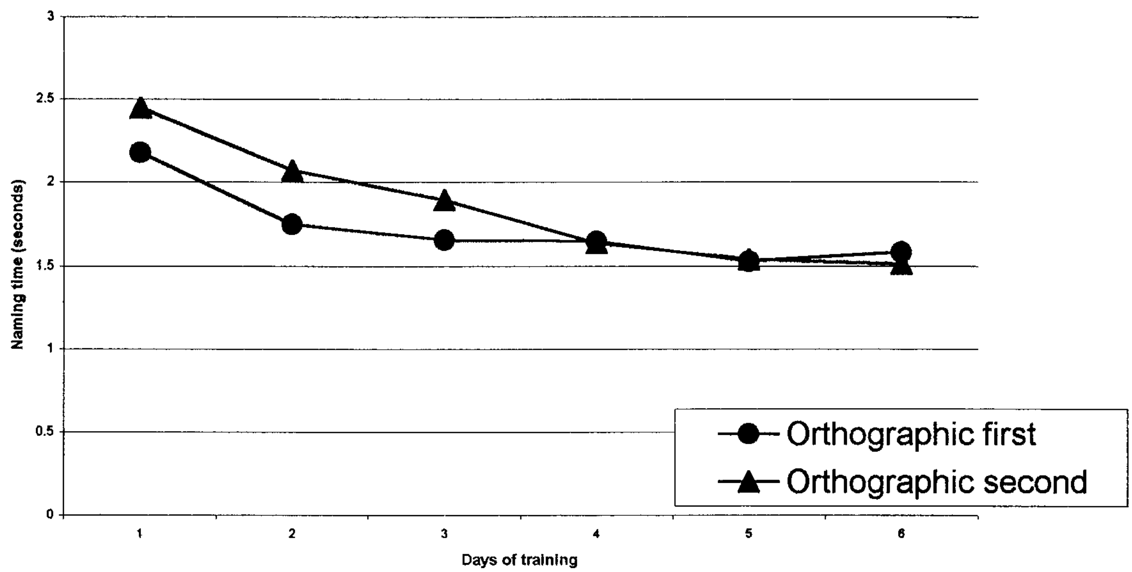

Figure 3: Orthographic training – Naming speed in seconds

Speeded Letter Recognition Training. Letter training was next examined to determine whether children learned to recognize letters more efficiently with practice. Very few errors were made in naming letters (2-3 errors per trial), and analysis of error rates revealed no significant effects and will not be discussed further. Differences between letter training in Phase 1 (letter first) and letter training in Phase 2 following orthographic training (letter second) were examined by looking at naming speed per trial. Data from the 30 trials were collapsed into six blocks of five trials each to give a mean naming time for each day of training. Figure 4 presents the speed function for both letter training first and letter training second following orthographic training. These data were subjected to a 2 x 6 mixed analysis of variance with training condition (first/second) as the between-subject factor and days (1 through 6) as the within-subject factor. There was a main effect of days, $F(5,140)=3.76$, $MSe=266.18$, $p<.05$, and a significant interaction between days and training condition, $F(5,140)=4.20$, $MSe=266.18$, $p<.01$. To examine this interaction further, separate one-way repeated measures analyses of variance were conducted for each training condition.

For the letter training first condition, there was no effect of days, $F(5,70)=1.27$, $MSe=323.844$, $p=.29$, indicating that children who received letter training first showed no improvement in the speed with which they identified individual letters. That is, for slow RAN children, practice in rapid naming did not lead to more efficient letter identification.

However, when letter training followed orthographic training, there was a significant effect of training days for the letter condition, $F(5,70)=8.20$, $MSe=208.51$, $p<.001$. Figure 4 indicates that naming times were faster across days of training. A comparison of Day 1 naming times with Day 6 naming times supports this observation, $t(14)=4.30$, $p<.001$. Therefore, while training with letter naming first did not improve letter recognition, letter recognition speed did improve over days when children had previously received orthographic training.

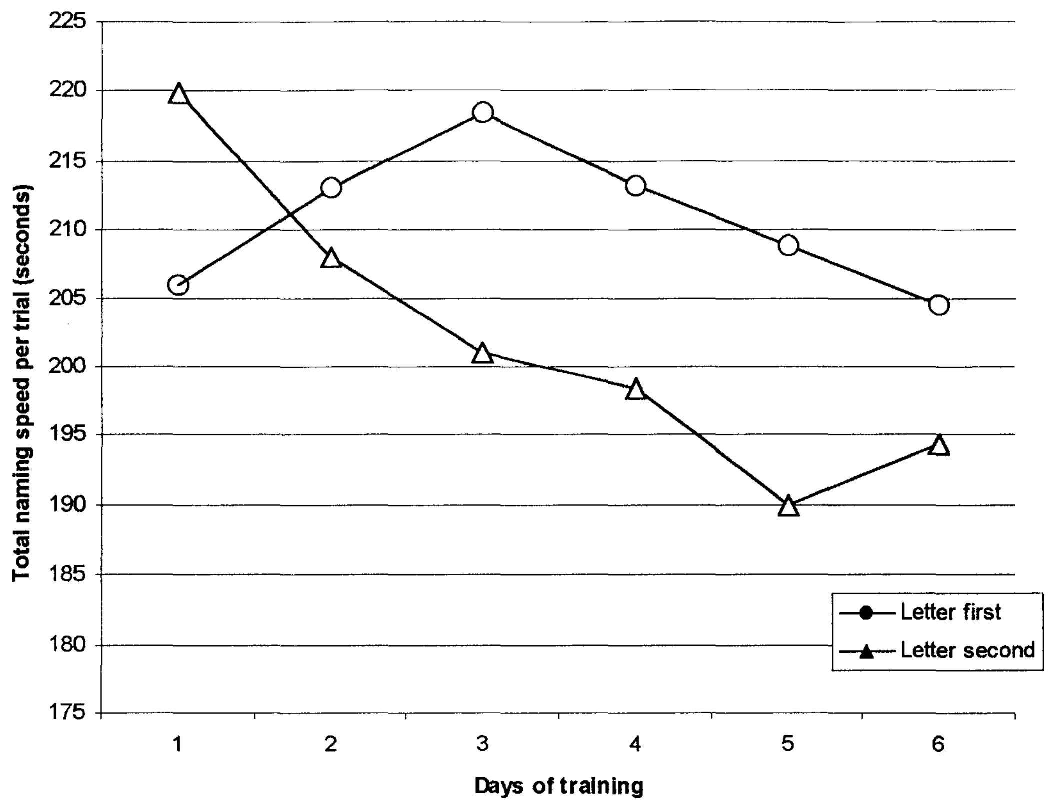

Figure 4: Letter training – naming speed in seconds

To summarize the training results, orthographic training produced benefits in learning to read the training words, as measured by both speed and accuracy. This benefit was the same whether children received orthographic training first or received orthographic training second following letter training. With letter training, receiving letter training alone did not improve the speed with which children identified letters; however, receiving letter training second following orthographic training did provide benefits in speeded letter recognition.

Outcome Measures

RAN digit task. RAN-digit scores are presented in Table 9 for each group at all three test times: prior to training, following Phase 1 training and following Phase 2 training. To determine whether training had an effect on RAN performance, scores for both experimental groups and the control group were compared (recall that the control group received no training, but completed all test measures on the same days as the experimental groups). Scores were submitted to a 3 x 3 mixed analysis of variance with group (orthographic first/letter first/control) as the between-subject factor and test time (pre-training/post-phase 1/post-phase 2) as the within-subject factor. Analysis revealed a significant main effect of test time, $F(2, 82)=14.56$, $MSe=26.83$, $p<.001$, a significant main effect of group $F(2,41)=3.50$, $MSe=134.75$, $p<.05$, and a marginal interaction between group and time $F(4,82)=2.27$, $MSe=26.83$, $p=.07$. Further analyses were conducted to better understand the nature of these effects. Separate repeated measures were conducted for each group.

The control group showed no improvement in RAN scores over test times, $F(2,26)=.260$, $MSe=36.33$, $p=.77$. However, both the group that received letter training first and the group that received orthographic training first showed improvements in RAN scores, $F(2,28)=7.34$, $MSe=27.55$, $p<.01$, and $F(2,28)=18.21$, $MSe=17.23$, $p<.001$ respectively. Post-hoc analyses revealed that for both experimental groups, RAN scores at Time 1 were equal to RAN scores at Time 2, and RAN scores at Time 3 were different than RAN scores at both Time 1 and Time 2. Thus, both experimental groups showed improvement in naming speed on the RAN-digits task upon completion of both types of training. Neither training condition alone produced a benefit in RAN scores.

Table 9

Mean score in seconds and standard deviations (SD) for RAN digits

Group	Pre-Training	Post-phase 1	Post-phase 2
Control (n=14)			
M	52.37	51.00	50.89
SD	8.48	10.23	11.74
Letter first (n=15)			
M	49.17	46.54	41.91
SD	7.54	8.20	6.16
Orthographic first (n=15)			
M	49.68	46.24	40.61
SD	6.06	6.20	4.76

Test of Word Reading Efficiency. The TOWRE was administered to examine whether training had an effect on a general test of reading efficiency. Standard scores for each group are presented for each test time in Table 10. Although the observed increases in standard scores were very small, a 3 x 3 mixed analysis of variance with group (letter first/orthographic first/control) as the between-subject factor and test time (pre-training/post-Phase 1/post-Phase 2) as the within-subject factor revealed a significant main effect of test time, $F(2,82)=3.45$, $MSe=10.93$, $p=.05$. No other effects were significant. Post hoc analysis revealed that all three groups scored higher at Test Time 3 than Test Time 1. Therefore, as all three groups, including the control group who received no training, showed small improvements in reading efficiency, this increase was unrelated to training. These small increases in reading efficiency are no doubt a result of developing reading skill over the three weeks of the study.

Table 10

Standard scores and standard deviations (SD) for Test of Word Reading Efficiency

Group	Pre-Training	Post-phase 1	Post-phase 2
Control (n=14)			
M	84.71	85.36	86.21
SD	5.57	6.91	6.25
Letter first (n=15)			
M	84.40	86.33	85.53
SD	7.99	8.76	9.23
Orthographic first (n=15)			
M	84.60	85.53	86.60
SD	4.15	4.64	5.10

Generalization Task. Children's ability to generalize the skills learned during training was examined at two points during the training study. First, the effects of letter training alone versus orthographic training alone at the end of Phase 1 were examined. Second, the effect of receiving both types of training, one following the other, at the end of Phase 2 was examined. At the end of Phase 1 training, children's ability to read new words that contained trained units compared with new words that did not contain trained units was examined. Table 11 suggests that following orthographic training, but not letter training, children were able to read more words with trained units than words without trained units. However, a 2 x 2 mixed analysis of variance with group (letter first/orthographic first) as the between-subject factor and word type (trained/untrained) as the within-subject factor revealed that this difference was not significant, $F(1,28)=1.88$, $MSe=5.54$, $p=.18$. That is, there was no difference in the number of words read correctly between words with trained units and words with untrained units for either the children who received letter training or those who received orthographic training during the first phase of training.

Next examined was the effect of receiving both types of training, one following the other. However, upon completion of both types of training, all new words in this task contained trained units - either trained letters or trained orthographic units. Therefore, to examine whether sequential training benefited word reading skill, the total number of words read correctly at each test time was examined. The control group was included in this analysis to ensure that any improvements were not a result of improvements in reading skill over the course of the study. Table 12 presents the total number of words read correctly by each group at each test time. These data were subjected to a 3 x 3 mixed analysis of variance with group as the between-subject factor (letter first/orthographic first/control) and test time (pre-training/post-phase 1/post-phase 2) as the within-subject factor. There was a significant main effect of test time, $F(2,82)=16.94$, $MSe=4.14$, $p<.001$, and a significant interaction between group and test time, $F(4,82)=3.32$, $MSe=4.14$, $p<.05$. To further explore this interaction, separate one-way analyses of variance were conducted for each group.

Table 11

Mean number of words read correctly at Post-phase 1 for trained and untrained units

Group	Trained	Untrained
Letter first (n=15)		
M	1.9	1.7
SD	2.8	1.3
Orthographic first (n=15)		
M	3.8	1.9
SD	3.3	2.4

Table 12

Mean number of words read correctly at each test time

Group	Pre-Training	Post-phase 1	Post-phase 2
Control (n=14)			
M	2.7	3.5	4.3
SD	2.3	2.7	3.8
Letter first (n=15)			
M	3.5	3.7	6.6
SD	3.8	3.3	4.9
Orthographic first (n=15)			
M	2.7	5.7	5.6
SD	2.3	4.4	4.9

The control group showed no difference in the number of words read correctly across the three test times, $F(2,26)=2.63$, $MSe=3.28$, $p>.05$. Both the group that received letter training first followed by orthographic training and the group that first received the orthographic training followed by letter training showed significant effects of test time, $F(2,28)=10.41$, $MSe=4.33$, $p<.001$ and $F(2,28)=9.52$, $MSe=4.73$, $p<.001$ respectively. However, the test time at which these two groups showed an increase in the number of words read correctly differed. Post-hoc analyses revealed that the letter training first group showed no difference in the number of words read correctly between Test Time 1 (pre-training) and Test Time 2 (post-phase 1), but showed an increase in the number of words read correctly at Test Time 3 (post-phase 2). The orthographic training first group showed a different pattern of results with an increase in the number of words read correctly between Test Time 1 with Test Times 2 and 3, and no difference in the number of words read correctly between Test Times 2 and 3. Thus, each training group showed an increase in the number of words read correctly following orthographic training, regardless of whether they received this training first or second. Letter training alone did not improve word reading, nor did it further enhance word reading when it followed orthographic training.

Response times of words read correctly at each test time were also examined to determine whether training resulted in faster reading times. However, no differences were found.

Probe Task. At Test Time 2 the probe task examined the effect of letter training alone versus orthographic training alone on the ability to detect trained units within words or nonwords. Percent correct in detecting probes following Phase 1 training is presented in Table 13 for both the group who first received letter training, and the group who received orthographic training first. A 2 x 2 x 3 mixed analysis of variance was conducted with group (letter first/orthographic first) as the between-subject factor and probe type (letter from word, cluster from word, letter from nonword) and trained probe or untrained probe as within-subject factors. Analysis revealed a significant main effect of probe type, $F(2,56)=10.39$, $MSe=.012$, $p<.001$. No other effects were significant. Training condition did not affect performance on this task. Post-hoc analysis revealed that both groups were more accurate in recognizing a letter probe within a word than recognizing a letter probe within a nonword or recognizing a cluster probe within a word. These results are consistent with results reported in Chapters 2 and 3 of this thesis, and are supportive of the argument that slow RAN children are able to make use of the orthographic structure present in a string to aid processing. Recognizing a letter was facilitated when this letter appeared in a word compared to a nonword. That slow RAN children are able to use orthographic structure to aid processing of a letter sequence is consistent with the model proposed by Bowers (2001).

Table 13

Post-phase 1 probe task % correct (standard deviations) for trained/untrained units

Probe Type	Letter first n=15	Orthographic first n=15
Trained		
Word–Letter (grape–g)	.71 (.15)	.73 (.12)
Word–cluster (grape–gra)	.63 (.14)	.65 (.09)
Nonword-letter (pgrt-t)	.65 (.14)	.60 (.10)
Untrained		
Word-letter (grape-g)	.76 (.14)	.65 (.15)
Word-cluster (grape-gra)	.62 (.15)	.65 (.10)
Nonword-letter (pgrt-t)	.67 (.14)	.59 (.12)

Next, the effects on detecting sublexical units following both types of training were examined. The total percent correct for each group with each probe type at each test time is presented in Table 14. These data were subjected to a 3 x 3 x 3 mixed analysis of variance with group (letter first/orthographic first/control) as the between-subject factor and test time (pre-training/post-phase 1/post-phase 2) and probe type (letter from word/cluster from word/letter from nonword) as the within-subject factors. A significant main effect of probe type was found, $F(2,82)=28.51$, $MSe=.007$, $p<.001$, and no other effects were significant. Training did not affect performance on this task. Consistent with the post-phase 1 data, all groups were more accurate at detecting a letter within a word than the other two probe conditions, which were equal. Once again, slow RAN children were able to make use of the orthographic structure in real words to aid in processing.

To summarize the results of the outcome tests, only RAN performance and the generalization task were influenced by training. Both training groups showed a decrease in naming speed on the RAN-digit task upon completion of both types of training. In addition, following completion of orthographic training, whether received first or second following letter training, there was an increase in the number of new words read correctly. Letter training alone provided little benefit to reading new words, and no additional benefit in reading new words when completed following orthographic training. Training did not impact performance on the TOWRE test or the probe task.

Table 14

Probe task percent correct (standard deviations) at all three test times

Test time	Control n=14	Letter first n=15	Orthographic first n=15
Pre-training			
Word–Letter	.69 (.09)	.74 (.09)	.66 (.11)
Word–cluster	.60 (.10)	.62 (.12)	.61 (.07)
Nonword-letter	.63 (.08)	.65 (.07)	.61 (.09)
Post-phase 1 training			
Word-letter	.63 (.12)	.74 (.11)	.69 (.10)
Word-cluster	.59 (.10)	.63 (.12)	.65 (.07)
Nonword-letter	.61 (.11)	.66 (.09)	.60 (.08)
Post-phase 2 training			
Word-letter	.64 (.10)	.73 (.09)	.67 (.11)
Word-cluster	.62 (.10)	.65 (.09)	.62 (.09)
Nonword-letter	.59 (.12)	.64 (.11)	.60 (.12)

Discussion

The present study examined both the separate effects of training in either speeded letter recognition or orthographic pattern recognition, and the effects of training both of these skills for slow RAN children. According to Bowers' (2001) model, training in either of these subskills alone should provide benefits to reading ability and training in both of these subskills should provide even greater benefits. However, it has also been suggested that speeded letter identification may not be responsive to training and may improve only through maturation (Bowers, 2001; Carver & David, 2001). The results of the present study suggest that speeded letter identification can improve through training, if it follows orthographic training. Orthographic training, either alone or following letter training, produced benefits in reading training words.

In the present study, orthographic training provided benefits in recognizing orthographic units, as children were both faster and more accurate in reading the training words. This finding is consistent with studies reported by Levy (2001) who found that making shared orthographic units within words maximally visible provided a benefit for slow RAN children in reading training words. This benefit of orthographic training in the present study was the same whether orthographic training occurred on its own, or was preceded by letter training. First receiving letter training provided no additional benefit in learning to read words with shared orthographic units. This finding is inconsistent with predictions from Bowers (2001) that suggest that receiving training in both speeded letter recognition and orthographic pattern recognition would produce greater benefits than orthographic training alone.

A different pattern of results was found with the letter training. Letter training alone had no impact on the speed with which slow RAN children identified individual letters. However, if children first received orthographic training, the following letter training phase did benefit, in that the speed with which children identified letters decreased across trials. Therefore, letter training alone had no effect on speed of letter recognition, but first receiving orthographic training followed by letter training did improve letter recognition speed. Together, the training results suggest that making the patterns within words visible to the children enables them to process these patterns more efficiently. The benefits in speed and accuracy for reading training words in orthographic training support this idea. By making the patterns visible, not only do these children process these patterns more efficiently, but they also process the internal elements, such as individual letters, more efficiently. This skill may generalize to processing internal elements of all letter strings, which would explain why letter recognition speed improves following orthographic training. Thus, this finding suggests that this is not an additive effect as suggested by Bowers (2001), but rather, a sequential effect. Children first must be aware that spelling consistencies exist within words before individual letter identification can improve.

However, the results of the RAN-digit task are difficult to interpret within this framework. RAN scores did not improve following single training in either skill; it was only when children received both training regimes in either order that RAN scores improved. This suggests that the improvements were not associated with one type of training, but rather, the combination of both types of training. Given the emphasis on speed throughout both training programs, it could be argued that the improvements in the RAN scores, and also the improvements in letter recognition speed following the orthographic training may be a result of training "speed". One of the hypotheses put forward by Wolf and Bowers (1999) suggested that slow naming speed on the RAN task may be indicative of a general timing deficit that impairs performance across a number of different domains. The present study may have trained a general speed factor, which resulted in improvements in speed of recognizing letters in a sequence and in speed of naming digits on the RAN task. However, if this were so, greater improvements in the speed of reading words in the orthographic second condition would be expected compared with the orthographic training alone condition, and this was not the case.

The two training programs also differed in their effects on reading ability as measured by the generalization task. Orthographic training produced small but reliable benefits in reading new words with trained units. This benefit occurred whether orthographic training occurred alone or following letter training. Letter training provided no additional benefit in reading new words, nor did letter training alone benefit reading new words. This finding suggests that these improvements in reading new words were related to orthographic training. However, the benefit orthographic training provided to reading new words was specific to trained orthographic units. Children did not show improvements in general reading ability as measured by the TOWRE test.

In summary, the present study illustrated the importance of orthographic pattern recognition training, not only for setting up orthographic representations that can be used to facilitate reading of words containing these units, but also for making children aware that words contain orthographic consistencies. Children may use this awareness to process individual letters within a string more efficiently, a by-product of "looking" for orthographic consistencies. In addition, and most interesting, the present study has clearly shown that speeded letter recognition is responsive to training under certain circumstances; we *can* improve the speed with which slow RAN children identify individual letters in a sequence.

CHAPTER 5

General Discussion

Research has clearly established that performance on the RAN task is related to reading (e.g., Blachman, 1984; Bowers & Swanson, 1991; Cornwall, 1992; McBride-Chang & Manis, 1996; Meyer et al., 1998; Scarborough, 1998; Watson & Willows, 1995; Wolf, 1982; 1987; Wolf, Bally & Morris, 1986; see Wolf, Bowers, & Biddle, 2000 for a review). Bowers and Wolf (1993; Wolf & Bowers, 1999) argued that deficits in naming speed on the RAN task, and problems with phonological processing can co-exist in children. Children with this "double-deficit" are at the bottom of the reading distribution and have the worst prognosis for developing reading skill (e.g., Bowers, 1995; Lovett et al., 2000; Manis et al., 2000; Manis & Freedman, 2001; Wolf, 1997). These are the children most resistant to traditional treatments. More effective treatments can only be developed with a greater understanding of the process or processes underlying performance on the RAN task. The present thesis offers significant steps towards understanding the nature of the deficit(s) exhibited by children with slow naming speed on the RAN task. Further, the present thesis begins an exploration of training children with slow RAN performance to overcome these deficits and improve their reading skill.

Experiments 1, 2, and 3 illustrated that slow RAN children have both a deficit in orthographic knowledge, and a deficit in letter processing. This deficit in letter processing is independent of phonological processing skill and of orthographic structure.

Even with comparable levels of phonological processing skills, the slow RAN children exhibited deficits in processing individual letters in a string compared with the fast RAN children. This finding suggests a deficit that is related to performance on the RAN task, but separate from phonological processing skills, consistent with the double-deficit hypothesis proposed by Wolf and Bowers (1999).

These results also suggest that the letter processing deficit and the deficit in orthographic knowledge may be independent. The deficit in processing letters in a sequence exhibited by slow RAN children was observed whether or not orthographic structure was present in the letter string. In fact, despite the deficit in orthographic knowledge shown by the children with a RAN deficit, they used orthographic structure to aid in processing letters in a string as indicated by their better performance with real words compared with nonwords in Experiments 2 and 3b. Orthographic structure was used to improve letter perception, for all groups of readers tested here, even the slow RAN group. This view is inconsistent with Wolf and Bowers' (1999) view that RAN performance is related to reading through its effects on orthographic knowledge. That is, a letter processing deficit does not affect reading skill *indirectly* through its effect on orthographic knowledge; rather, letter processing is separate from orthographic knowledge and it may have a more direct influence on reading skill as argued by Bowers (2001). Therefore, the children with slow RAN performance in the current studies exhibited deficits in letter processing, deficits in orthographic knowledge and deficits in phonological processing. This characterization of deficits associated with slow RAN performance is consistent with ideas put forth by Wolf and Bowers (1999) in their double-deficit hypothesis, and supports the notion that children with slow RAN performance have the worst prognosis for developing adequate reading skills.

Experiment 3 indicated that the letter processing difficulty exhibited by children with slow RAN performance is not simply a problem of not having enough time to process the letter string. Slower processing of letters in a string may impair the quality of the memorial representation that is established, and this may impact reading ability, but simply giving these children more time to process a letter string does not alleviate the problem. Therefore, the slower processing of letters for these children is not caused by time per se, rather, these data suggest that there is an underlying problem that causes these speed deficits and it is these underlying problems that need to be fixed. This idea can be likened to the rusting process – it takes time for an object to rust, but time is not the cause of rust.

There are several possibilities as to the underlying cause of the deficits in the speed of processing individual letters. The problem may lie within the magnocellular pathway of the visual system, which may impair the ability to recognize a visual symbol (e.g., a letter, or a digit in the RAN-digit task) as suggested by Wolf, Bowers, and colleagues (Wolf & Bowers, 1999; Wolf, Bowers, & Biddle, 2000). Although researchers have examined visual deficits in poor readers (e.g., Chase, 1996; Demb et al., 1998; Livingstone et al., 1991) visual deficits have not yet been explored specifically for children with slow RAN performance.

A second potential cause of the letter processing deficit comes from the work of Manis and colleagues (1999). Children with slow RAN performance may have difficulty applying an arbitrary verbal label to a visual symbol (e.g., 5 and its name, or L and its name) and this may slow down their processing of individual letters. In this case, the underlying cause is not a problem with visual recognition; rather it is a verbal labeling problem. This difficulty making arbitrary associations may slow down processing of letters in a sequence. However, this is not a sufficient explanation as it is unclear what the reasons are for this potential difficulty making these associations. Whether children with slow RAN performance have difficulties processing visual information through the magnocellular pathway of the visual system, or have difficulty making arbitrary associations, remain interesting directions for future research.

The training study in Experiment 4 illustrated the importance of orthographic pattern recognition training for children with naming speed deficits. Orthographic pattern recognition training enables children to become aware that orthographic consistencies exist within words. This awareness helps children improve their reading skill in several ways. First, it allows children to establish better memory representations of words, which can facilitate learning these words. These representations can also be recruited to aid in reading new words with these same units (Goswami, 1988). The results of the generalization task here support this argument. Children were able to read more new words following orthographic training, whether it came first or second, compared to children who received letter training or received no training (i.e., the control group). Blocking words with shared orthographic units together, and highlighting these common units may have been critical in helping these children recognize the larger orthographic units and to store them in memory. This finding strengthens the position of Levy (2001) that making shared orthographic units within words maximally visible is a valuable educational tool.

A second benefit of orthographic pattern recognition training is evident in the letter training data. There was little support for the notion of additive benefits following training of both skills, as suggested by Bowers (2001). Rather, the results suggest a sequential effect, as letter training was only successful when children first received orthographic training. If orthographic pattern recognition training fostered an awareness for the existence of orthographic consistencies within words, this awareness may further benefit children with letter processing deficits. In searching for orthographic consistencies within letter strings, children may process the internal elements more efficiently, resulting in an increase in the speed with which individual letters in a sequence are identified. I would argue that orthographic pattern recognition training is not only beneficial in its own right, by addressing the orthographic knowledge deficits of children with slow naming speed, but orthographic pattern recognition training may also be the route through which we can improve processing of individual letters.

References

Ackerman, P. T., & Dykman, R. A. (1993). Phonological processes, confrontational naming, and immediate memory in dyslexia. *Journal of Learning Disabilities, 26,* 597-609.

Adams, M. J. (1990). *Beginning to Read: Thinking and Learning about Print.* Cambridge, MA: MIT press.

Ball, E. W., & Blachman, B. A. (1991). Does phonemic awareness training in kindergarten make a difference in early word recognition and developmental spelling? *Reading Research Quarterly, 26,* 49-65.

Barker, T. A., Torgesen, J. K., & Wagner, R. K. (1992). The role of orthographic processing skills on five different reading tasks. *Reading Research Quarterly,* 27, 334-345.

Berninger, V. W. (1987). Global, component, and serial processing of printed words in beginning of reading. *Journal of Experimental Child Psychology, 43,* 387-418.

Blachman, B. A. (1994). What we have learned from longitudinal studies of phonological processing and reading, and some unanswered questions: A response to Torgesen, Wagner, and Rashotte. *Journal of Learning Disabilities, 27,* 287-291.

Blachman, B. A. (1984). Relationship of rapid naming ability and language analysis skills to kindergarten and first-grade reading achievement. *Journal of Educational Psychology, 76,* 610-622.

Bowers, P. G. (2001). Exploration of the basis for rapid naming's relationship to reading. In M. Wolf (Ed.) *Dyslexia, Fluency, and the Brain* (pp.41-63), Timonium, Maryland: York Press.

Bowers, P. G. (1995, April). Re-examining selected reading research from the viewpoint of the "double deficit hypothesis". Paper presented at the Annual Meeting of the Society for Research in Child Development, Indianapolis, IN.

Bowers, P. G. (1993). Text reading and rereading: Predictors of fluency beyond word recognition. *Journal of Reading Behaviour, 25*, 133-153.

Bowers, P. G. (1989). Naming speed and phonological awareness: Independent contributors to reading disabilities. In S. McCormick & J. Zutell (Eds.), *Cognitive and Social Perspectives for Literacy Research and Instruction: 38th Yearbook of the National Reading Conference*. (pp.165-172). Chicago: National Reading Conference Incorporated.

Bowers, P. G., & Kennedy, A. (1993). Effects of naming speed differences on fluency of reading after practice. *Annuals of the New York Academy of Sciences, 682*, 318 -320.

Bowers, P. G., & Swanson, L. B. (1991). Naming speed deficits in reading disability: multiple measures of a single process. *Journal of Experimental Psychology, 51*, 195-219.

Bowers, P. G., & Wolf, M. (1993). Theoretical links among naming speed, precise timing mechanisms and orthographic skill in dyslexia. *Reading and Writing, 5*, 69-85.

Bowers, P. G., Steffy, R. A., & Swanson, L. B. (1986). Naming speed, memory, and visual processing in reading disability. *Canadian Journal of Behavioural Science, 18*, 209-223.

Bowers, P. G., Steffy, R. A., & Tate, E. (1988). Comparison of the effect of IQ control methods on memory and naming speed predictors of reading disability. *Reading Research Quarterly, 23*, 304-319.

Bowers, P. G., Sunseth, K., & Golden, J. (1999). The route between rapid naming and reading progress. *Scientific Studies in Reading, 3*, 31-53.

Bradley, L., & Bryant, P. (1983). Categorizing sounds and learning to read: A causal connection. *Nature, 301*, 419-421.

Bradley, L., & Bryant, P. (1991). Phonological skills before and after learning to read. In S. A. Brady, & D. P. Shankweiler (Eds.), *Phonological Processes in Literacy*, (pp.37-45). New York: Lawrence Erlbaum Associates.

Carver, R. P., & David, A. H. (2001). Investigating reading achievement using a causal model. *Scientific Studies of Reading, 5*, 107-140.

Chase, C. H. (1996). A visual deficit model of developmental dyslexia. In C. H. Chase, G. D. Rosen, & G. F. Sherman (Eds.), *Developmental Dyslexia: Neural, Cognitive, and Genetic Mechanisms*. Baltimore, Maryland: York Press.

Cornwall, A. (1992). The relationship of phonological awareness, rapid naming, and verbal memory to severe reading and spelling disability. *Journal of Learning Disabilities, 25*, 532-538.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19*, 450-466.

Das-Smaal, E. A., Klapwijk, M. J. G., & van der Leij, A. (1996). Training of perceptual unit processing in children with a reading disability. *Cognition and Instruction, 14*, 221-250.

Demb, J. B., Boynton, G. M., Best, M., & Heeger, D. J. (1998). Psychophysical evidence for a magnocellular pathway deficit in dyslexia. *Vision Research, 38*, 1555-1559.

Denckla, M. B., & Cutting, L. E. (1999). History and significance of rapid automatized naming. *Annals of Dyslexia, 49*, 29-42.

Denckla, M. B., & Rudel, R. G. (1976). Rapid "automatized" naming (RAN): Dyslexia differentiated from other learning disabilities. *Neuropsychologica, 14*, 471-479.

Ehri, L. C. (1992). Reconceptualizing the development of sight word reading and its relationship to recoding. In P. G. Gough, L. C. Ehri, & R. Treiman (Eds.), *Reading Acquisition* (pp.107-143). Hillsdale, NJ: Lawrence Erlbaum Associates.

Ehri, L. C. (1980). The development of orthographic images. In U. Frith (Ed.). *Cognitive Processes in Spelling* (pp.311-338). London, England: Academic Press.

Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: A review. *Psychonomic Society, 2*, 460-493.

Felton, R. H., Naylor, C. E., & Wood, F. B. (1990). Neuropsychological profile of adult dyslexics. *Brain and Language, 39*, 485-497.

Felton, R. H., Wood, F. B., Brown, I. S., Campbell, S. K., & Harter, M. R. (1987). Separate verbal memory and naming speed deficits in attention deficit disorder and reading disability. *Brain and Language, 31*, 171-184.

Goswami, U. (1999). Causal connections in beginning reading: The importance of rhyme. *Journal of Research in Reading, 22*, 217-240.

Goswami, U. (1988). Orthographic analogies and reading development. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 40A*, 239-268.

Goswami, U. (1986). Children's use of analogy in learning to read: A developmental study. *Journal of Experimental Psychology, 42*, 73-83.

Keen, A. G., & Lovegrove, W. J. (2000). Transient deficit hypothesis and dyslexia: Examination of whole-parts relationship, retinal sensitivity, and spatial and temporal frequencies. *Vision Research, 40*, 705-715.

Klein, R. M. (2002). Observations on the temporal correlates of reading failure. *Reading and Writing: An Interdisciplinary Journal, 15*, 207-231.

Levy, B. A. (2001). Moving the bottom: Improving reading fluency. In M. Wolf (Ed.). *Dyslexia, Fluency, and the Brain* (pp.357-379), Timonium, Maryland: York Press.

Levy, B. A., & Hinchley, J. (1990). Individual and developmental differences in the acquisition of reading skills. In T. H. Carr, & B. A. Levy (Eds.), *Reading and its development: Component skills approaches*. (pp.81-128). New York: Academic Press.

Levy, B. A., & Lysynchuk, L. (1997). Beginning word recognition: Benefits of training by segmentation and whole word methods. *Scientific Studies of Reading, 1*, 359-387.

Levy, B. A., Abello, B., & Lysynchuk, L. (1997). Transfer from word training to reading in context: Gains in fluency and comprehension. *Learning Disabilities Quarterly, 20*, 173-188.

Levy, B. A., Bourassa, D. C., & Horn, C. (1999). Fast and slow namers: Benefits of segmentation and whole word training. *Journal of Experimental Child Psychology, 73,* 115-138.

Livingstone, M. S., & Hubel, D. (1988). Segregation of form, color, movement, and depth: Anatomy, physiology, and perception. *Science, 240*, 740-749.

Livingstone, M. S., Rosen, G. D., Drislane, F. W., & Galaburda, A. M. (1991). Physiological and anatomical evidence for a magnocellular defect in developmental dyslexia. *Proceedings of the National Academy of Science, 88*, 7943-7947.

Lovett, M. W., Steinbach, K. A., & Frijters, J. (2000). Remediating the core deficits of developmental reading disability: A double-deficit perspective. *Journal of Learning Disabilities, 33*, 334-358.

Manis, F. R., & Freedman, L. (2001). The relationship of naming speed to multiple reading measures in disabled and normal readers. In M. Wolf (Ed.). *Dyslexia, Fluency, and the Brain* (pp.65-92). Timonium, Maryland: York Press Incorporated.

Manis, F. R., Seidenberg, M. S., & Doi, L. M. (1999). See Dick RAN: Rapid naming and the longitudinal prediction of reading subskills in first and second graders. *Scientific Studies of Reading, 3*, 129-157.

Manis, F. R., Doi, L. M., & Bhadha, B. (2000). Naming speed, phonological awareness, and orthographic knowledge in second graders. *Journal of Learning Disabilities, 33*, 325-333.

Mayzner, M., & Tresselt, M. E. (1965). Tables of single-letter and bigram frequency counts for various word-length and letter position combinations. *Psychonomic Monograph Supplements, 1*, 13-32.

McBride-Chang, C., & Manis, F. R. (1996). Structural invariance in the associations of naming speed, phonological awareness, and verbal reasoning in good and poor readers: A test of the double deficit hypothesis. *Reading and Writing: An Interdisciplinary Journal, 8*, 323-339.

Meyer, M. S., Wood, F. B., Hart, L. A., & Felton, R. H. (1998). Selective predictive value of rapid automatized naming in poor readers. *Journal of Learning Disabilities, 31*, 106-117.

Neuhaus, G., Foorman, B. R., Francis, D. J., & Carlson, C. D. (2001). Measures of information processing in rapid automatized naming (RAN) and their relation to reading. *Journal of Experimental Child Psychology, 78*, 359-373.

Olson, R., Forsberg, H., Wise, B., & Rack, J. (1994). Measurement of word recognition, orthographic, and phonological skills. In G. R. Lyons (Ed.), *Frames of Reference for the Assessment of Learning Disabilities: New Views on Measurement Issues* (pp. 243-277). Baltimore, MD: Paul H Brookes Publishing Company.

Perfetti, C. A. (1992). The representation problem in reading acquisition. In P. B. Gough, L. C. Ehri, & R. Treiman (Eds.), *Reading Acquisition* (pp.145-174). Hillsdale, NJ: Lawrence Erlbaum Associates.

Rosner, J. (1979). *Test of Auditory Analysis Skills.* Novato, CA: Academic Therapy Publications.

Sattler, J. M. (1992). *Assessment of Children's Intelligence: Revised and Updated Third Edition.* San Diego: Jerome M. Sattler Publisher Incorporated.

Scarborough, H. S. (1998). Predicting the future achievement of second graders with reading disabilities: Contributions of phonemic awareness, verbal memory, rapid naming and IQ. *Annals of Dyslexia, 48*, 115-136.

Semrud-Clikeman, M., Guy, K., Griffin, J. D., & Hynd, G. W. (2000). Rapid naming deficits in children and adolescents with reading disabilities and attention deficit hyperactivity disorder. *Brain and Language, 74*, 70-83.

Spring, C., & Perry, L. (1983). Naming speed and serial recall in poor and adequate readers. *Contemporary Educational Psychology, 8*, 141-145.

Stein, J. (1993). Dyslexia – impaired temporal information processing? *Annals of the New York Academy of Sciences, 682*, 83-86.

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language, 9,* 182-198.

Torgesen, J. K., & Wagner, R. K. (1998). Alternative diagnostic approaches for specific developmental reading disabilities. *Learning Disabilities Research and Practice, 13*, 220-232.

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1999). *Test of Word Reading Efficiency*. Austin, Tx: PRO-ED.

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1994). Longitudinal studies of phonological processing and reading. *Journal of Learning Disabilities, 27*, 276-286.

Torgesen, J. K., Wagner, R. K., Rashotte, C. A., Burgess, S., & Hecht, S. (1997). Contributions of phonological awareness and rapid automatic naming ability to the growth of word-reading skills in second to fifth grade children. *Scientific Studies of Reading, 1,* 161-185.

Touchstone Applied Science Associates. (1996). *Educator's Word Frequency Guide* [Computer Software].

van den Bos, K. P., Zijlstra, B., & lutje-Spelberg, H. C. (2002). Life-span data on continuous-naming speed of numbers, letters, colors, and picture objects, and word-reading speed. *Scientific Studies of Reading, 6*, 25-49.

van Daal, V. H. P., Reitsma, P., & van der Leij, A., (1994). Processing units in word reading by disabled readers. *Journal of Experimental Child Psychology, 57*, 180-210.

Waber, D. P. (2001). Aberrations in timing in children with impaired reading: Cause, effect, or correlate? In M. Wolf (Ed.). *Dyslexia, Fluency and the Brain* (pp.103 125). Timonium, Maryland: York Press Incorporated.

Wagner, R. K., & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin, 101*, 192-212.

Wagner, R. K., Torgesen, J. K., Laughon, P., Simmons, K., & Rashotte, C. (1993). Development of young readers' phonological processing abilities. *Journal of Educational Psychology, 85*, 83-103.

Watson, C., & Willows, D. M. (1995). Information processing patterns in specific reading disability. *Journal of Learning Disabilities, 28*, 216-231.

Wilkinson, G. S. (1993). *Wide Range Achievement Test – Third Edition.* Wilmington, DE: Wide Range Incorporated.

Williams, M. C., & LeCluyse, K. (1990). Perceptual consequences of a temporal processing deficit in reading disabled children. *Journal of the American Optometric Association, 61*, 111-121.

Wimmer, H. (1993). Characteristics of developmental dyslexia in a regular writing system. *Applied Psycholinguistics, 14*, 1-33.

Wimmer, H., Mayringer, H., & Landerl, K. (2000). The double-deficit hypothesis and difficulties in learning to read a regular orthography. *Journal of Educational Psychology, 92*, 668-680.

Wolf, M. (1997). A provisional, integrative account of phonological and naming speed deficits in dyslexia: Implications for diagnosis and intervention. In B. Blachman (Ed.), *Foundations of Reading Acquisition and Dyslexia: Implications for Early Intervention.* (pp.67-92). Mahwah, NJ: Lawrence Erlbaum Associates.

Wolf, M. (1986). Rapid alternating stimulus naming in the developmental dyslexias. *Brain and Language, 27*, 360-379.

Wolf, M. (1982). The word retrieval process and reading in children and aphasics. In K. E. Nelson (Ed.). *Children's Language Volume 3* (pp.437-493). Hillsdale, NJ: Lawrence Erlbaum Associates.

Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for the developmental dyslexias. *Journal of Educational Psychology, 91*, 415-438.

Wolf, M., Bally, H., & Morris, R. (1986). Automaticity, retrieval processes and reading: A longitudinal study in average and impaired readers. *Child Development, 57*, 988-1005.

Wolf, M., Bowers, P. G., & Biddle, K. (2000). Naming-speed processes, timing, and reading: A conceptual review. *Journal of Learning Disabilities, 33*, 387-407.

Wolf, M., Pfeil, C., Lotz, R., & Biddle, K. (1994). Towards a more universal understanding of the developmental dyslexias: The contribution of orthographic factors. In V. W. Berninger (Ed.). *The Varieties of Orthographic Knowledge I. Theoretical and Developmental Issues. Neuropsychology and Cognition, 8*, 137-171.

Wolf, M., Goldberg-O'Rourke, A., Gidney, C., Lovett, M., Cirino, P., & Morris, R. (2002). The second deficit: An investigation of the independence of phonological and naming-speed deficits in developmental dyslexia. *Reading and Writing: An Interdisciplinary Journal, 15*, 43-72.

Appendix A

Training Words for Experiment 4

List A Training Words

grape	**bra**ve
grave	**bra**y
gray	**bra**very
gravy	**bra**dy
w**are**	perv**ade**
p**are**	par**ade**
r**are**	ev**ade**
prep**are**	b**ade**
radar	**dr**ead
ray	**dr**awer
ragweed	**dr**yer
rage	**dr**ab
w**ay**	gr**ad**
d**ay**	br**ad**
p**ay**	d**ad**
j**ay**	eg**ad**
r**ea**r	g**ar**bage
r**ea**p	y**ar**d
b**ea**d	b**ar**ber
ber**ea**ve	b**ar**d

List B Training Words

chili	**sti**ck
chick	**sti**muli
chinook	**sti**tch
chino	**sti**lt
qu**ick**	st**uck**
sl**ick**	m**uck**
l**ick**	l**uck**
t**ick**	t**uck**
finish	**fl**inch
film	**fl**oss
fill	**fl**unk
fiction	**fl**out
kn**ot**	kn**it**
sl**ot**	qu**it**
l**ot**	l**it**
h**ot**	s**it**
f**un**ction	l**oo**m
s**un**lit	n**oo**n
n**un**s	h**oo**t
h**un**t	k**oo**k

Appendix B

Generalization Words in Experiment 4

List A		List B	
grade	graze	chin	chill
grazed	grader	chit	chink
brazed	braze	stiff	stint
brag	bragged	stink	still
rag	ragged	thick	click
raze	rave	kick	sick
drew	dredge	cluck	stuck
drape	draw	shuck	chuck
read	weave	flint	flock
beaver	reader	fluff	flush
jarred	garb	fish	fifth
barge	regard	finch	fist
beware	aware	skunk	lunch
dare	bare	munch	chunk
degrade	regrade	tooth	sooth
jade	wade	school	stool
array	away	clot	shot
prepay	pray	tot	cot
rad	bad	skit	slit
pad	gad	mit	kit